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

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

doi:10.15199/48.2023.10.34

Modified compensated asynchronous machine for increasing energy efficiency of autonomous alternator in low-power supply system

***Abstract.** The paper is devoted the operating modes of a compensated asynchronous machine of low power in the alternator mode in order to increase its energy efficiency for autonomous power supply systems by constructively improving the base machine. Mathematical model was Improved to calculate the characteristics of a compensated asynchronous machine in alternator mode with different space-time orientation currents of stator phase semi-windings in symmetrical mode with constant sliding.Numerical modelling and comparative analysis of the external characteristics of an autonomous asynchronous alternator according to different schemes for including compensating was completed. capacities. The ways to ensure the rigidity of external characteristics and increase the energy efficiency of autonomous low-power power supply systems are shown.*

***Streszczenie.** Artykuł zawiera studium trybów pracy kompensowanej maszyny asynchronicznej małej mocy w trybie generatorowym w celu zwiększenia jej sprawności energetycznej dla autonomicznych układów zasilania poprzez udoskonalenie konstrukcyjne maszyny podstawowej. Udoskonalono model matematyczny do obliczania charakterystyk skompensowanej maszyny asynchronicznej w trybie generatorowym o różnej orientacji czasoprzestrzennej prądów półuzwojeniowych faz stojana w trybie symetrycznym ze stałym poślizgiem. Przeprowadzone modelowanie numeryczne i analiza porównawcza charakterystyk zewnętrznych autonomicznego generatora asynchronicznego według różnych schematów włączenia kondensatorów kompensacyjnych wskazały sposoby zapewnienia sztywności charakterystyk zewnętrznych i zwiększenia efektywności energetycznej autonomicznych układów zasilania małej mocy.(**Zmodyfikowana skompensowana maszyna asynchroniczna do zwiększenia efektywności energetycznej autonomicznego alternatora w układzie zasilania małej mocy**)*

Keywords: Autonomous low-power supply system, compensated autonomous asynchronous alternator, energy efficiency, external characteristic
Słowa kluczowe: Autonomiczne układy zasilania typu catch-power, skompensowany autonomiczny generator asynchroniczny, efektywność energetyczna, charakterystyki zewnętrzne

Introduction

Modern technology development requires a stable and reliable power supply. More Increasing relevance under conditions of frequent outages of centralized power supply reservation system are acquired. The first, the priority in most cases remains for simple and reliable asynchronous alternator (AA) as components of autonomous low-power supply system (ALPS) [1]. The main advantage of the application AA with a squirrel-cage rotor in ALPS is absence, as opposed to synchronous, rather complex excitation system [2].

As known, an asynchronous machine is reversible and can work in motor and alternator modes [3]. A low-power asynchronous alternator made on the basis of an asynchronous motor with a short-circuited rotor has small weight and dimensions and high reliability. It is quite easy to operate, however, compared to a synchronous alternator, it has worse performance in terms of voltage stabilization when working on an alternating load [4, 5]. The idea of research is to justify the technical improvements of the asynchronous machine (without interfering with its design) for its use in the alternator mode as part of increased energy efficiency ALPS.

Due to the wide nomenclature fleet of autonomous low-power supply system with internal combustion engines, the scientific research of asynchronous alternators with new operational properties is an actual task.

Literature survey

Various approaches are known to solve the problem of energy efficiency of autonomous asynchronous alternator (AAA). An AA, as an element of a two-way supply of an autonomous power supply system (ALPS), needs capacitive reactive energy for self-excitation and compensation of the reactive energy of the load [6, 7]. The operation of an asynchronous alternator on a variable load without dynamic transients leads to a decrease in voltage and, as a result, a decrease in the production of reactive power by compensating capacitors. To stabilize the voltage of an AAA when the load changes, such methods as compounding, the use of variable capacity batteries, the use of ferro resonance type stabilizers, the use of controlled saturation chokes, etc. are known. [8, 9].

Materials and methods

The compensated asynchronous machine, as one of the modifications, has great reserves for further improvement and increasing its efficiency, primarily due to the use of internal capacitive compensation of reactive power. The research task is to substantiate the parameters of the compensated autonomous asynchronous alternator as an alternative to the autonomous synchronous generator.

The compensated autonomous asynchronous alternator (CAAA), as well as the compensated asynchronous motor is manufactured on the mass production three-phase asynchronous motor with a short-circuited rotor. Each phase winding of the stator is divided into two parallel parts (half-windings), spatially offset from each other in the grooves of the stator core at an angle of 30^o [3]. In the simplest case with an even number of grooves per pole and phase $q = Z/2pm$ and groove step $\gamma = (360^o \cdot p)/Z$ phase zone of the stator winding $q\gamma = 60^0$ is divided into two equal parts by 30^o each and with an angle θ = 30^o between the axes of the semi-windings of the stator phases. In other cases, the half-windings are made in two separate layers of slots and offset between them by any angle proportional to the slot pitch γ. The half-windings of the stator phases of the compensated asynchronous alternator are connected according to the scheme of the rotary autotransformer (RA) to the electrical capacity C_Δ (fig. 1).

One of the half-windings of the stator phase is considered the main one, since the consumer is connected to its terminals. We will consider it as the primary winding of the RA. The other half-winding, as the secondary winding of the RA, would be as additional (compensating) winding. The axis of the additional winding is spatially shifted relative to the axis of the main winding by an angle of 30° in the direction rotation of alternator field. As it was proved earlier [3], to strengthen the effect of internal capacitive compensation of reactive power, the secondary winding of RA can be shunted with additional capacity C_k.

When the rotor is rotated by the drive motor, the flow of residual magnetism, crossing the stator windings, induces electromotive force (EMF) in them. Under their action, capacitive currents arise in the stator circuit closed to electrical capacitors, which, exciting the machine, increase

a)

b)

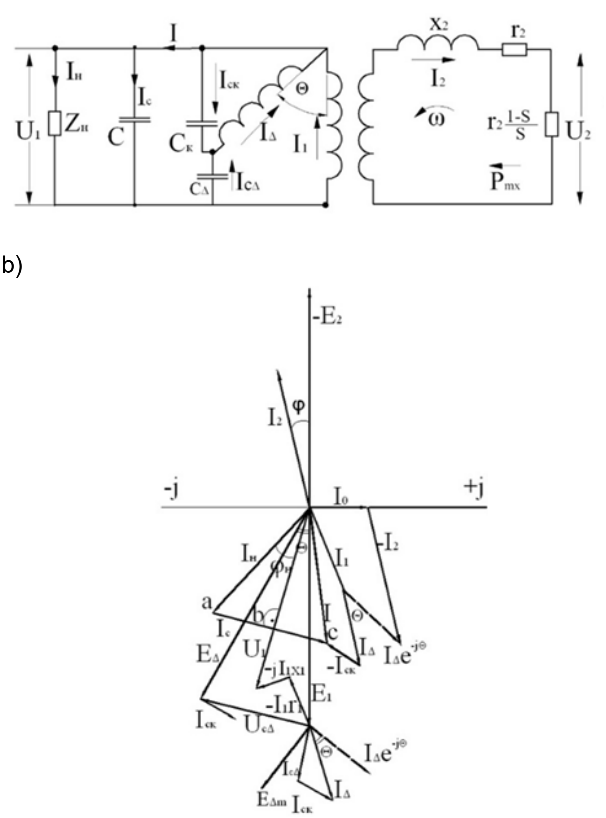

Fig. 1. Basic electrical diagram of the CAAA phase with additional capacitive magnetizing (a) and its vector diagram (b)

its magnetic flux. Self-excitation of the machine occurs as in a classic autonomous asynchronous alternator. But in the CAAA three compensating capacitors are used in this process: internal working C_Δ, internal shunt C_k and external C.

In accordance with their functional purpose, the internal working capacity C_Δ in the scheme of the rotary RA mainly provides excitation of the alternator and stabilizes its voltage under load. The internal shunt capacity increases the efficiency of the internal capacitive compensation of reactive power, providing a reduction in the magnetizing current of the machine. The external capacity C at the output of the alternator is designed to compensate for the reactive power of the load Z_n.

Generalized solutions and constructive improvements for a compensated autonomous asynchronous alternator with external, internal and additional internal capacitive compensation of reactive power ($C \neq 0$, $C_\Delta \neq 0$ and $C_k \neq 0$) opened the way for finding the most energy-efficient modes of operation an autonomous alternator. Using the certain algorithms and circuits for turning on the compensating capacitors are allowed to find possibility the energy parameters of the machine for the characteristic modes of operation of the CAAA.

Calculation equations of the CAAA phase which working on a static load in a steady-state process of a symmetric mode according to the diagram (fig. 1) have the form:

$$\begin{aligned}
&\dot{U}_1 = \dot{E}_1 - \dot{I}_1 z_1 - jx_1 \cos\Theta \cdot \dot{I}_\Delta = \dot{I} \cdot Z,\\
&\dot{U}_1 = \dot{U}_\Delta - \dot{U}_{c\Delta} = \dot{E}_\Delta - \dot{I}_\Delta z_\Delta - jx_1 \cos\Theta \cdot \dot{I}_1 + jx_{c\Delta} \cdot I_{c\Delta},\\
&\dot{U}_\Delta = \dot{E}_\Delta - \dot{I}_\Delta z_\Delta - jx_1 \cos\Theta \cdot \dot{I}_1 = -jx_{c\kappa} \cdot \dot{I}_{c\kappa},\\
&0 = \dot{E}_2 - \dot{I}_2 z_2.
\end{aligned} \tag{1}$$

In the equations of system (1) the parameters of the substitution circuit (fig. 1, a) are specified: constant parameters of the basic asynchronous machine r_1, x_1, r_2, x_2, x_m – variable resistance of the magnetization circuit. Entered parameters are capacitive resistances x_c, $x_{c\Delta}$, x_{ck} and load resistance $Z_n = k_n Z_{nb}$ at $Z_{nb} = r_{nb} + jx_{nb} = 80 + j60 = 100e^{j\varphi}$ Ohm. $Z_n = var$ with a variable load factor k_n. The resistance of the main and additional stator windings to be the same as $z_1 = r_1 + jx_1 \equiv z_\Delta$.

The rotation speed of the alternator rotor is set by the drive motor. Therefor determines the frequency of the EMF and currents of the no-load alternator and is the basic condition for bringing the rotating machine to the equivalent stationary one.

The first of the unknown parameters is the EMF of the alternator. It is the main energy parameter of the al. Then we find the currents and voltages at the output of the alternator and at individual sections of its circuit. The calculation is carried out in the operating mode of a rotating machine, equivalently reduced to a stationary, for which, according to the diagram in fig. 1 are valid as:

$$\begin{aligned}
&\dot{E}_1 = \dot{E}_2 = -jx_m \dot{I}_0;\ \dot{E}_\Delta = \dot{E}_1 e^{j\theta};\ \dot{I}_0 = \dot{I}_1 + \dot{I}_\Delta e^{-j\theta} + \dot{I}_2;\\
&\dot{I}_2 = \frac{\dot{E}_2}{\dot{Z}_2};\ \dot{I} = \dot{I}_1 + \dot{I}_\Delta - \dot{I}_{c\kappa} = \frac{\dot{U}_1}{Z} = \dot{I}_н + \dot{I}_c;\\
&\dot{I}_н = \frac{\dot{U}_1}{Z_н};\dot{I}_{c\kappa} = \frac{\dot{U}_\Delta}{-jx_{c\kappa}};\dot{I}_c = \frac{\dot{U}_1}{-jx_c};\\
&\dot{I}_\Delta = \dot{I}_{c\Delta} + \dot{I}_{c\kappa};\ \dot{I}_{c\Delta} = \frac{\dot{U}_{c\Delta}}{-jx_{c\Delta}};Z = \frac{-jx_c Z_н}{Z_н - jx_c}
\end{aligned} \tag{2}$$

Taking into account relations (2), system (1) is reduced to two equations of tie between the currents $\dot{I}_1$ and $\dot{I}_\Delta$ half-windings of the stator phases and the main EMF $\dot{E}_1$ of the alternator:

$$a\dot{E}_1 = b\dot{I}_1 + c\dot{I}_\Delta,\ d\dot{E}_1 = e\dot{I}_1 + f\dot{I}_\Delta, \tag{3}$$

where the parametric coefficients are represented as:

$$\begin{aligned}
&a = 1 + k_z e^{j\theta};\ b = z_1 + Z + k_{\ z} jx_1 \cos\theta;\\
&c = z_1 k_z + Z + jx_1 \cos\theta; d = (k_c + k_z) e^{j\theta};\\
&e = Z + (k_c + k_z) jx_1 \cos\theta;\ f = (k_c + k_z) z_1 + Z - jx_{c\Delta}.
\end{aligned} \tag{4}$$

The solution of system (3) determines the stator currents as $\dot{I}_1 = \gamma \dot{E}_1$, $\dot{I}_\Delta = \Delta \cdot \dot{E}_1$ at

$$\begin{aligned}
&\gamma = \frac{af - cd}{bf - ce} = \frac{(k_c + k_z)(z_1 - jx_1 \cos\theta e^{j\theta}) + Z(1 - e^{j\theta}) - jx_{c\Delta}}{G},\\
&\Delta = \frac{bd - ae}{bf - ce} = \frac{(k_c + k_z)(z_1 e^{j\theta} - jx_1 \cos\theta) + Z(k_c e^{j\theta} - 1)}{G},\\
&G = bf - ce = [(k_c + k_z)(z_1 + jx_1 \cos\theta) + Z(k_c + 1)](z_1 - jx_1 \cos\theta) -\\
&- jx_{c\Delta}(Z_1 + Z + k_z jx_1 \cos\theta)\\
&k_c = 1 + \frac{x_{c\Delta}}{x_{c\kappa}},\ k_z = \frac{jZ}{x_{c\kappa}}.
\end{aligned} \tag{5}$$

The parametric coefficients are given for CAAA in a generalized view for a set of options for capacitive compensation, which includes external and double internal.

Expressions (4, 5) can also be used for partial variants of capacitive compensation. Thus, for CAAA with $C_k = 0$, $k_c = 1$, $k_z = 0$ the given coefficients will have the following form:

$$\gamma = \frac{z_1 - jx_1 \cos\theta \cdot e^{j\theta} + Z(1-e^{j\theta}) - jx_{c\Delta}}{G},$$

(6) $$\Delta = \frac{z_1 e^{j\theta} - jx_1 \cos\theta + Z(e^{j\theta}-1)}{G}$$

$$G = (z_1 + jx_1 \cos\theta + 2Z)(z_1 - jx_1 \cos\theta) - jx_{c\Delta}(z_1 + Z),$$

for CAAA with two parallel parts in the stator winding, the axes of which are not shifted in space, $\theta = 0$, $C_k = 0$, $x_{c\Delta} = 0$, $k_c = 1$, $k_z = 0$, $x_c \neq 0$ from (5) is determined:

(7) $$\gamma = \Delta = \frac{1}{z_1 + jx_1 + 2Z} = \frac{1}{2(Z_{10} + Z)},$$

at $\dot{I}_1 = \dot{I}_\Delta = \frac{\dot{I}}{2} = \gamma \dot{E}_1 = \Delta \dot{E}_1$.

During calculating the external characteristics of the CAAA, the change in the resistance of magnetization circuit was taken into account according the method given in [10].

Results

The efficiency of an AA is evaluated by its external characteristic [9]. The external characteristics of the AAA based on mass production using different modes of reactive power internal capacitive compensation and without it were calculated (fig. 2).

The external characteristics of an AAA with external capacitive compensation of reactive power (fig. 2, a) indicates that with increasing of load (the resistance of the load Z_n decreases with $cos\varphi_n = const$ and $x_c = const$, both the active and reactive components of the alternator's current increase. This requires the capacitive current of the external capacitor bank to increase for compensation of the load's reactive power and reduces the excitation current of the alternator. As a result, the alternator is getting demagnetized, its EMF and the output voltage decreased. This leads to decreasing of the current I_c and subsequent demagnetization of the machine.

The external characteristics of CAAA are steeply descending, soft (fig. 2, a). To achieve the nominal voltage and load current, a sufficiently large capacitance of the external capacitor bank C is required (low resistance $x_c \approx$ 76 Ohm).

The presence of capacitance C_Δ in one of the working circuits of the CAAA with load increasing leads to an increase of the capacitive current and hinders magnet circuit demagnetization. The external characteristics become more rigid (fig. 2, b). The external capacitance C, necessary to achieve the nominal values of voltage and current, decreases.

In the CAAA, as the load increases, the active components of the both stator windings currents and the reactive component of the load current also increase. This, as in the AAA, requires increasing capacitive current $\dot{I}_C$. It reduces the part of the reactive current of the main stator winding necessary for the alternator excitation.

The additional capacitance C_Δ in the circuit of the secondary RA winding increases the total current of this winding and increases reactive power generation. In result it decreases demagnetization of the machine and increases rigidity of external characteristics (fig. 2, c). In order to ensure a nominal voltage 230 V and current $I_n == 2.3\ A$ at the nominal load resistance $Z_n = (80 + j60)$ Ohm, a smaller external capacitance C (x_c > 76 Ohm) is required.

Due to the obtain working capacity C_Δ in the circuit of the additional stator phase half-winding, their currents $\dot{I}_1$ and $\dot{I}_\Delta$ have different both in magnitude and phase. Only for x_c = 102 Ohm, $x_{c\Delta}$ = 60 Ohm, they have the same magnitude, but are significantly shifted from each other in phase. It drastically reduces the energy efficiency of the alternator (fig. 3). However, due to the magnetizing effect of the capacitive current, the consumption of reactive power Q_0 for the excitation of the alternator at this point will be less than for the same load in the alternator without internal compensation (AAA Q_0 = 327 VAr, and for CAAA Q_0 = 280 VAr).

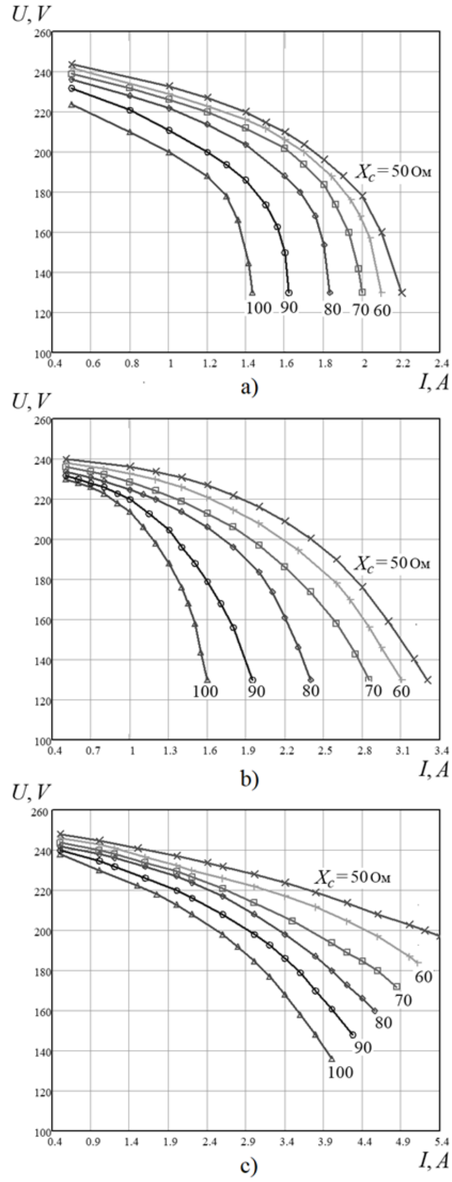

Fig. 2. External characteristics of autonomous asynchronous alternators: a – asynchronous alternator with external capacity; b – compensated asynchronous alternator with external and internal capacities; c – compensated asynchronous alternator with external, internal and additional capacities

Discussion

The combination of external (C) and double internal (C_Δ, C_k) capacitances compensation in the CAAA strengthens the advantages and eliminates the disadvantages of the CAAA, Shunting by the capacity C_k additional stator phase half-winding increases the value and changes the phase of the additional winding current $\dot{I}_\Delta = \dot{I}_{c\Delta} + \dot{I}_{c\kappa}$. At the same time, the additional EMF $\dot{E}_{\Delta m} = -jx_m \dot{I}_\Delta e^{-j\theta}$ increases as part of the main EMF $\dot{E}_1 = -jx_m(\dot{I}_1 + \dot{I}_\Delta e^{-j\theta} + \dot{I}_2) = -jx_m \dot{I}_0$, which increases the voltage of the alternator $\dot{U}_1$. And the further increase of current $\dot{I}_\Delta$ due to the active part of the load current of the alternator increases the rigidity of the external alternator's characteristic. As the load increases, the voltage decreases within the permissible limits, decreasing from no-load to nominal load not more than 5%.

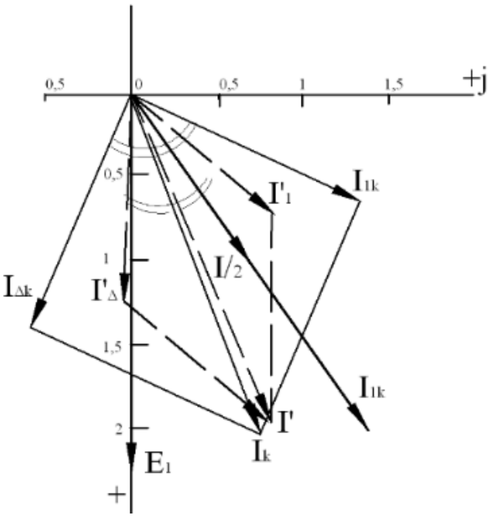

Fig. 3. Fragment of vector diagrams of stator currents of AAA with external capacity, CAAA with external and internal capacities, CAAA with internal and additional capacitance at U_n = 230 V, Z_n = 80+j60 Ohm

The data is obtained as a result of the calculation CAAA characteristics are confirmed with sufficient accuracy by the data of experiments. In particular, in fig. 4 is shown the compensated AA external characteristics, based on calculated and experimental data.

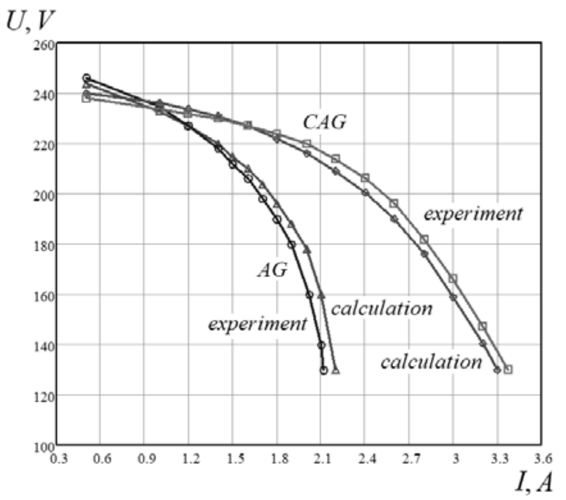

Fig. 4. External characteristics of the usual AA and compensated AAA obtained by calculation and experiment

Conclusions

The research results indicate, that in CAAA under a constant load due to the magnetizing action of the internal capacitive compensation current $I_Δ$, the volume of the magnetizing inductive current I_0 decreases. An increasing of the magnetization circuit resistance x_m leads to decrease of the alternator's reactive power consumption $Q_0 = I_0^2 x_m$ to create main magnetic flux. The alternator's power factor exceeds the value of 0.9 (compared to $\cos φ_{AAA}$ = 0.745), reaching 0.96 for CAAA.

The displacement of the additional winding current's phase $\dot{I}_Δ$ caused by the action of the current $\dot{I}_{Ck}$ and its transformer connection with the main winding brings the stator half-windings currents phases closer to each other, bringing them closer to the active components (Fig. 4) relative to the voltage $\dot{U}_1$ (EMF $E_1 \approx U_1$). It increases the efficiency of the alternator by reducing the magnitudes of the currents I_1 and $I_Δ$. Forming the total current, the alternator increases it's power factor and reduces power losses in the windings.

The EMF of the additional and main windings are close to each other by magnitude and to the output voltage of the alternator. Therefore, for changing in the magnitude and phase of the current $\dot{I}_Δ$, and $\dot{I}_{CK}$ relatively small values of the capacitance C_k (are required. It possible to adjust the voltage U of alternator by changing the additional capacity C_k. It is also possible to force the voltage during operation of the alternator with a sharply changing load and with a power of the consumer comparable to the power of alternator. The research work will be conducted in these directions.

***Authors**: prof. dr. eng. sc., Victor Kaplun, National University of Life and Environmental Sciences of Ukraine, 12 Heroyiv Oborony str., Kyiv, 03041 Ukraine, E-mail: wwwanten@gmail.com; assoc. prof. Roman Chuienko, National University of Life and Environmental Sciences of Ukraine, 12 Heroyiv Oborony str., Kyiv, 03041 Ukraine, E-mail: roman_chuenko@ukr.net; assoc. prof. Svitlana Makarevych, National University of Life and Environmental Sciences of Ukraine, 12 Heroyiv Oborony str., Kyiv, 03041 Ukraine, E-mail: birma0125@gmail.com;*

REFERENCES

[1] Viktor Kaplun, Svitlana Makarevych, Roman Chuenko. Modelling of Asynchronous Motor with Split Stator Windings on the Principle of a Rotary Autotransformer. *Przegląd Elektrotechniczny* (2022), nr. 3, 39-44.

[2] Oleg Gubarevych, Svitlana Golubieva, Inna Melkonova. State University of Infrastructure and Technologies (1), Volodymyr Dahl East Ukrainian National University Comparison of the results of simulation modeling of an asynchronous electric motor with the calculated electrodynamic and energy characteristics *Przegląd Elektrotechniczny* (2022), nr. 10, 61-67.

[3] Kopylov I. P. Mathematical Modelling of Electrical Machines, M.: H. Sch., 2001, 326 p. (in Russian)

[4] Mykhailiuk, O. B. (2016). Problems that need a solution while using asynchronous generator of renewable energy in power plants. Visnyk of Vinnytsia Politechnical Institute, (1), 96–100.

[5] Vali, A. A., Hosseini, S. M. H., & Olamaei, J. (2022). Control of doubly-fed induction generator with extended state observer under unbalanced grid conditions. Scientia Iranica, 29(5), 2498-2514. doi: 10.24200/sci.2020.55054.4054.

[6] H. Santoso, R. Hasanah, I. Wardana, B. Mismail, "Loading Performances of Low-Power Low-Speed Single-Phase Induction Generator with Energy Saving Lamps", Applied Mechanics and Materials, Vol. 785, p. 290, 2015.

[7] Mishin, V.I., Kaplun, V.V. & Makarevich, S.S. Self-contained induction generator with internal capacitive compensation. *Russ. Electr. Engin.* 82, 138–143 (2011). https://doi.org/10.3103/S1068371211030060

[8] O. Alabed Alkhamis and A. Abusafe. Study of induction generators performance of two-speed used in standalone wind turbines, International Journal of Energy and Smart Grid, vol. 1, no. 2, pp. 37-57, Dec. 2016, doi:10.23884/IJESG.2016.1.2.02

[9] Vasko, P., Holovko, V., & Verbovij, A. (2016). The high harmonic components of voltage and current of the asynchronous generator with short-circuited rotor winding in small wind and hydroelectric installations. Vidnovluvana Energetika, 4 (47), 63-67.

[10] Mykhaylo Zagirnyak, Volodymyr Chenchevoi, Vita Ogar, Olha Chencheva, Rostyslav Yatsiuk. Refining Induction Machine Characteristics at High Saturation of Steel. Przegląd Elektrotechniczny (2020), nr 11. 119-123. doi:10.15199/48.2020.11.24.