1. Viktor Kaplun [1], 2. Svitlana Makarevych [1], 3. Roman Chuenko

National University of Life and Environmental Sciences of Ukraine (1),
ORCID,1. 0000-0001-7040-9344, 2. 0000-0002-9601-5156, 3. 0000-0002-9339-9764

doi:10.15199/48.2022.03.10

Modelling of Asynchronous Motor with Split Stator Windings on the Principle of a Rotary Autotransformer

Abstract. *A mathematical model of electromagnetic and electromechanical processes with compensation of the reactive power of an induction motor by splitting the stator windings and their connection according to the scheme of a rotary autotransformer with the inclusion of additional capacities in each phase is proposed. It is proved that the shear angle between the main and additional half-windings of the stator phases of the compensated asynchronous motor is provided by the division of the phase zone into two equal parts and is. The results of numerical implementation of the model with the analysis of the influence of the spatial angle of shear of the additional winding on the nature of the action of magnetomotive forces, currents, torque and losses in the compensated asynchronous motor are shown*

Streszczenie. *Zaproponowano model matematyczny procesów elektromagnetycznych i elektromechanicznych z kompensacją mocy biernej silnika indukcyjnego poprzez rozdzielenie uzwojeń stojana i ich połączenie według schematu autotransformatora obrotowego z uwzględnieniem dodatkowych mocy w każdej fazie. Udowodniono, że kąt ścinania między głównym i dodatkowym uzwojeniem faz stojana kompensowanego silnika asynchronicznego jest zapewniony przez podział strefy fazowej na dwie równe części i jest. Przedstawiono wyniki numerycznej implementacji modelu z analizą wpływu przestrzennego kąta ścinania uzwojenia dodatkowego na charakter działania sił magnetomotorycznych, prądów, momentu obrotowego i strat w kompensowanym silniku asynchronicznym* (***Modelowanie silnika asynchronicznego z dzielonymi uzwojeniami stojana na zasadzie autotransformatora obrotowego***)

Keywords: asynchronous motor, internal capacitive compensation, principle of a rotary autotransformer voltage deviation..
Słowa kluczowe: silnik asynchroniczny, modelowanie, autotransformator

Introduction

Modern technological processes of production require efficient operation of power consumption systems [1-3]. The transformations that occur in the energy sector are primarily related to the reform of electricity markets with the introduction of energy-efficient equipment to reduce energy consumption and environmental impact [4]. The problem of reducing energy losses in modern technological complexes is becoming increasingly important.

An asynchronous electric motor with a short-circuited rotor (AM) is the most common means of converting electrical energy into mechanical energy in electric drives of working machines [5-6]. Electric drives with induction motors consume about half of the electricity consumed for production needs in industry and agricultural production. In the conditions of sustainable economic development it is important to improve the energy characteristics of asynchronous machines. Therefore, the development of simple (without making radical design changes) technical solutions that will increase the energy efficiency of induction motors while maintaining their reliability is an urgent research task. It is obvious that the search for such competitive methods lies in the plane of coordination of operational modes of the technological complex with the internal parameters of the asynchronous machine

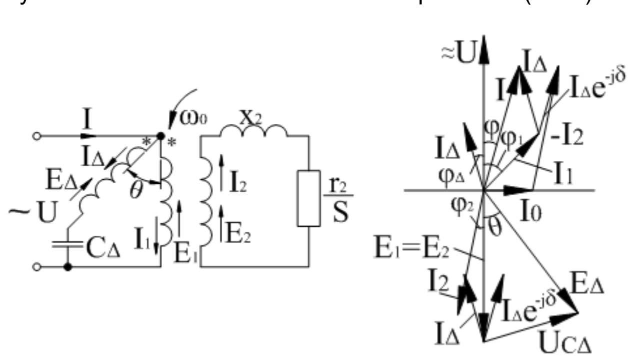
There are various approaches to solving the problem of improving the energy efficiency of induction motors. In particular, asynchronous electric motors have been developed, the energy performance of which increases due to the reduction of mass and dimensional parameters and the improvement of the quality of active materials [2]. Another way to improve the energy performance of AM is the use of external relative to the motor devices, especially inverters. Reduction of power consumption is achieved by adjusting the speed when powered by inverters. This increases the efficiency of the motor at low loads with any speed [2-3, 9, 11].

Among the new hardware used to improve the energy performance of unregulated asynchronous electric drive, we should note the so-called "soft start" devices - fairly simple thyristor devices that allow you to regulate the voltage at the motor terminals, and, accordingly, control the start and stop of the drive. and to provide energy saving mode by reducing the voltage on the underloaded motor [3,5].

There are also known developments to improve the power and starting-regulating characteristics of induction motors [1] through the use of a stator winding of special design with the connection of capacitors of electric capacity. However, the motors proposed [2], are characterized by a relatively high consumption of active materials (copper, electrical steel) per unit of useful power and a decrease in technical and economic indicators. In addition, the complexity of the technological process of manufacturing the windings of these motors leads to an increase in their cost.

Research Methods.

The design of the ferromagnetic core of the stator of an induction motor with its longitudinal grooves, spatially distributed along the circuit of the internal bore allows you to perform different schemes of windings that are functionally aligned and spatially displaced. This design of the armature core is quite favorable for finding new technical solutions to increase the energy efficiency of asynchronous motors based on internal capacitive compensation [5]. Such asynchronous motors will be called compensated (CAM).



a) b)

Fig. 1. Schematic electrical diagram and vector phase diagram of a compensated asynchronous motor

It is proposed to lay an additional winding with the number of turns w_1 in the grooves of the stator core in addition to the main winding with the number of turns w_Δ and turn them on according to the circuit of the rotary autotransformer (AT) to the electric capacitor C_Δ (Fig. 1).

The principle of internal capacitive compensation is explained as follows. In accordance with the properties of the AT [7] its output capacitive current $\dot{I}_\Delta$ due to electrical and electromagnetic communication with other currents will magnetize the magnetic circuit of the motor and compensate for its reactive power.

The output voltage of the autotransformer is equal to the geometric sum of the EMF vectors of its windings (fig. 1, b). Under the action of this voltage a current will flow in the additional winding $\dot{I}_\Delta = \frac{\dot{U}_{C\Delta}}{-jX_{C\Delta}}$, which is ahead of the voltage at the capacitance by 90°. The current $\dot{I}_\Delta$ is not purely reactive with respect to the EMF $\dot{E}_1$ and $\dot{E}_\Delta$, but has active components that coincide with them in phase.

In fact, the capacitive current $\dot{I}_\Delta$ at its spatial displacement relative to the EMF of the additional winding $\dot{E}_\Delta$ will have both reactive and active components. As a result, the secondary winding of the rotary AT will take over part of the total active power of the motor, there will be a combination of functions of the main (working) and additional (compensating) windings of the motor.

It is established that the spatial displacement of the current $\dot{I}_\Delta$ the secondary winding of the AT relative to the primary change in time by the angle of displacement of the time coordinate (phase) of this current, spatially reduced to the axis of the main winding. Under the conditions of mathematical modeling [7-8], the current $\dot{I}_2$ of the rotating rotor with periodic circular change of the angle of rotation, reduced to the axis of the main stator winding, equivalent to the magnetomotive force does not depend on the angle of rotation, and the current $\dot{I}_\Delta$ of the fixed secondary winding, is reduced $\delta=\pm180^{\circ}+\theta$ to its spatial axis with a change in its time phase at this angle by rotating the vector $\dot{I}_\Delta$ at an angle $\delta=\pm180^{\circ}+\theta$ toward the axis of the main winding.

With a wide range of changes in the spatial angle of displacement of the compensating winding relative to the main combined stator winding you can without changing the nature and magnitude of relativities (inductance, capacitance) to change the temporal nature of magnetic forces, currents and other electrical quantities. Based on the equivalence of changes in the spatial and temporal coordinates of electrical quantities and the effect of internal capacitive compensation of reactive power, it is possible to increase the energy efficiency of electric machines with a rotating magnetic field [8, 10].

In AM, a circuit is used to connect the primary and secondary windings of a rotary AT to a common assembly with terminals of the same name. This connection of the windings can provide both increase and decrease the voltage at the output of the rotary AT with a change in its phase depending on the angle *θ* between the windings (Fig. 1).

The characteristics of compensated induction motors in transient and steady-state processes of normal and abnormal modes, a mathematical model based on the electrical substitution circuit was developed [7-8].

The classical mathematical model of an asynchronous machine with constant parameters was taken as a basis. It is presented in real phase coordinates of the main stator winding with reduction to its phase axes of fixed rotor currents equivalent the rotating and additional stator winding spatially offset relative to the main by some angle *θ*. A system of equations of electrical equilibrium of stator and rotor circuits, equations of electromagnetic moment of the motor is used for modeling of electromagnetic and electromechanical processes of compensated asynchronous machine (CAM) and used for previous experimental studies [7,8].

$$\begin{cases} e_A - e_B = i_{1A}(r_1 + r_{1d} + r_{LA}) + (L_s + L_{1d} + L_{LA})\frac{di_{1A}}{dt} - i_{1B}(r_1 + r_{LB}) - (L_s + L_{LB})\frac{di_{1B}}{dt} - i_{\Delta A} r_{LA} \\ + \left[2kM\cos\left(\theta + 60^{\circ}\right) - L_{LA}\right]\frac{di_{\Delta A}}{dt} + i_{\Delta B} r_{LB} + \left[2kM\cos\left(\theta + 120^{\circ}\right) + L_{LB}\right]\frac{di_{\Delta B}}{dt} + M\frac{di'_a}{dt} - M\frac{di'_b}{dt}, \\ e_A - e_B = i_{1A}(r_1 + r_{LA}) + (L_s + L_{LC})\frac{di_{1A}}{dt} + i_{1B}(2r_1 + r_{LB} + r_{LC}) + (2L_s + L_{LB} + L_{LC})\frac{di_{1B}}{dt} - i_{\Delta A} r_{LC} + \\ + \left[2kM\cos\left(\theta - 60^{\circ}\right) - L_{LC}\right]\frac{di_{\Delta A}}{dt} - i_{\Delta B}(r_{LB} + r_{LC}) + \left[2kM\cos\theta - L_{LB} - L_{LC}\right]\frac{di_{\Delta B}}{dt} + \\ + M\frac{di'_a}{dt} + 2M\frac{di'_b}{dt} \end{cases}$$

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

$$\begin{cases} e_A - e_B = i_{1A} + \left[2kM\cos\left(\theta + 120^{\circ}\right) + L_{LA}\right]\frac{di_{\Delta A}}{dt} - i_{1B} r_{LB} - \left[2kM\cos\left(\theta + 60^{\circ}\right) - L_{LB}\right]\frac{di_{1B}}{dt} - \\ - i_{1A}(r_1 + r_{1d} + r_{LA}) - (L_{s\Delta} + L_{\Delta d} + L_{LA})\frac{di_{1A}}{dt} - \frac{1}{C_A}\int i_{\Delta A}dt + i_{\Delta B}(r_\Delta + r_{LB}) + (L_{s\Delta} + L_{LA})\frac{di_{\Delta B}}{dt} + \\ + \frac{1}{C_B}\int i_{\Delta B}dt + 2kM\cos\left(\theta + 120^{\circ}\right)\frac{di'_a}{dt} + 2kM\cos\left(\theta + 60^{\circ}\right)\frac{di'_b}{dt}; \\ e_B - e_C = i_{1\Delta} r_{LC} - \left[2kM\cos\left(\theta + 60^{\circ}\right) - L_{LC}\right]\frac{di_A}{dt} + i_{1B}(2r_\Delta + r_{LC} + r_{LB}) - \left[2kM\cos\theta - L_{LC} - L_{LB}\right]\frac{di_{LB}}{dt} - \\ - i_{\Delta A}(r_\Delta + r_{LC}) - (L_{s\Delta} + L_{LC})\frac{di_{\Delta A}}{dt} - \frac{1}{C_C}\int \Delta A\,dt - i_{\Delta B}(2r_\Delta + r_{LC} + r_{LB}) - (2L_{s\Delta} + L_{LC} + L_{LB})\frac{di_{\Delta B}}{dt} - \\ - \left(\frac{1}{C_B} + \frac{1}{C_C}\right) i_{\Delta B}dt - 2kM\cos\left(\theta + 60^{\circ}\right)\frac{di'_a}{dt} - 2kM\cos\theta\frac{di'_b}{dt}. \end{cases}$$

$$M_E = \frac{-M}{\sqrt{3}}\left[\left(i_{1A} + ki'_{\Delta A}\right)\left(i'_b - i''_c\right) + \left(i'_{1B} + ki'_{\Delta B}\right)\left(i'_c - i''_a\right) + \left(i'_{1C} + ki'_{\Delta C}\right)\left(i'_b - i''_b\right)\right]$$

$$M_E = M_c + J\frac{d\omega}{dt}$$

In experimental studies of the effect of voltage deviation on the technological characteristics of working machines, the voltage on the motor was changed using autotransformers, while measuring the motor speed with a tachometer.

In experimental studies of the effect of voltage asymmetry on the stiffness of mechanical characteristic and angular speed of the asynchronous motor a rheostat was switched on in one of the stator phases. The researched motor loading was a DC machine with independent excitation, angular speed of which was regulated by the system "generator - motor". The speed of the electric motor was measured by a tachometer, and the current of the loading machine was measured by an ammeter, which was used to determine the torque of the motor.

Voltage was measured with voltmeters in each phase of the motor and voltage asymmetry coefficient was determined in reverse order.

Results

In accordance with the magnetization curve of the motor [7-8] the main EMF of the stator winding nonlinearly depends on the resistance of the magnetization circuit, which was taken into account calculating the characteristics of the ring (Fig. 2).

For objectivity, the results obtained to calculate model and object of research the both basic motor (AM 4A71V2), low power to 11 kW, $cos\varphi$=0,7-0,9 and CAM of the stator r_1=20 Ohm, x_1=4,72 Ohm in each branch is accepted. Rotor windings with r_2=5,91 Ohm, x_1=7,2 Ohm, the resistance of the magnetizing circuit at idle X_{mn}=250 Ohm [7], in the magnetizing mode X_{mn}=300 Ohm, in the starting at s=1 X_{mn}=400 Ohm.

The calculation of the characteristics of the base AM and CAM was carried out in the range of changes in the angle of spatial displacement between the axes of the half-windings of the stator phases $-180^o \le \theta \le 180^o$ - for the nominal mode (nominal slip) and during start-up.

$$
Xm(s) := \begin{cases}
278 & \text{if } 0 \le s < 0.01 \\
290 & \text{if } 0.01 \le s < 0.02 \\
301 & \text{if } 0.02 \le s < 0.03 \\
312 & \text{if } 0.03 \le s < 0.04 \\
322 & \text{if } 0.04 \le s < 0.05 \\
333 & \text{if } 0.05 \le s < 0.06 \\
344 & \text{if } 0.06 \le s < 0.07 \\
353 & \text{if } 0.07 \le s < 0.08 \\
364 & \text{if } 0.08 \le s < 0.09 \\
379 & \text{if } 0.09 \le s < 0.1 \\
405 & \text{if } 0.1 \le s < 0.2 \\
418 & \text{if } 0.2 \le s < 0.3 \\
421 & \text{if } 0.3 \le s < 0.4 \\
423 & \text{if } 0.4 \le s < 0.5 \\
424 & \text{if } 0.5 \le s < 0.6 \\
425 & \text{if } 0.6 \le s < 0.7 \\
425 & \text{if } 0.7 \le s < 0.8 \\
426 & \text{if } 0.8 \le s < 0.9 \\
426 & \text{otherwise}
\end{cases}
$$

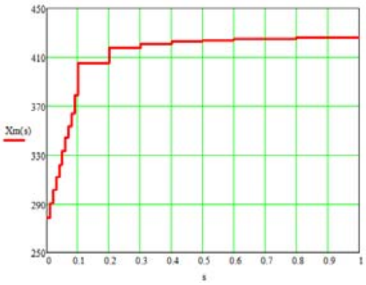


Fig. 2 Change the resistance of the magnetization circuit CAM

According to the results of numerical studies, the starting and operating currents of the ring, its torque and losses at the selected value of the capacitance C_Δ=32μF, depends on the angle of displacement of the axes of the half-windings of the stator phases. The starting and operating currents of the ring, its torque and internal losses at the selected value of the capacitance largely depend on the angle of displacement of the axes of the half-windings of the stator phases (Fig. 3, 4).

In contrast to the base AM, where the current of the single stator winding has an active-inductive nature in both the starting and operating modes, the stator winding CAM has two operating windings. The main current $\dot{I}_1$ retains the active-inductive character, and the current of the additional $\dot{I}_\Delta$ (secondary winding AT) at the capacitive load AT is capacitive-active. As in a normal AM the starting current $\dot{I}_1$ of the main winding exceeds the nominal 5-6 times, and the current $\dot{I}_\Delta$ depends on the magnitude of the capacitance C_Δ and the angle of spatial displacement of the axes of the main and auxiliary windings The current $\dot{I}_\Delta$, as capacitive, increases the voltage $\dot{U}_\Delta = -\dot{E}_\Delta + \dot{I}_\Delta z_\Delta + j\, x_1 \cos\theta \cdot \dot{I}_1$ on the secondary winding of the AT. The voltage $\dot{U}_{C\Delta} = \dot{U} - U_\Delta$ at the output of AT is equal to that at constant voltage $\dot{U}$ of the network increases $\dot{U}_{C\Delta}$ changes its phase and the magnitude, phase of the capacitive current $\dot{I}_\Delta = \dfrac{\dot{U}_{c\Delta}}{-jx_{c\Delta}}$ (Fig. 1, b).

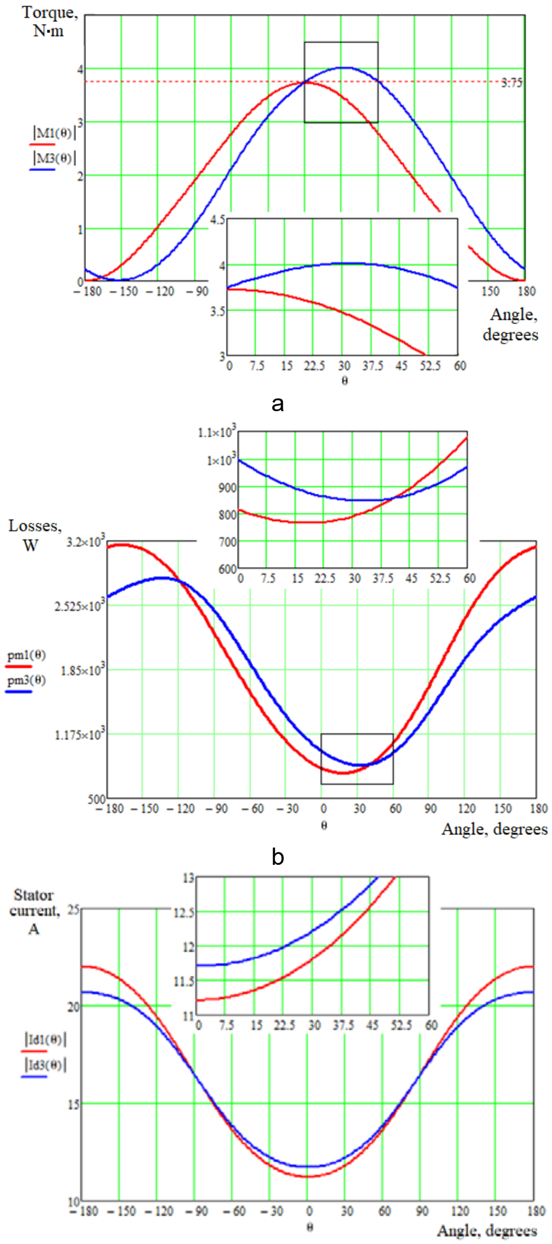


Fig. 3. Dependencies parametrs of the motor: a)torque from angle, b) losses from angle, c) stator current from angel is consumed by the motor at slip s= 1

In this case, the current $\dot{I}_\Delta e^{-j\theta}$, reduced to the axis of the main winding, participates in part in the generated magnetizing current $\dot{I}_0 = \dot{I}_1 + \dot{I}_\Delta e^{-j\theta} + \dot{I}_2$ and additional EMF EPC $\dot{E}_{\Delta m} = -j\, X_m \dot{I}_\Delta e^{-j\theta}$, which is close in phase to the EMF and EPC $\dot{E}_1 = \dot{E}_2$ and $\dot{E}_\Delta$, and increases them. Increasing the EMF along the magnetization curve requires increase in the magnetizing current $\dot{I}_\Delta e^{-j\theta}$, replacing part of the inductive component, reduces $\dot{E}_2$ the value at an equivalent overall increase in the magnetizing current. The reduction of the inductive component of the magnetizing current under the magnetizing action of the capacitive spatially shifted current $\dot{I}_\Delta e^{-j\theta}$ leads to a reduction in the consumption CAM reactive power Q_0 ring to create the main magnetic flux. This shows the effect of current $\dot{I}_\Delta$ in the circuit of the rotary AT. The electrical action of this current leads to a direct exchange of reactive energy between the consumer KAM and the source of reactive power (capacitors with capacitance $C_Д$) to increase the power factor $cos\varphi_1$ of the motor [8].

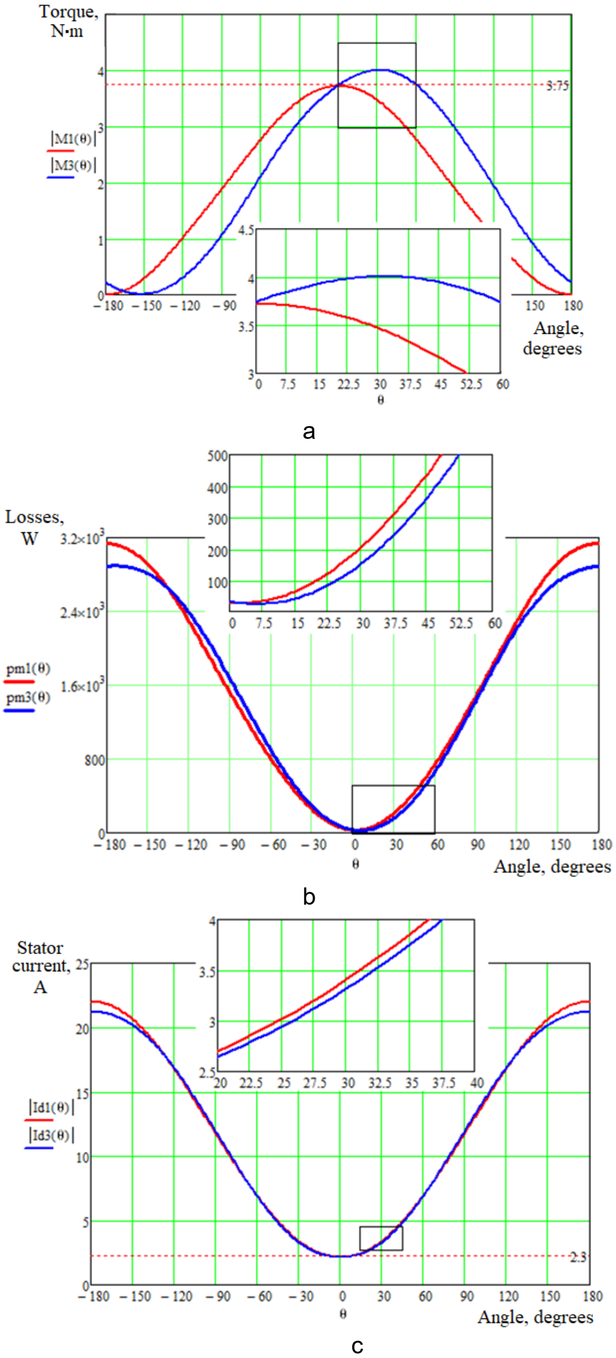


Fig. 4. Dependenices parametrs of the motor: a)torque from angle b) losses from angle, c) stator current from angel is consumed from power supply network at nominal slip s_n= 0,06.

In CAM the additional EMF $\dot{E}_{\Delta m} = -jX_m\dot{I}e^{-j\theta}$ from the spatially offset relative AT axis of the main winding of the capacitive current pressure increases the main EMF of the stator and rotor $\dot{E}_1 = \dot{E}_2$. The increase in the EMF $\dot{E}_2$ of the rotor at constant parameters r_2/s and x_2 is equivalent to the introduction of additional EMF in the circuit, but through the stator. When starting CAM this leads to an increase in the starting current of the rotor $\dot{I}_2 = \frac{\dot{E}_2}{r_2/S + jx_2}$ at $S = 1$ and $\frac{r_2}{S} = r_2$, and, accordingly, the starting torque $M_S = \frac{mI_2^2 r_2}{\omega_0 S} = \frac{mI_{2S}^2 r_2}{\omega_0}$.

The analysis of the obtained calculated data (Fig. 3-4) shows that the most favorable angle of displacement of the axes of the main and additional half-windings of the stator phases of the CAM is the angle θ=30°. There is an increase of motor's torque (23% during start-up and 15% during nominal slip). Under the action of the increased starting moment the process of dispersal of CAM, rigidity of mechanical characteristic in an operating mode in comparison with the characteristic of base AM is accelerated At the angle θ=30° is a decrease in losses in the motor and motor current at rated slip (by 25% and 3%) respectively.

In addition, from the point of view of manufacturability, the angle θ=30° between the windings of the AT in the stator of the compensated induction motor is easily obtained by dividing the phase zone 60° of the three-phase stator winding of the base motor into two equal parts that are spatially offset in the grooves.

The results of research conducted using the proposed mathematical model of the compensated induction motor indicate that it is advisable to choose the amount of spatial shift between the axes of the half-windings of the stator phases of the compensated induction motor θ=30°. Because this increases the starting torque of the motor and the torque at rated slip, and the current consumed by the motor from the mains and the losses in the motor are reduced compared to the basic AM. In addition, the angle θ=30° is technologicallysimple to provide by dividing the phase zone of the base motor into two equal parts. The aim of further research should be to establish the connect between the characteristics AM and the value of the capacitances of the internal capacitive compensation of reactive power at a reasonable angle of spatial shift of the half-windings of the stator phases θ=30°.

Conclusions

A mathematical model of a compensated asynchronous motor high energy efficiency was developed. It was based on the theory of electric circuits. Researches have shown the correlation of the main energy parameters of the ring mode CAM with the design changes of the stator winding. The research concerned the substantiation spatial displacement the current secondary winding of the autotransformer into the primary by the angle of displacement the time coordinate, spatially reduced to the axis of the main winding. In accordance with the properties of the autotransformer due to electrical and electromagnetic connect with other currents, its output capacitive current will magnetize the magnetic circuit of the ring and thus compensate for its reactive power. The range of the spatial angle displacement of the compensating winding relative to the main combined stator winding changes the time diagram of the action of magnetomotive forces, winding currents are turned out, Equivalence of spatial and temporal coordinates of electric quantities of CAM allowed to establish better conditions of manifestation of effect of internal capacitive compensation of reactive power with the minimum constructive improvements of AM. The magnitude of the spatial shift between the axes of the half-windings stator phases CAM, in which there is an improvement in its characteristics compared to the base motor 30° was proved. Quantitative assessment of the energy efficiency of CAM requires additional research.

***Authors**: Prof. Viktor Kaplun, assoc. prof. Svitlana Makarevych, assoc. prof. Chuenko Roman, National University of Life and Environmental Sciences of Ukraine, Ukraine, str. Heroiv Oborony, 15, Kyiv, 03041, E-mail: wwwanten@gmail.com, birma0125@gmail.com, roman_chuenko@ukr.net.*

REFERENCES

[1] Lushchik V.D. Perspective directions of improvement of electric machines. Kyiv: Komprint, 2015, p.265 (Ukr).
[2] Yu. Shurub; Al. Dudnyk; Vi. Vasilenkov; Dm. Lavinskiy "Application of a Kalman Filter in Scalar form for Discrete Control of Electromechanical Systems". *IEEE Problems of Automated Electric Drive. Theory and Practice* (PAEP), November 2020, pp. 1-4.
[3] Yu. Shurub, "Research on a self-contained induction-machine based electromachanical system in unbalanced working conditions", Electrical Engineering & Electromechanics, no. 2, 2009., pp. 55-56.
[4] I. Kopylov *Mathematical modeling of electric machines*. Moskva: Vysshaia Shkola, 2001, p.327 (Rus).
[5] O. Chornii., A. Lugovoi., D. Rodkin., G..Sysiuk., O. Sadovoi. *Modelling of electromechanical systems*. Kremenchuk, 2001, p. 410 (Rus).
[6] V. Mishin,., N. Lut,., S. Makarevich and R. Chuenko, "Analogs and characteristics of compensated asynchronous machines with different numbers of phases" in Russian Electrical EngineeringVolume 87, Issue 12, 1 December 2016, pp. 653-660.
[7] V. Mishin, R. Chuenko and S. Makarevich, "Conditions for stable joint operation of asynchronous machines of different types in an autonomous electromechanical system", Russ. Electr. Engin, vol. 84, pp. 518-527, September, 2013.
[8] M. Zablodskiy, V. Pliuhin and R. Chuenko, "Simulation of induction machines with common solid rotor".in Technical electrodinamic. 2018. № 6, pp. 42-45.
[9] Chavaporn Bumroongphuck, Vijit Kinnares, Performance Analysis of a modified three-phase induction motor with optimal capacitance fed by single-phase AC supply. *PRZEGLĄD ELEKTROTECHNICZNY* (2020), nr. 10, 62 – 70.
[10] Vasyl Malyar, Orest Hamola, Volodymyr Maday, Ivanna Vasylchyshyn, Mathematical modeling start-up and steady state modes of asynchronous motors operation with capacitive compensation of reactive power. *PRZEGLĄD ELEKTROTECHNICZNY* (2020), nr. 11, 109 – 114.
[11] Maciej Gwozdziewicz, Piotr Kisielewski, Enclosure-less six-phase induction motor. *PRZEGLĄD ELEKTROTECHNICZNY* (2019), nr. 6, 141 – 144.