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Asynchronous generator replacement scheme with internal capacitive reactive power compensation

Abstract. The relevance of using compensated induction machines in the generator mode of autonomous power supply systems is determined by their ability to provide a stable and reliable power supply even in the absence of an external grid. The research aims to develop a procedure for determining the characteristics of an equivalent circuit of compensated induction generators that considers the mutual influence between the main and additional phase windings of the armature. The theory of an idealised induction machine with the representation of electromechanical energy conversion processes and basic physical parameters in the form of equations of electrical equilibrium and drive motion was used to obtain the calculated characteristics of the generator's operating modes of this class. The generalised system of differential equations made it possible to calculate dynamic and static processes for symmetrical and asymmetrical modes at given machine parameters under different methods of excitation and voltage stabilisation under variable load. For the practical implementation of modelling the parameters of an induction generator, the equations of electrical equilibrium of the stator and rotor circuits for the symmetrical steady-state mode are used, which is a special case of the generalised mathematical model of the machine for both transient and steady-state processes with constant parameters of the substitution scheme. Consideration of the structural and functional features of compensated induction generators was made possible by using a mathematical model with the armature winding divided into two coaxial or spatially offset half-windings. In this case, the number of calculation equations doubles. The use of an autotransformer scheme for switching on the stator phase half-windings to capacitors required the introduction of an additional differential equation

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for the electrical equilibrium of the stator phases. This made it possible to substantiate the values of active and inductive resistances used in the replacement circuit of an induction generator with internal capacitive reactive power compensation. The mutual inductive coupling of the main and additional half-windings of the generator stator phase windings due to both the operating magnetic flux and the magnetic fluxes of dissipation was considered. The practical significance of the obtained results is to increase the efficiency and stability of the power supply, which helps to reduce losses and improve the operation of electric power systems

Keywords: asynchronous machine; internal capacitive compensation; reactive power; active resistance; inductive resistance; mutually inductive coupling

INTRODUCTION

The study and calculation of the characteristics of induction machines (IMs) is an important task, as it helps to develop and improve the electrical industry, contributing to the conservation of energy resources and the creation of more stable and efficient power supply systems. With the development of new materials and production technologies, the design of induction machines needs to be adapted to new designs and functional properties. This helps to create more powerful, efficient, and stable machines. C.A.C. Wengerkievicz *et al.* (2017), the characteristics of an induction machine are calculated using a system of design equations for the electrical equilibrium of the stator and rotor windings, compiled according to Kirchhoff's second law. This system of equations is based on the generally accepted assumptions of the classical theory of electric machines at constant values of stator and rotor resistances and is a special case of the general mathematical model of an induction machine for both steady-state and transient operating modes.

To calculate the characteristics of compensated induction generators (CIG), S.V. Kumar *et al.* (2023) used a mathematical model that considers its new design and functional properties. The manufacture of stator phase windings consisting of two parts that are coaxially or spatially offset by an arbitrary angle necessitates a twofold increase in the electrical equilibrium equations. In addition, H. Terzioğlu & M. Selek (2017) described that the use of an autotransformer scheme for switching on additional stator phase windings to capacitors leads to the need to write an additional differential equation of electrical equilibrium of the stator phases.

An important problem that arises when using a compensated induction generator (CIG) in autonomous power supply systems is voltage stabilisation under variable load. V.I. Mishin *et al.* (2022) established the quantitative and qualitative dependencies of an induction machine analytically, which was carried out considering the classical theory of an idealised induction machine, where the main physical parameters and electromechanical energy conversion processes are represented in the form of equations of electrical equilibrium and drive motion. The presented generalised equation system in differential form in M. Popp *et al.* (2017) makes it possible to calculate dynamic and static processes for symmetrical and asymmetrical modes under given machine parameters and excitation conditions. Physical processes and features of CIG design solutions, caused by the presence of additional spatially displaced electromagnetic circuits with capacitance, complicate the mathematical model and increase the order of the system of differential equations. According to M.M. Tezcan *et al.* (2018), this requires the adoption of additional special conditions and approaches for calculating physical processes in machines of this class.

It is commonly used to calculate the characteristics of induction machines in the L-shaped substitution scheme and to bring them to the equivalent parameters of the T-shaped scheme. The L-shaped scheme is simple, and the magnetisation current is assumed to be constant, independent of the AM load. However, to ensure greater accuracy in reflecting physical processes in an induction machine, the T-shaped substitution scheme should be preferred in our case. According to M. Liu *et al.* (2023), the design of a compensated induction generator differs from the basic asynchronous machine, so the parameters of the replacement scheme of the basic asynchronous machine cannot be used to calculate its characteristics.

O.M. Popovych & M.O. Smahliuk (2014) considered a variant of an induction machine with a compensation winding. The use of such a winding when the machine operates in motor mode allows for controlling its energy efficiency. However, the compensation winding carries only reactive power and does not carry an active load. The study proposes variants of the stator windings of a compensated asynchronous generator, where both the main and additional stator phase windings are carriers of both reactive and active powers.

The study aims to develop a methodology for calculating the parameters of the replacement circuit of compensated asynchronous generators, considering their design features and the mutually inductive connection between the main and additional phase windings of the armature.

MATERIALS AND METHODS

Experimental studies of the compensated asynchronous generator were carried out at the Department of Electrical Engineering, Electromechanics and Electrical Technologies of the Educational and Research Institute of Energy, Automation and Energy Saving of the National University of Life and Environmental Sciences of Ukraine. A Metrix-3252 digital oscilloscope (manufactured by Chauvin Arnoux, France) was used to obtain the waveforms. The following methods were used to substantiate the parameters of the compensated asynchronous generator replacement circuit, considering its design features, and to verify the results obtained: analytical using the theory of a generalised electromechanical energy converter; mathematical and electrical modelling; and experimental. A compensated asynchronous generator manufactured on a serial asynchronous motor AIR71V2 (АИР71В2, Ukraine) was selected as the object of computational and experimental studies.

Studies of A.E. Kravchik *et al.* (1982), J. Rolek & G. Utrata (2018), and A.R. Helonde & M.M. Mankar (2019), which contain information on the parameters of induction machines, were used. At the same time, either an L-shaped replacement scheme (Fig. 1a) or a T-shaped replacement scheme for an induction machine (Fig. 1b) was used. For the L-shaped substitution scheme, the active resistance of the stator phase winding $R_1^/$ and the inductive resistance of the stator phase winding $X_1^/$, as well as the active resistance of the rotor phase winding $R_2^{//}$ and the inductive resistance of the rotor phase winding $X_2^{//}$ were considered. In addition, the inductive resistance due to the mutually inductive coupling between the armature and rotor phase windings in the case of their axes coincidence and the total main inductive resistance of the armature phase winding X_m at the rated load of the combined induction machine was considered.

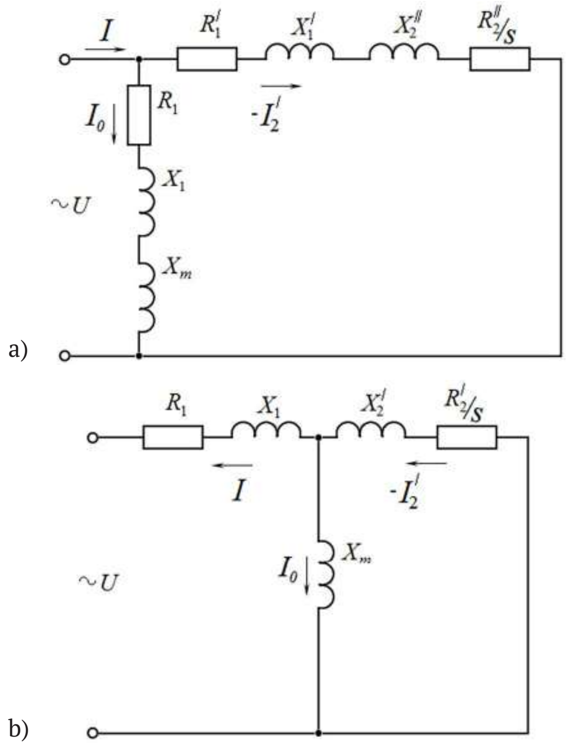


Figure 1. Asynchronous generator replacement scheme
Note: a – L-shaped; b - T-shaped; $R_1^/$ – active resistance of the stator phase winding, $X_1^/$ – inductive resistance of the stator phase winding, $R_1^{//}$ – active resistance of the rotor phase winding, and $X_1^{//}$ inductive resistance of the rotor phase winding, X_m – main inductive resistance of the armature phase winding, *s* – sliding
Source: R. Chuenko & O. Kryvoshey (2014)

To calculate the characteristics of the AG under a steady-state symmetrical load, a T-shaped substitution scheme was used (Fig. 1b), which describes the physical processes occurring in the generator with high accuracy (Mishin *et al.*, 2022). The transition from the active and inductive resistances of the L-shaped substitution scheme to the resistances of the T-shaped substitution scheme was carried out using the following formulas (Mishin *et al.*, 2011):

$$X_1 = \frac{2X_1^/ X_m}{X_m+\sqrt{{X_m}^2+4X_1^/ X_m}} R_1 = R_1^/ \frac{X_1}{X_1^/};\ R_2 = \frac{R_2^{//}}{c^2};$$
$$X_2 = \frac{X_2^{//}}{c^2},\ c \approx 1+\frac{X_1}{X_m}\dot{I}_2 = c\cdot \dot{I}_2'. \qquad (1)$$

To express parameters in a system of relative units R_1 (*r.u.*), X_1 (*r.u.*), and R_2 (*r.u.*) it is necessary to have the values of the corresponding resistances in named units and use the following formulas:

$$R_1(r.u.) = \frac{R_1(Ohm)}{Z_n(Ohm)} A;\ X_1(r.u.) = \frac{X_1(Ohm)}{Z_n(Ohm)};$$
$$R_2(r.u.) = \frac{R_2(Ohm)}{Z_n(Ohm)} \ldots , \qquad (2)$$

where $Z_n = \frac{U_n}{I_n}$ – total resistance of the armature phase winding of an induction machine at rated mode operation in case of star connection of the armature winding, Ohm; $I_n = \frac{P_n}{3\cdot U_n \eta_n \cos\phi_n}$ – current of the armature phase winding at rated operation, A; U_n – phase voltage at rated load, B, η_n – asynchronous machine efficiency, $\cos_{\varphi n}$ – asynchronous machine power factor, P_n – rated asynchronous power output.

RESULTS AND DISCUSSION

Unlike a basic induction machine, each phase winding of a compensated induction generator armature consists of two half-windings: the main winding and the auxiliary winding. The main and auxiliary windings can be connected either in series (Fig. 2a) or in parallel (Fig. 2b).

Depending on the connection scheme of the main and auxiliary windings, the number of turns of the main and auxiliary windings will also change, as well as the possible voltage on the armature terminals of the compensated generator. Accordingly, to conduct numerical studies of the characteristics of the CIG, the corresponding parameters of its substitution scheme should be used. The phase winding of the armature of the base machine contains *w* turns. In the case of using internal capacitive reactive power compensation with a series connection of the main and auxiliary windings, the winding of the base machine is divided into two equal parts with the number of turns *w*/2 each, which are switched on in series. In this case, the resistance of the main and auxiliary windings of the generator armature phases will be equal to $R_1/2$. The inductive resistance due to the presence of magnetic fluxes of the main and auxiliary windings will also be halved compared to the basic machine – $X_1/2$. Similarly, the total main resistance of the main and auxiliary windings of the armature phase of the CIG – $X_m/2$ – will be halved. In this case, the phase replacement scheme of an induction generator with a series connection of half-windings is as shown in Figure 3a.

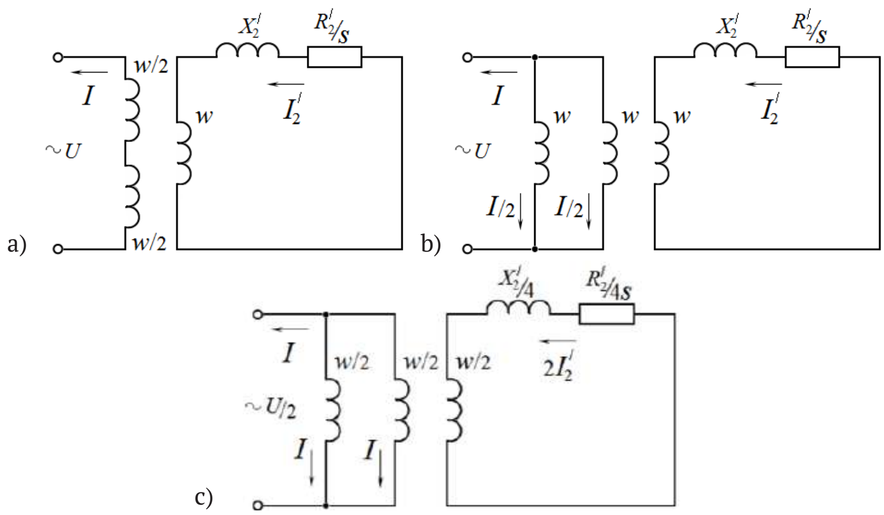


Figure 2. Schematic diagrams of the phase winding of the armature CIG

Note: a – when the main and auxiliary windings of the armature phase are switched on sequentially; b – when the main and auxiliary windings are switched on in parallel; c – for switching the winding of the base machine to a circuit with two parallel windings, where R_1, R_2 – resistance of the main and auxiliary windings of the generator armature phases, X_1, X_2 – inductive resistance of the main and auxiliary windings, w – number of coils, S – sliding, X_m – main resistance of the main and auxiliary windings of the CIG armature phase

Source: compiled by the authors based on R. Chuenko & O. Kryvoshey (2014)

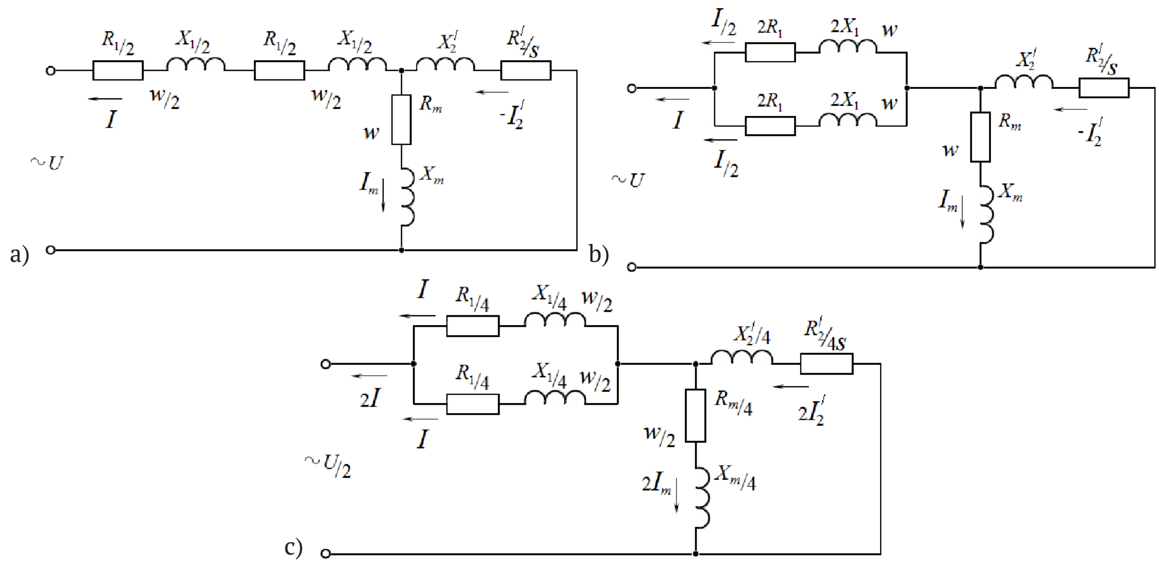


Figure 3. Phase replacement schemes for compensated induction generators

Note: a – the main and additional windings of the armature phase are switched on in series; b – the main and auxiliary windings of the armature phase are switched on in parallel; c – for switching the series winding to two parallel windings, where R_1, R_2 – resistance of the main and auxiliary windings of the generator armature phases, X_1, X_2 – inductive resistance of the main and auxiliary windings, w – number of coils, S – sliding, X_m – main resistance of the main and auxiliary windings of the CIG armature phase

Source: compiled by the authors

The total inductive reactance of the phase winding of an induction machine armature consists of its inductive reactance, the value of which depends directly on the square of the number of windings, and the inductive reactance due to the mutual inductive coupling with neighbouring magnetically coupled windings, which depends on the product of the number of turns of these windings. At the same time, the mutually inductive coupling between the windings by magnetic fluxes is not considered. When the main and auxiliary windings of the armature phases of the CIG are connected in series, their inductive reactance will depend on w^2 and will be determined by the inductive dissipation resistance:

$$X_{1i} = \frac{X_1}{4} \equiv \left(\frac{w}{2}\right)^2, \quad (3)$$

and the main resistance:

$$X_{mc} = \frac{X_m}{4} \equiv \left(\frac{w}{2}\right)^2. \quad (4)$$

The discrepancy between the total resistance of consecutive half-windings $\frac{X_1}{2}$, $\frac{X_m}{2}$ and their values $X_{1c} = \frac{X_1}{4}$, $X_{mc} = \frac{X_m}{4}$ is caused by the mutually inductive connection between the main and auxiliary windings of the armature phases of the CIG as in terms of operating magnetic flux, and terms of magnetic flux dissipation. As a result, the total inductive reactances of the main and auxiliary windings increase by $X_{1b} = \frac{X_1}{4} \equiv \left(\frac{w}{2}\right)^2$ due to the action of the magnetic flux scattering and on the value of $X_{mb} = \frac{X_m}{4} \equiv \left(\frac{w}{2}\right)^2$ due to the action of the main magnetic flux.

Thus, the inductive dissipation resistance of the main and auxiliary windings of the phase winding of the armature of the CIG, which are located without spatial displacement of their axes, will be determined by the following formula: $\frac{X_1}{2} = X_{1i} + X_{1b} = \frac{X_1}{4} + \frac{X_1}{4}$. The main inductive resistance is equal to $\frac{X_m}{2} = X_{mi} + X_{mb} = \frac{X_m}{4} + \frac{X_m}{4}$, and the mutual induction resistance of the stator half-windings with the rotor winding, respectively – $\frac{X_m}{2} \equiv \frac{w}{2} \cdot w$.

In a basic induction machine, there is a mutually inductive connection in terms of operating magnetic flux between all armature and rotor windings of different phases (Rolek & Utrata, 2017; Tezcan *et al.*, 2018). In its turn, the magnetic flux is closed only between the armature half-windings of the same phase. Considering a CIG with sequential switching on of the main and auxiliary windings, which do not have spatial displacement of the axes, the mutually inductive coupling by the magnetic flux should be considered as a component of the inductive resistance $X_{1b} = \frac{X_1}{4}$. If there is a spatial offset between the axes of the main and auxiliary windings by an angle θ, then the inductive resistance component due to the magnetic flux scattering will be equal to $\frac{X_1}{4} \cdot \cos\theta$.

In the case of using the variant of internal capacitive reactive power compensation with a parallel connection of the main and additional windings of the generator armature phase (Fig. 2b), each of these windings will be under the same voltage. Accordingly, if the base machine had the armature winding parameters R_1, X_1, X_m, then the resistances of each of the two parallel branches of the phase winding of the CIG will be equal to $2R_1$, $2X_1$, $2X_m$, respectively, and at the total rated current I_n, the rated current of the main and auxiliary windings will be half the total rated current – $I_n/2$.

If the main and auxiliary windings of the armature phase of the CIG have the same number of turns as the armature phase winding of the base machine w, then the inherent inductive resistance of the scattering and the main inductive resistance, as well as the inductive resistance due to the mutually inductive coupling by the scattering magnetic flux and the operating magnetic flux, will be equal to the corresponding inductive resistances of the base machine winding $X_{1v} = X_{1b} = X_1$, $X_{mv} = X_{mb} = X_m$. In this case, the inductive resistances of the main and additional windings will be $X_{1v} + X_{1b} = 2X_1$, $X_{mv} + X_{mb} = 2X_m$. The rotor parameters remain unchanged R_2, X_2, X_m (Fig. 3b)

In practice, it may be necessary to change the switch scheme of the main and auxiliary windings of the armature phase of an induction generator from series to parallel (Fig. 2c). In this case, the number of turns of the generator armature phase winding will remain unchanged, and the main and auxiliary windings will have *w*/2 coils each. For the generator energy characteristics to remain unchanged under different schemes of switching on the main and auxiliary windings (Fig. 2b) and (Fig. 2c), it is necessary to reduce the generator output voltage (*U*/2) by half and to increase the rated armature current and the rated rotor current by 2 times. The inductive dissipation resistance of the main and additional armature windings will be equal to $\frac{X_1}{2} = \frac{X_{1c}}{4} + \frac{X_{1b}}{4}$, standard resistance $\frac{X_m}{2} = \frac{X_{1c}}{4} + \frac{X_{mb}}{4}$, and the general parameters of the entire stator winding are respectively $\frac{X_1}{4}, \frac{X_m}{4}, \frac{R_1}{4}$. When switching from a real CIG to a reduced CIG, the number of turns of the rotor winding must be reduced by a factor of 2. Accordingly, the inductive dissipation resistance of the rotor of the combined CIG will be equal to $X_2^/ = \frac{X_2}{4}$. In turn, the active rotor impedance of the combined gas turbine will also be halved $R_2{}^/ = \frac{R_2}{4}$, as its current has doubled (Fig. 3c).

When a compensated induction machine operates in the motor mode, it consumes active and reactive power from the power supply network and converts electrical energy into mechanical energy (Fig. 4a). When operating in the generator mode as part of an autonomous power supply system, the compensated induction machine itself is a source of active and reactive power for the consumer and converts mechanical energy into electrical energy (Fig. 4b):

$$\begin{aligned}
&1)\ \dot{U}_1 = \dot{E}_1 - \dot{I}_1 z_1 - jx_1 \cos\Theta \cdot \dot{I}_\Delta = \dot{I} \cdot Z,\\
&2)\ \dot{U}_1 = \dot{U}_\Delta - \dot{U}_{c\Delta} = \dot{E}_\Delta - \dot{I}_\Delta z_\Delta - jx_1 \cos\Theta \cdot \dot{I}_1 + jx_{c\Delta} \cdot I_{c\Delta},\\
&3)\ \dot{U}_\Delta = \dot{E}_\Delta - \dot{I}_\Delta z_\Delta - jx_1 \cos\Theta \cdot \dot{I}_1 = -jx_{CK} \cdot \dot{I}_{CK},\\
&4)\ 0 = \dot{E}_2 - \dot{I}_2 z_2.
\end{aligned} \quad (5)$$

The design equations of the CIG phase when operating on a static load in a steady-state process of the symmetrical mode by the schematic diagram of its phase (Fig. 5) are as follows (Mishin *et al.*, 2011):

One of the most common characteristic variants of an autonomous power supply system is the operation of an autonomous generator for an induction motor. In particular, the external characteristics of a compensated induction generator were calculated, from which an induction motor AIR71V2 with a capacity of 0.75 kW is started and powered. The values of the compensating capacitances were equal: external capacity $C = 30$ μF, internal capacitance $C_\Delta = 28$ μF and additional internal capacity $C_k = 10$ μF.

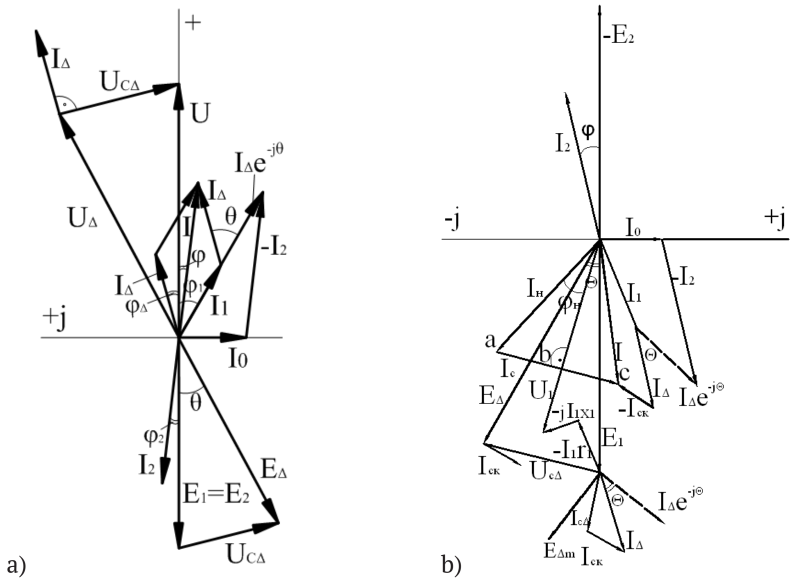


Figure 4. Vector diagrams of a compensated induction motor (a) and a compensated induction generator (b)

Note: U – power supply voltage; $U_Δ$ – voltage on the additional stator winding; $U_{CΔ}$ – voltage on the internal capacity; E_1 – electromotive force of the main stator winding; $E_Δ$ – electromotive force of the additional stator winding; E_2 – electromotive force of the rotor winding; I – stator current of an induction machine; Z_l – load resistance; I_l – load current; I_C – external capacitance current; I_{Ck} – current of additional internal capacitance; I – stator current of a compensated induction generator; $I_{CΔ}$ – internal capacitance current; $I_Δ$ – current of the additional stator winding; I_1 – stator main winding current; I_0 – magnetising current of an induction machine; θ – angle of spatial displacement of the main and auxiliary stator phase windings; I'_2 – rotor current of an induction machine; r_1 – active stator resistance of an induction machine; X_1 – inductive resistance of the stator of an induction machine; $φ$ – angle between the stator current and voltage vectors at the stator of an induction machine; $φ_1$ – angle between the voltage vectors on the stator and the current of the main stator winding of the induction machine; $φ_Δ$ – angle between the voltage vectors on the stator and the current of the additional stator winding of an induction machine; $φ_2$ – angle between the rotor electromotive force vectors and the rotor current of an induction machine;

Source: compiled by the authors

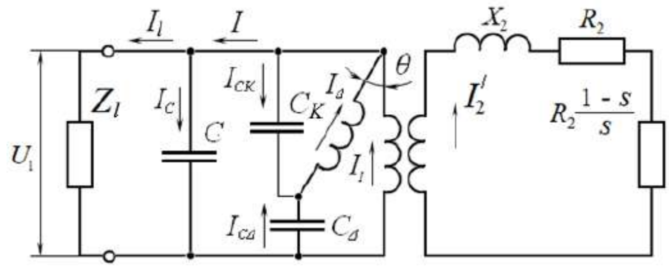
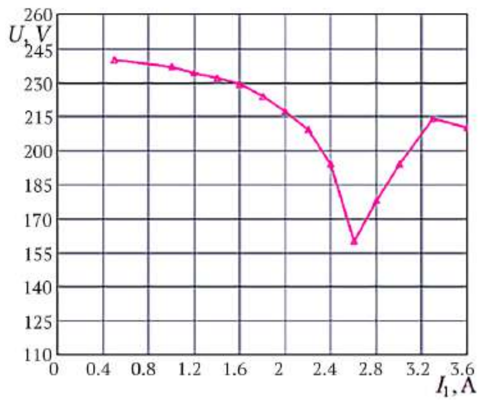


Figure 5. Wiring diagram of CIG phases

Note: U_1 – load voltage; Z_l – load resistance; I_l – load current; C – external capacity; I_C –external capacity current; C_k – additional internal capacity; I_{Ck} – additional internal capacity current; I – stator current of a compensated induction generator; $C_Δ$ – internal capacity; $I_{CΔ}$ – internal capacity current; $I_Δ$ – additional stator winding current; I_1 – stator main winding current; $θ$ – angle of spatial displacement of the main and auxiliary stator phase windings; I'_2 – generator rotor current; X_2 – inductive resistance of the rotor; R_2 – active rotor resistance; s – sliding

Source: compiled by the authors based on V.I. Mishin *et al.* (2022)

The external characteristic of the compensated induction generator obtained by calculation when operating in conjunction with an induction motor (Fig. 6a), where the voltage drops to 165 V, is confirmed by the experimental oscillogram (Fig. 6b). It was found that the voltage recovery (Fig. 6b) after starting the motor from a compensated induction generator occurs within 0.5 s. The stator current (Fig. 7) of the compensated induction generator when the motor is powered in a steady state is 2 A.



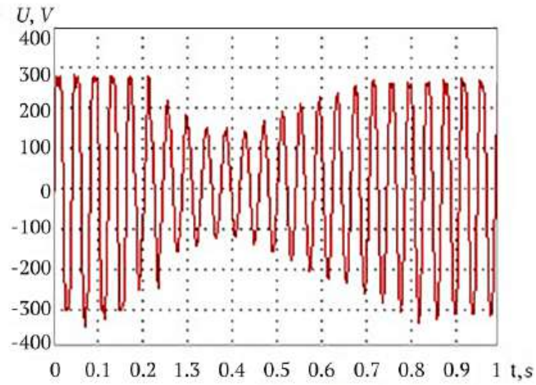


Figure 6. Calculated external compensated asynchronous generator in a joint operation with an induction motor (a) and experimental voltage waveform on the stator of a compensated asynchronous generator (b)
Source: compiled by the authors

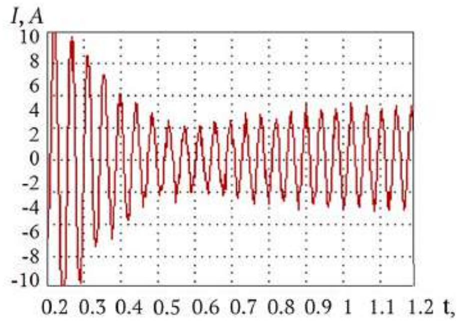


Figure 7. Oscillogram of the stator current of a compensated induction generator when supplying an induction motor
Source: compiled by the authors

The data obtained as a result of calculating the characteristics of compensated induction generators are confirmed with sufficient accuracy by experimental studies. In particular, Figure 8 shows the external characteristics of the compensated induction generator when using the external capacitance C and the internal capacitance C_Δ (curves 1) and when using the external capacitance C, the internal capacitance C_Δ, and the additional internal capacitance C_k (curves 2), based on the calculated and experimental data.

The system of equations for the electrical equilibrium of the stator and rotor circuits of a CIG (Al-Jufout *et al.*, 2018) used the parameters of the substitution scheme (r_1, x_1, r_2, x_2) calculated according to the above methodology. The introduced parameters were the capacitive resistances x_c, $x_{c\Delta}$, x_{ck} and load resistance $Z_n = k_n Z_{nb}$ at $Z_{nb} = r_{nb} + jx_{nb} = 80 + j60 = 100i^{j\varphi}$ Ohm. $Z_n = var$ with a variable load factor k_n, the resistance of the main and auxiliary stator windings was assumed to be the same $z_1 = r_1 + jx_1 = z_\Delta$.

The use of internal capacitive reactive power compensation to improve the characteristics of an induction generator causes changes in the basic electrical circuit of its stator winding. Accordingly, the active and inductive resistances of the stator winding of the compensated induction generator change compared to the basic induction generator, which should be considered in numerical studies.

The parameters of the L-shaped and T-shaped replacement schemes for an induction machine can be found in reference books or the manufacturer's documentation. However, the use of these parameters without considering the operating mode and conditions of the induction machine may be unacceptable or lead to unacceptably large errors in the calculations.

In particular, E.R. Ferrucho-Alvarez *et al.* (2021) considered an induction welding generator with valve excitation. While an L-shaped substitution scheme is used for a conventional induction generator operating in voltage stabilisation mode, it is unacceptable for an induction generator with valve excitation operating on a welding arc. In this case, as in the case of a compensated induction generator, a T-shaped substitution scheme for the basic induction generator is used. The distinctive feature is that the valve excitation system in the replacement circuit is represented by an additional variable capacitive resistance.

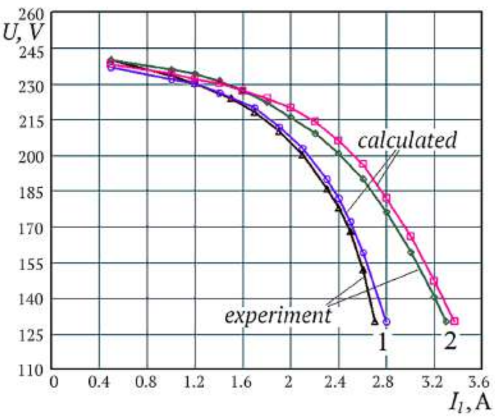


Figure 5. External characteristics of a compensated asynchronous generator obtained by calculation and experiment
Note: curve 1 – when using an external container C and internal container C_Δ; curve 2 – and when using an external container C, internal container C_Δ and additional internal container C_k
Source: compiled by the authors

L.A. Lopes & R.G. Almeida (2006), I. Boldea & S.A. Nasar (2009) noted that the T-shaped replacement scheme for an induction machine is also used to calculate the characteristics of an induction motor with a squirrel-cage rotor that has rotor eccentricity or rotor winding defects. In this case, the T-shaped substitution scheme is supplemented with additional elements that characterise the increase in losses in the damaged motor. The obtained characteristics are used to monitor and predict the condition of motors during their operation, as well as for their diagnosis.

If an induction machine is operated in the motor mode using various speed control devices, the parameters of the L-shaped and T-shaped substitution schemes change, as shown in L. Mazurenko *et al.* (2011), O.M. Popovych & M.O. Smahliuk (2014). This should be considered when calculating the characteristics of an induction motor with a certain method of speed control.

A single-phase substitution scheme for a three-phase induction machine is used to calculate its characteristics in steady-state symmetrical modes with sinusoidal voltages. Depending on the task at hand, the substitution scheme can consider steel losses in the stator cores and rotor, the presence of a double cage in the rotor, changes in machine parameters, such as the surface effect and saturation of the stator and rotor cores. L. Mazurenko *et al.* (2011), and J. Rolek & G. Utrata (2017) considered methods for determining the parameters of an induction machine substitution scheme by alternative methods other than the standard ones (based on the data of no-load and short-circuit experiments). The developed methods for determining the parameters of the induction machine substitution scheme can be used to refine the parameters of the substitution scheme of a compensated induction generator when calculating its characteristics in transient modes. M. Vazifehdan *et al.* (2020) described in detail a complex and high-level control strategy used in the field of electrical engineering and industrial automation. It combines several control methodologies to achieve accurate and efficient control of induction machines, particularly in situations where sensor data is limited or unavailable. They explored sliding control, which helps to make the system state converge to a given sliding surface. This is especially useful in systems with uncertainty and external influences. In this context, sliding control helps maintain precise control of an induction machine.

The determination of the parameters of the induction machine replacement scheme based on the data of no-load and short-circuit experiments carried out using induction machine models implemented in MATAB/Simulink and ETAR environments is the subject of the work by M. Popp *et al.* (2017) Using MATLAB/Simulink models, S. Al-Jufout *et al.* (2018) also proposed a two-step optimisation of the parameters of the induction machine replacement scheme, which ensures the minimum error of the results obtained. The above approaches can also be used to determine the parameters of a compensated induction generator replacement scheme, but for this purpose, it is necessary to develop appropriate MATLAB/Simulink or ETAR models.

CONCLUSIONS

The basic electrical circuit of the stator winding of a compensated induction generator differs from the stator winding circuit of a basic induction machine. It has been shown that the main and additional windings of the stator phase windings of a compensated induction generator can be connected in series or parallel, and their axes can be shifted in space by an arbitrary angle. As a result, the degree of mutual inductive coupling between the windings in terms of operating magnetic flux and dissipation magnetic flux changes. Accordingly, to conduct correct numerical studies of the characteristics of compensated induction generators, the appropriate parameters of the substitution scheme should be used. It has been established that the active and inductive resistances of the stator and rotor windings of a compensated induction generator should be determined by recalculating the parameters of the basic induction machine according to the developed methodology, depending on the connection scheme of the stator phase windings and the generator output voltage. In particular, when the main and auxiliary stator windings of a compensated induction generator are connected in series, their active and inductive impedances must be halved compared to the basic induction machine. If the main and auxiliary stator windings are connected in parallel, the corresponding resistances must be doubled compared to the basic induction machine. The parameters of the rotor winding and the magnetising winding remain unchanged. In the case of using the scheme of parallel connection of the stator phase windings at a halved voltage at the output of the compensated induction generator, the active and inductive resistances of the main and additional stator phase windings, as well as the rotor winding and the magnetisation winding, should be reduced by a factor of 4 compared to the parameters of the basic induction machine. The calculated characteristics of the compensated induction generator, obtained using the appropriately calculated parameters of the substitution scheme, are confirmed with sufficient accuracy by experimental data.

Further research will aim to improve the energy efficiency of induction generators with internal capacitive reactive power compensation as part of autonomous power supply systems. They will focus on analysing the stability and reliability of an autonomous power supply system with a compensated induction generator under different operating conditions and variable load parameters. Particular attention will be paid to the justification of the algorithm for changing the compensating capacities of the generator and to the study of the possibilities of using new switching devices for their switching.

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CONFLICT OF INTEREST

None.

REFERENCES

[1] Al-Jufout, S., Al-rousan, W., & Wang, C. (2018). Optimization of induction motor equivalent circuit parameter estimation based on manufacturer's data. *Energies*, 11(7), article number 1792. doi: 10.3390/en11071792.

[2] Boldea, I., & Nasar, S.A. (2009). *The induction machines design handbook* (2nd ed.). Boca Raton: CRC Press. doi: 10.1201/9781315222592.

[3] Chuenko, R.M., & Kryvoshey, O.A. (2014). Determination of the parameters of the replacement scheme of the compensated asynchronous motor. *Scientific Bulletin of the National University Environment and Science of Ukraine. Series: Agricultural Machinery and Energy*, 194(3), 265-270.

[4] Ferrucho-Alvarez, E.R., Martinez-Herrera, A.L., Cabal-Yepez, E., Rodriguez-Donate, C., Lopez-Ramirez, M., & Mata-Chavez, R.I. (2021). Broken rotor bar detection in induction motors through contrast estimation. *Sensors*, 21, article number 7446. doi: 10.3390/s21227446.

[5] Helonde, A.R., & Mankar, M.M. (2019). Identifying three phase induction motor equivalent circuit parameters from nameplate data by different analytical methods. *International Journal of Trend in Scientific Research and Development*, 3(3), 642-645. doi: 10.31142/ijtsrd22934.

[6] Kravchik, A.E., Shlaf, M.M., Afonin, V.I., & Sobolenskaya, E.A. (1982). *Asynchronous motors series 4A*. moscow: Energoizdat.

[7] Kumar, S.V., Kathirvel, C., & Jude, P.S.V. (2023). A new method of sensor-less speed vector control of asynchronous motor drive in model-reference adaptive system. In *Smart grids for smart cities* (vol. 2, pp. 127-141). Hoboken: Wiley.

[8] Liu, M., Chen, L., Sheng, X., Yang, Y., Yu, F., Li, Y., Yuan, X., Li, Y., Wang, Q., & Ma, Q. (2023). Dynamic simulation of life cycle environmental benefits of remanufacturing asynchronous motors to permanent magnet synchronous motors. *Journal of Cleaner Production*, 426, article number 138932. doi: 10.1016/j.jclepro.2023.138932.

[9] Lopes, L.A., & Almeida, R.G. (2006). Wind-driven self-excited induction generator with voltage and frequency regulated by a reduced-rating voltage source inverter. *IEEE Transactions on Energy Conversion*, 21(2), 297-304. doi: 10.1109/TEC.2006.874244.

[10] Mazurenko, L.I., Romanenko, V.I., & Jura, O.V. (2011). Calculation of operating characteristics of an autonomous welding asynchronous generator with valve excitation according to the substitution scheme. *Proceedings of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine: Collection of Scientific Papers*, 28, 64-69.

[11] Mishin, V.I., Kaplun, V.V., & Makarevich, S.S. (2011). Self-contained induction generator with internal capacitive compensation. *Russian Electrical Engineering*, 82, 138-143. doi: 10.3103/S1068371211030060.

[12] Mishin, V.I., Lut, M.T., Makarevych, S.S., & Chuienko, R.M. (2022). *Asynchronous electric machines* (2nd ed.) Kyiv: Komprint Publishing House.

[13] Popovych, O.M., & Smahliuk, M.O. (2014). Research and design of induction motors with internal compensation using simulation and structural modeling. *Bulletin of the National Technical University of Ukraine "Kyiv Polytechnic Institute". Series "Mining"*, 25, 138-144.

[14] Popp, M., Mathis, W., Korolova, O., & Ponick, B. (2017). Modeling and simulation of electrical machines within a CCM framework. In *2017 IEEE International Electric Machines and Drives Conference (IEMDC)* (pp. 1-8). doi: 10.1109/IEMDC.2017.8002174.

[15] Rolek, J., & Utrata, G. (2017). A methodology for electromagnetic parameter estimation of an induction motor equivalent circuit based on the load curve test. In *2017 International Symposium on Electrical Machines (SME)* (pp. 1-6). Naleczow: IEEE. doi: 10.1109/ISEM.2017.7993570.

[16] Rolek, J., & Utrata, G. (2018). An identification procedure of electromagnetic parameters for an induction motor equivalent circuit including rotor deep bar effect. *Archives of Electrical Engineering*, 67(2), 279-2 425/119640.

[17] Terzioğlu, H., & Selek, M. (2017). Determination of equivalent circuit parameters of induction motors by using heuristic algorithms. *Selcuk University Journal of Engineering, Science and Technology*, 5(2), 170-182. doi: 10.15317/Scitech.2017.80.

[18] Tezcan, M.M., Yetgin, A.G., Canakoglu, A.I., Cevher, B., Turan, M., & Ayaz, M. (2018). Investigation of the effects of the equivalent circuit parameters on induction motor torque using three different equivalent circuit models. *MATEC Web of Conferences*, 157, article number 01019. doi: 10.1051/matecconf/201815701019.

[19] Vazifehdan, M., Zarchi, H.A., & Khoshhava, M.A. (2020). Sensorless vector control of induction machines via sliding mode control based model reference adaptive system. In *28th Iranian Conference on Electrical Engineering (ICEE)* (pp. 1-6). Tabriz: IEEE. doi: 10.1109/ICEE50131.2020.9260920.

[20] Wengerkievicz, C.A.C., Elias, R.A., Batistela, N.J., Sadowski, N., Kuo-Peng, P., Sandro Lima, C., da Silva Jr., P.A., & Beltrame, A.Y. (2017). Estimation of three-phase induction motor equivalent circuit parameters from manufacturer catalog data. *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, 16(1), 90-107. doi: 10.1590/2179-10742017v16i1873.

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Схема заміщення асинхронного генератора з внутрішньою ємнісною компенсацією реактивної потужності

Анотація. Актуальність застосування компенсованих асинхронних машин у режимі генератора автономних систем електроживлення полягає в їх здатності забезпечувати стабільне та надійне електропостачання навіть у відсутність зовнішньої мережі. Метою цієї роботи є створення процедури для визначення характеристик еквівалентної схеми компенсованих асинхронних генераторів, яка враховує взаємний вплив між головними та додатковими фазними обмотками якоря. Для одержання розрахункових характеристик режимів функціонування генератора такого класу аналітичним було використано теорію ідеалізованої асинхронної машини з представленням електромеханічних процесів перетворення енергії та основних фізичних параметрів у вигляді рівнянь електричної рівноваги і руху привода. Узагальнена система диференційних рівнянь дала можливість розрахувати динамічні і статичні процеси для симетричних і несиметричних режимів при заданих параметрах машини при різних способах її збудження та стабілізації напруги при змінному навантаженні. Для практичної реалізації моделювання параметрів асинхронного генератора використані рівняння електричної рівноваги кіл статора і ротора для симетричного усталеного режиму, яка є частковим випадком узагальненої математичної моделі машини як для перехідних, так і усталених процесів з постійними параметрами схеми заміщення. Урахування конструктивних та функціональних особливостей компенсованих асинхронних генераторів стало можливим на основі використання математичної моделі з поділом обмотки якоря на дві співвісні або зміщені у просторі напівобмотки. У такому випадку кількість розрахункових рівнянь збільшується удвічі. Використання автотрансформаторної схеми увімкнення напівобмоток фаз статора на конденсатори вимагало введення додаткового диференційного рівняння електричної рівноваги фаз статора. Це дало змогу обґрунтувати величини активних та індуктивних опорів, які використовуються у схемі заміщення асинхронного генератора із внутрішньою ємнісною компенсацією реактивної потужності. При цьому враховувався взаємний індуктивний зв'язок основних і додаткових напівобмоток фазних обмоток статора генератора обумовлений як робочим магнітним потоком, так і магнітними потоками розсіяння. Практичне значення отриманих результатів полягає в підвищенні ефективності та стабільності електроживлення, що сприяє зменшенню втрат та покращенню роботи електроенергетичних систем

Ключові слова: асинхронна машина; внутрішня ємнісна компенсація; реактивна потужність; активний опір; індуктивний опір; взаємоіндуктивний зв’язок