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MODELING AND INVESTIGATION OF STEADY-STATE OPERATING MODES OF A SELF-EXCITED AUTONOMOUS INDUCTION GENERATOR WITH CAPACITIVE EXCITATION

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This paper investigates the steady-state operating modes of an autonomous self-excited induction generator (SEIG) equipped with a capacitive excitation system and operating under active and active-inductive load conditions. The growing demand for autonomous and decentralized power generation systems based on renewable and alternative energy sources has significantly increased interest in induction generators due to their simplicity, reliability, low maintenance requirements, and absence of a separate excitation source. However, the operation of self-excited induction generators is characterized by substantial variations in output voltage and frequency depending on load magnitude and power factor, which complicates the analysis and design of such systems.

The objective of this study is to develop and validate an improved method for calculating the static characteristics of a low-power autonomous induction generator, taking into account the variation of generated voltage frequency under changing load conditions. Unlike many conventional calculation methods that assume constant output frequency or neglect its dependence on load, the proposed approach incorporates the actual influence of load-induced frequency changes. This consideration is particularly important for low-power induction generators, which typically exhibit higher rated slip values and are therefore more sensitive to variations in operating conditions.

The proposed mathematical model is based on the equivalent circuits of

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both the induction generator and the induction motor load. The analysis employs a system of electrical equilibrium equations that describe electromagnetic processes in the generator-load system. To simplify calculations, the induction motor load is represented by an equivalent RL circuit with parameters dependent on motor slip. The resulting mathematical formulation enables simultaneous determination of the generator magnetizing reactance and the relative frequency of the generated voltage. This approach allows accurate prediction of generator voltage, frequency, and loadability under various operating conditions.

Using the developed methodology, static characteristics were calculated for an induction generator based on a standard squirrel-cage induction machine of type AIR80A4SU2 with a rated power of 1.2 kW. The generator was analyzed under both resistive and active-inductive loading conditions. The results demonstrate that neglecting frequency variation leads to significant errors in estimating voltage regulation, overload capability, and stable operating limits. The discrepancy becomes especially pronounced when the generator supplies induction motor loads characterized by high starting currents and variable power factors.

To verify the adequacy of the proposed model, extensive experimental investigations were carried out using a laboratory test bench incorporating an induction generator, a DC drive motor, a configurable capacitor bank, and various types of electrical loads. Experimental measurements included generator voltage, load current, rotor speed, excitation capacitance, and output power. The obtained results demonstrated good agreement with theoretical predictions. Comparative analysis of calculated and measured characteristics showed that the deviation between experimental and theoretical data does not exceed 4–6%, confirming the validity and practical applicability of the developed calculation method.

Keywords: Self-Excited Induction Generator (SEIG); Autonomous Induction Generator; Capacitive Self-Excitation; Capacitor Bank; Static Characteristics; Steady-State Analysis; Frequency Variation; Voltage Regulation; Load Characteristics; Active-Inductive Load; Overload Capability.

Statement of problem. The operation of an induction generator (IG) under varying output voltage, frequency, load magnitude, and load type is traditionally analyzed using its steady-state characteristics. These characteristics provide valuable information about the generator's voltage regulation, frequency stability, overload capability, and overall operating performance under different loading conditions. Consequently, the accurate determination of steady-state characteristics is one of the key tasks in the design and analysis of autonomous power supply systems based on self-excited induction generators.

Numerous methods for calculating the steady-state characteristics of self-excited induction generators have been proposed in the scientific literature. Most of these methods are based on simplified mathematical models and assumptions that significantly reduce computational complexity. While such assumptions are generally acceptable for medium- and high-power machines, they often lead to substantial inaccuracies when applied to low-power induction generators. As a result, the practical applicability of many conventional calculation techniques becomes limited when analyzing small autonomous generating units used in isolated power systems, renewable energy installations, agricultural facilities, and backup power applications.

One of the most common assumptions adopted in existing analytical approaches is that the rotational speed of the generator rotor varies in such a way that the frequency of the generated voltage remains constant regardless of the magnitude and nature of the connected load. Under this assumption, the prime mover is considered capable of continuously adjusting its mechanical speed to compensate for variations in generator slip caused by load changes. Such an approach considerably simplifies the mathematical description of the generator but does not accurately reflect the operating conditions encountered in real autonomous power systems.

In practical applications, the majority of prime movers used to drive autonomous induction generators, such as internal combustion engines, microturbines, hydraulic turbines, and renewable-energy-based drives, operate with approximately constant rotational speed. Implementing continuous speed regulation as a function of load magnitude and power factor in order to maintain a strictly constant output frequency requires sophisticated control systems, additional sensors, and advanced power electronics. Such solutions increase both the complexity and cost of the generating system and are often economically unjustified, particularly in low-power installations. Therefore, in many practical cases, the rotor speed remains nearly constant, while the frequency of the generated voltage changes according to the loading conditions.

In addition, several published studies, particularly those devoted to medium- and high-power induction generators, neglect the influence of load variations on the frequency of the generated voltage altogether. Experimental and theoretical investigations reported in the literature indicate that this simplification can be considered acceptable for machines with a nominal slip of approximately 0.03 or lower. Under such conditions, the frequency deviation remains relatively small, and its impact on the calculated operating characteristics is limited. However, the validity of this assumption rapidly decreases as the nominal slip increases.

The situation becomes significantly different when a squirrel-cage induction machine with more than one pair of poles is used as a generator and its nominal slip reaches values of 0.05–0.06, which is typical for low-power machines. Under these conditions, load-induced variations in slip produce noticeable changes in the frequency of the generated voltage. Ignoring this phenomenon leads to substantial errors in the calculation of generator voltage, excitation requirements, overload capability, and stability limits. Consequently, the predicted operating characteristics may differ considerably from the actual behavior of the generator under practical operating conditions.

The shortcomings of conventional calculation methods become especially evident when the generator supplies dynamic or active-inductive loads. Such loads are characterized by variable power factors, transient operating conditions, and significant reactive power consumption. A typical example is the supply of induction motors, which represent one of the most widespread categories of electrical consumers in autonomous power systems. During startup, induction motors draw high inrush currents several times greater than their rated current and simultaneously exhibit low power factor values. These factors create substantial disturbances in the generator excitation process and cause significant deviations in voltage and frequency.

Under such operating conditions, neglecting the influence of load on the generated frequency may result in incorrect estimation of the permissible loading range, capacitor bank parameters, voltage regulation characteristics, and stable operating boundaries of the self-excited induction generator. Therefore, the development of improved calculation methods capable of accounting for frequency variation under changing load conditions is of considerable theoretical and practical importance.

For these reasons, the present study focuses on the development of a refined methodology for analyzing the steady-state operating modes of low-power self-excited induction generators. The proposed approach incorporates the effect of load-dependent frequency variation and enables a more accurate assessment of generator performance under active and active-inductive loading conditions. Such a methodology can significantly improve the design and optimization of autonomous power generation systems, ensuring higher reliability, better voltage quality, and more realistic prediction of operating characteristics.

Recent research and publication analysis. The increasing deployment of autonomous power supply systems based on renewable and distributed energy sources has stimulated growing interest in self-excited induction generators (SEIGs). Owing to their simple construction, ruggedness, low maintenance requirements, and ability to operate without an external excitation source, induction generators have become a promising solution for isolated and stand-alone power generation applications. However, the operating characteristics of SEIGs are strongly influenced by excitation capacitance, rotor speed, load magnitude, and load power factor, which complicates the analysis of their steady-state operating modes.

Over the past decades, numerous studies have been devoted to the investigation of self-excited induction generators, including excitation system design, voltage build-up mechanisms, performance characteristics, mathematical modeling, and practical applications in autonomous power systems. The most relevant contributions related to the present study are discussed below.

Makowski and Leicht [1] investigated the performance characteristics of single-phase self-excited induction generators manufactured using different grades of non-grain-oriented electrical steel sheets. Based on field-circuit analysis and experimental investigations, the authors demonstrated that magnetic core properties significantly affect voltage build-up capability, efficiency, and output characteristics. Their results confirmed the importance of accurately considering magnetic saturation and magnetic circuit parameters when modeling autonomous induction generators.

Ion and Marinescu [2] presented a comprehensive overview of three-phase induction generators used for single-phase power generation. The study analyzed various generator configurations, excitation methods, and operating modes. Particular attention was paid to voltage regulation, frequency stability, and the influence of load conditions on generator performance. The authors concluded that maintaining stable operating parameters remains one of the main challenges in stand-alone induction generation systems.

Sharma and Kaur [3] focused on determining the excitation capacitance required to sustain a constant air-gap voltage under variable speed and load conditions. Their research demonstrated that appropriate capacitor selection substantially improves voltage stability and extends the stable operating range of self-excited induction generators. The obtained results highlighted the critical role of the excitation system in ensuring reliable autonomous operation.

Metello et al. [4] investigated a self-excited three-phase induction generator operating as a single-phase generator in rotating excitation systems for synchronous generators. The authors analyzed voltage characteristics, excitation requirements, and operating stability under different loading conditions. The study confirmed that excitation capacitance and load parameters have a significant influence on the quality of generated electrical energy.

Krishna et al. [5] carried out an experimental study of self-excited induction generators intended for small-scale isolated rural electrification systems. The research examined the influence of excitation capacitance, rotor speed, and load characteristics on output voltage and generated power. Experimental results demonstrated that inductive loads substantially reduce voltage stability and limit the operating capabilities of low-power autonomous generators.

Zobaa and Bansal [6] summarized the theoretical foundations and practical applications of renewable-energy-based electrical generation systems. Their work described the principles of self-excitation in induction generators, methods of capacitor-bank selection, and factors affecting voltage build-up and generator stability. The authors emphasized the necessity of accurate mathematical models for predicting generator behavior under varying operating conditions.

Singh and Jain [7] investigated the performance characteristics and optimum utilization of cage-rotor induction generators. Their analysis established relationships between excitation capacitance, loading conditions, generated voltage, and output power. The study provided important theoretical foundations for the evaluation of steady-state operating characteristics of autonomous induction generators and demonstrated the influence of excitation parameters on generator performance.

Williamson [8] proposed finite-element-based approaches for modeling induction machines. Although the study focused primarily on induction motors, the developed methodology provided a deeper understanding of electromagnetic processes, magnetic saturation effects, and flux distribution within electrical machines. These approaches subsequently became an important basis for improving the accuracy of induction generator models.

The analysis of the reviewed literature shows that significant attention has been devoted to excitation systems, magnetic circuit properties, voltage build-up processes, and performance optimization of self-excited induction generators [1–8]. However, most existing studies concentrate on voltage regulation and excitation capacitance selection while assuming constant generated frequency or neglecting frequency variations caused by load changes. Such assumptions are generally acceptable for medium- and high-power machines but may lead to considerable errors in the analysis of low-power autonomous induction generators supplying active-inductive and dynamic loads. Therefore, further development of calculation methods accounting for load-dependent frequency variations remains an important scientific and practical task.

Setting article objectives. The objective of this study is to develop and validate an improved method for calculating the steady-state load characteristics of a low-power autonomous self-excited induction generator operating under active and active-inductive loads, taking into account load-dependent variations in the frequency of the generated voltage, in order to improve the accuracy of predicting voltage regulation, overload capability, and stable operating limits.

Main part. To analyze the load operating modes of the autonomous induction generator (IG), the study considers the most typical and practically significant type of electrical load connected to the generator terminals, namely an induction motor (IM). The selection of an induction motor as the load object is justified by its widespread application in autonomous power supply systems used in agricultural facilities, small industrial installations, renewable energy systems, pumping stations, and other isolated consumers. In addition, induction motors represent one of the most demanding categories of electrical loads due to their substantial reactive power consumption, variable power factor, and high starting currents, which considerably affect the operating characteristics of self-excited induction generators.

The interaction between an autonomous self-excited induction generator and an induction motor load is characterized by complex electromagnetic processes associated with the exchange of active and reactive power. During operation, variations in load torque and motor slip influence the electrical parameters of the entire generator–load system, resulting in changes in generated voltage, frequency, excitation conditions, and overall stability. Therefore, the accurate analysis of such operating modes requires a mathematical model capable of adequately describing the electromagnetic coupling between the generator and the connected induction motor.

For this purpose, one of the widely accepted equivalent circuit representations of induction electrical machines is employed. Equivalent circuit models are extensively used in the analysis of induction generators and motors because they provide a convenient balance between computational simplicity and sufficient accuracy for engineering calculations. The selected equivalent circuit reflects the electrical and electromagnetic relationships between the stator circuits, rotor circuits, magnetizing branches, and excitation capacitors, making it possible to evaluate the steady-state characteristics of the entire system under various loading conditions.

The developed mathematical model is based on the equivalent circuit of the induction generator–induction motor system shown in Fig. 1. The model incorporates the electrical parameters of both machines, including stator and rotor resistances, leakage reactances, magnetizing reactances, and the parameters of the capacitor bank used for generator self-excitation. Unlike conventional approaches that assume constant generated frequency, the proposed model additionally accounts for the variation of generated voltage frequency caused by changes in load conditions. This feature is particularly important for low-power induction generators, where the influence of load on slip and frequency cannot be neglected without introducing significant calculation errors.

The steady-state behavior of the generator–motor system is described by a set of electromagnetic equilibrium equations derived from the equivalent circuit shown in Fig. 1. These equations establish the relationships between currents, voltages, active and reactive power flows, excitation capacitance, generator slip, motor slip, and the frequency of the generated voltage. By solving the resulting system of equations, it becomes possible to determine the operating point of the autonomous induction generator under various active and active-inductive loading conditions, as well as to evaluate its voltage regulation characteristics, overload capability, and stability limits.

Thus, the adopted modeling approach provides a comprehensive framework for analyzing the steady-state operating modes of a low-power autonomous self-excited induction generator supplying an induction motor load. The corresponding equivalent circuit is described by the following system of equations:

$$\begin{cases} -(R_{1n} + \alpha jX_{1n})I_{1n} - \alpha jX_{\mu n}I_{\mu n} - \alpha jX_c I_c = 0; \\ (R_{2n} / s_m + \alpha jX_{2n}^{/})I_{2n} + \alpha jX_{\mu n}I_{\mu n} = 0; \\ -(R_1 + \alpha jX_1)I_1 - \alpha jX_\mu I_\mu + \alpha jX_c I_c = 0; \\ (R_2 / s_g + \alpha jX_2^{/})I_2 + \alpha jX_\mu I_\mu = 0; \\ I_1 - I_{1n} - I_c = 0; \\ -I_1 - I_2 + I_\mu = 0, \end{cases} \tag{1}$$

where R_{1n}, $R_{2n}^{/}$, $R_{\mu n}$ are the active resistances of the stator circuit, rotor circuit, and magnetizing branch of the induction motor (IM), respectively; X_{1n}, $X_{2n}^{/}$, $X_{\mu n}$ are the reactances of the stator circuit, rotor circuit, and magnetizing branch of the induction motor; I_{1n}, I_{2n}, $I_{\mu n}$ are the currents of the stator circuit, rotor circuit, and magnetizing branch of the induction motor; I_c is the excitation capacitor current; X_c is the reactance of the excitation capacitors; R_1, $R_2^/$, R_μ are the active resistances of the stator circuit, rotor circuit, and magnetizing branch of the induction generator (IG), respectively; X_1, $X_2^/$, X_μ are the reactances of the stator circuit, rotor circuit, and magnetizing branch of the induction generator; I_1, $I_2^/$, I_μ are the currents of the stator circuit, rotor circuit, and magnetizing branch of the induction generator; s_g, s_m are the slips of the induction generator and induction motor, respectively; $\alpha = f / f_n$ is the relative frequency of the generated voltage U_g.

When determining the characteristics of system (1) under steady-state operating conditions, the unknown parameters include all reactances of both the induction generator and the induction motor, as well as the frequency of the generated voltage in the circuit. All remaining parameters are assumed to be constant. In this case, the slip of the induction generator is represented as a function of frequency according to $s_g = (1-\alpha)/\alpha$

This relationship makes it possible to account for the influence of load-dependent frequency variations on the operating characteristics of the autonomous self-excited induction generator.

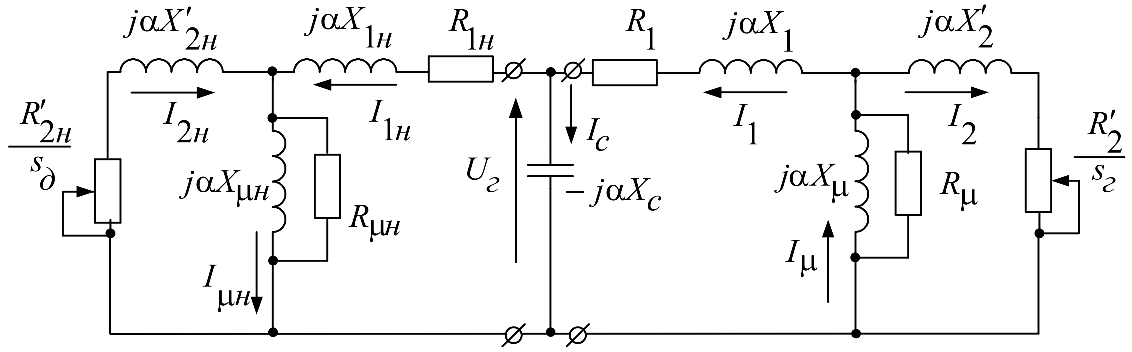

Fig. 1. Equivalent circuit of the autonomous induction generator–induction motor system

To determine the unknown parameters, the well-known method of representing the induction motor under steady-state operating conditions by an equivalent RL circuit (Fig. 2) with the following parameters is used:

$$R_n = R_{1n} + \frac{X_{\mu n}^2}{s_m (X_{\mu n} + X_{2n}^/)^2 + R_{2n}^{/2}},$$
$$X_n = X_{1n} + \frac{X_{\mu n} R_{2\text{н}}^/}{R_{2n}^/} - \frac{R_n s_m (X_{\mu n} + X_{2n}^/)}{R_{2n}^/}, \qquad (2)$$

which can be calculated for any value of the motor slip s_m.

Thus, the equivalent circuit of the system can be represented in the form shown in Fig. 2.

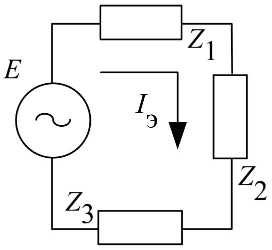

Fig. 2. Equivalent circuit of the induction generator–induction motor system

Taking into account the performed transformations and applying Kirchhoff's second law, the following equation can be obtained:

$$I_\Sigma Z_\Sigma = 0 \tag{3}$$

where $Z_\Sigma = Z_1 + Z_2 + Z_3$ is the total circuit impedance, defined as follows: $Z_1 = R_1 + j\alpha X_1$ is the total impedance of the induction generator stator circuit; $Z_2 = R_1 + j\alpha X_1 + Z_3 - j\alpha X_c$ is the total impedance of the load circuit (induction motor) and the capacitive excitation system; $Z_3 = \dfrac{-\alpha^2 X_2' X_\mu + \alpha^3 X_2' X_\mu + j\alpha X_2' R_\mu - j\alpha^2 X_2' R_\mu + j\alpha^2 R_2' X_\mu + \alpha R_2' R_\mu}{j\alpha X_2' - j\alpha^2 X_2' + \alpha R_2' + j\alpha X_\mu - j\alpha^2 X_\mu + R_\mu - \alpha R_\mu}$ is the total impedance of the rotor and magnetizing branches of the induction generator; $E = \phi\omega_0 = L_\mu I_\mu \omega_0$ is the generator electromotive force (EMF); I_Σ is the equivalent circuit current.

Under load operating conditions, the stator current cannot be equal to zero, i.e., $I_\Sigma \neq 0$

Therefore, in order to satisfy Equation (3), the following condition must hold:

$$Z_\Sigma = Z_3 + Z_2 + Z_1 = \mathrm{Re}(Z_\Sigma) + \mathrm{Im}(Z_\Sigma) = 0 \tag{4}$$

As a result of straightforward mathematical transformations, the following system of equations is obtained:

$$\begin{cases} C_1 X_\mu^2 + C_2 X_\mu + C_3)\alpha^4 + (C_4 X_\mu^2 + C_5 X_\mu + C_6)\alpha^3 + \\ +(C_7 X_\mu^2 + C_8 X_\mu + C_9)\alpha^2 + C_{10}\alpha + C_{11} = 0 \\ (D_1 X_\mu^2 + D_2 X_\mu + D_3)\alpha^5 + (D_4 \cdot X_\mu^2 + D_5 X_\mu + D_6)\alpha^4 + \\ +(D_7 X_\mu^2 + D_8 X_\mu + D_9)\alpha^3 + D_{10}\alpha^2 + D_{11}\alpha = 0 \end{cases} \tag{5}$$

where the coefficients $C_1 - C_{11}$ and $D_1 - D_{11}$ are functions of the induction generator parameters, the equivalent parameters of the induction motor load, the excitation capacitor bank, and the rotor rotational speed.

By simultaneously solving the system of equations (5), the values of the magnetizing reactance X_μ of the induction generator and the relative frequency of the generated voltage α can be determined. These parameters subsequently allow the terminal voltage of the generator to be calculated for a given operating condition.

A more detailed description of the calculation algorithm is presented in [9].

Based on the developed method, the characteristics of an industrial squirrel-cage induction motor of type AIR80A4SU2 with the following parameters: (P_N = 1.2) kW, (n_N = 2740) rpm, (I_1 = 2.93) A, (R_1 = 9.37) Ω, (R_2 = 5.13) Ω, (X_1 = 7.03) Ω, and (X_2 = 6.5) Ω, with an excitation capacitance of (C = 30) µF, were calculated for operation under resistive and active-inductive loads.

In Fig. 3, Curve 1 represents the external characteristic of the induction generator calculated using the proposed method, while Curve 2 represents the generator characteristic obtained without taking into account the variation of the generated voltage frequency. It follows from the presented characteristics that, in the case of a low-power induction generator, neglecting the load-induced variation of frequency results in significant errors in the analysis of its load capability and, consequently, leads to inaccurate information regarding the characteristics of the capacitive excitation system, namely the required capacitance and the number of switching stages of the regulating capacitors.

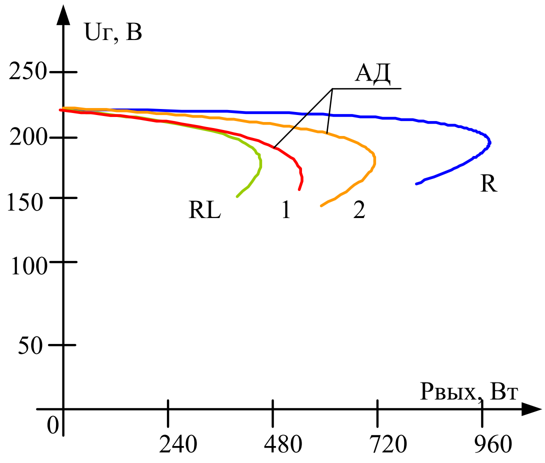

Fig. 3. Generator voltage as a function of output power

The proposed method for calculating the steady-state characteristics of the induction generator–load system was used to evaluate the performance of an autonomous induction generator developed on the basis of a standard squirrel-cage induction machine of type AIR80A4SU2 with a rated power of 1.2 kW. In addition, the method was applied to investigate the influence of the parameters of the capacitive excitation system on the operating characteristics of the generator. The calculated results are presented in Figs. 4 and 5.

The obtained characteristics make it possible to evaluate the effects of excitation capacitance and load type on voltage regulation, overload capability, and the overall stability of the autonomous induction generator. Particular attention was paid to the influence of the initial excitation capacitance, since this parameter directly affects the magnetization level of the machine and determines the amount of reactive power available for maintaining the self-excitation process.

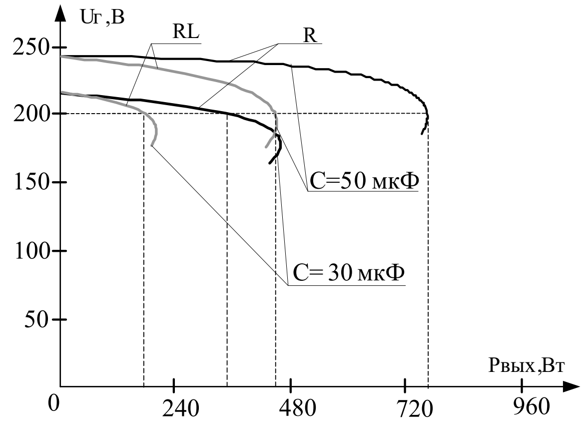

Fig. 4. Generator voltage as a function of load power for excitation capacitances of 30 and 50 μF

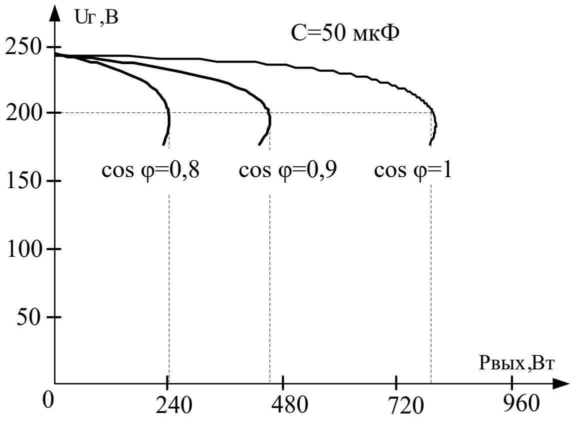

Fig. 5. External characteristics of the generator under varying load power factor conditions

As can be seen from the characteristics presented in Fig. 4, an increase in the calculated value of the initial excitation capacitance ((C_calc=27 μF)) leads to a noticeable improvement in the operating performance of the generator. Specifically, the overload capability increases, while the external characteristics become significantly stiffer, indicating a reduced voltage drop under increasing load conditions. This behavior can be explained by the increased reactive power supplied by the capacitor bank, which enhances the magnetizing flux and improves voltage support during loading.

For an excitation capacitance of (C = 30μF), the overload capability of the generator reaches 0.375. However, according to the requirements specified in [10], assuming an allowable voltage reduction of 10%, the practical overload capability of the generator is limited to only 0.3 under purely resistive load conditions ((cosφ = 1)). Therefore, although the generator is capable of operating beyond its rated conditions, the acceptable loading range is constrained by power-quality requirements related to voltage regulation.

The load capability decreases even further when the generator supplies consumers with an active-inductive load characteristic. As shown in Fig. 4, for the same excitation capacitance of (C = 30 μF), the overload capability satisfying the prescribed power-quality requirements is only 0.15 when the load power factor is (cosφ = 0.9). This substantial reduction demonstrates the strong sensitivity of self-excited induction generators to reactive power demand. Under active-inductive loading conditions, a considerable portion of the reactive power generated by the capacitor bank is consumed by the load, reducing the amount available for maintaining generator excitation.

The calculated characteristics clearly indicate that the influence of load power factor becomes increasingly significant as the load approaches the stability limit of the generator. A reduction in power factor not only decreases the maximum permissible load but also causes a more pronounced voltage drop and deterioration of voltage regulation characteristics. Consequently, the operating range of the autonomous induction generator becomes substantially narrower.

An increase in the initial excitation capacitance to (C = 50 μF) results in partial saturation of the magnetic system of the generator. Nevertheless, the additional reactive power supplied by the larger capacitor bank significantly improves the generator load capability. Under these conditions, the overload capability increases to 0.6 for a purely resistive load and to 0.37 for an active-inductive load. These results indicate that increasing excitation capacitance can effectively compensate for the adverse influence of reactive loading and extend the stable operating range of the generator.

The obtained results confirm that the parameters of the capacitive excitation system play a decisive role in determining the performance of autonomous self-excited induction generators. Proper selection of excitation capacitance makes it possible to improve voltage stability, increase overload capability, and enhance the quality of generated electrical energy. At the same time, excessive capacitance may lead to magnetic saturation and should therefore be selected on the basis of a comprehensive analysis of the generator operating conditions and load characteristics.

The influence of load type on the external characteristics of the autonomous induction generator is illustrated in Fig. 5. As can be seen from the figure, a decrease in the power factor of the active-inductive load results in a significant reduction in the overload capability of the induction generator. In addition, the stiffness of the external characteristics deteriorates considerably, leading to a more pronounced voltage drop as the load increases.

The obtained characteristics clearly demonstrate that the operating performance of a self-excited induction generator is highly sensitive not only to the magnitude of the load but also to its electrical nature. As the active-inductive component of the load increases, the reactive power demand rises accordingly. Since a self-excited induction generator relies on a capacitor bank to supply the reactive power required for magnetization, part of the available reactive power is diverted to the load. As a consequence, the amount of reactive power available to sustain the excitation process decreases, resulting in a reduction of the generated voltage and a deterioration of the generator operating characteristics.

For the generator under consideration, a decrease in the power factor of the active-inductive load from ($\cos\varphi = 1$) to ($\cos\varphi = 0.8$) causes a substantial reduction in overload capability. This effect is observed even when the initial excitation capacitance is increased almost twofold, from its nominal value to (C = 50 μF). Under these conditions, the overload capability decreases by more than three times compared with operation under purely resistive loading conditions. Such a significant reduction highlights the dominant influence of reactive power consumption on the performance and stability of autonomous induction generators.

The deterioration of generator characteristics is also reflected in the reduced stiffness of the external voltage characteristics. As the power factor decreases, the generator terminal voltage becomes increasingly dependent on load variations, leading to larger voltage deviations and poorer power quality. Consequently, maintaining acceptable voltage levels under active-inductive loading conditions becomes considerably more difficult, especially when the load approaches the stability limit of the generator.

The obtained results indicate that increasing the excitation capacitance can only partially compensate for the adverse influence of inductive loads. Although a larger capacitor bank provides additional reactive power and improves voltage support, its effectiveness becomes limited when the load consumes a substantial amount of reactive power. Furthermore, excessive capacitance may result in magnetic saturation of the machine, increased losses, and deterioration of operating efficiency.

Therefore, the analysis confirms that active-inductive loads represent one of the most challenging operating conditions for autonomous self-excited induction generators. The results demonstrate that a decrease in load power factor significantly narrows the stable operating range of the generator and reduces its permissible overload capability. This fact practically excludes the use of autonomous induction generators for supplying active-inductive consumers without additional voltage stabilization or reactive power compensation systems. Consequently, the implementation of automatic voltage regulation devices, switched capacitor banks, static VAR compensators, or other reactive power control systems becomes essential for ensuring reliable and stable operation under such loading conditions.

Verification of the adequacy of the proposed method for calculating the steady-state characteristics of the IG–CES–load system was carried out using an experimental laboratory test bench, the schematic electrical diagram of which is shown in Fig. 6.

The main part of the installation consists of an induction machine and a prime mover mounted on a common frame. A three-phase squirrel-cage induction motor of type AIR80A4SU2, whose rated parameters are given above, was used as the generator. A separately excited DC motor (DCM) was used as the prime mover. The rotational speed of the induction generator rotor and the power of the DC motor were varied by changing the armature voltage of the latter using a thyristor converter.

The total capacitance of the excitation capacitors in each phase was formed by connecting all or several capacitors in parallel by means of switch K2 and circuit breakers AB3–AB6. Thus, during the experimental investigation it was possible to regulate the rotational speed of the induction generator rotor, vary the parameters and connection scheme (star or delta) of the capacitor excitation system (CB), and adjust the power of the DC prime mover.

The test bench provides the possibility of connecting various types of symmetrical loads to the induction generator:

– a three-phase resistive load represented by lighting devices, the connection and disconnection of which is performed by means of the package switch SA1 in “Position 1”;

– a three-phase load in the form of two induction motors of different ratings and with different shaft load torques, connected by means of the package switch SA1 in “Position 2” and circuit breaker K4, respectively;

– a resistive load (R_1), connected through a rectifier (VD5–VD11 assembled according to the Larionov rectifier circuit) and switch K5.

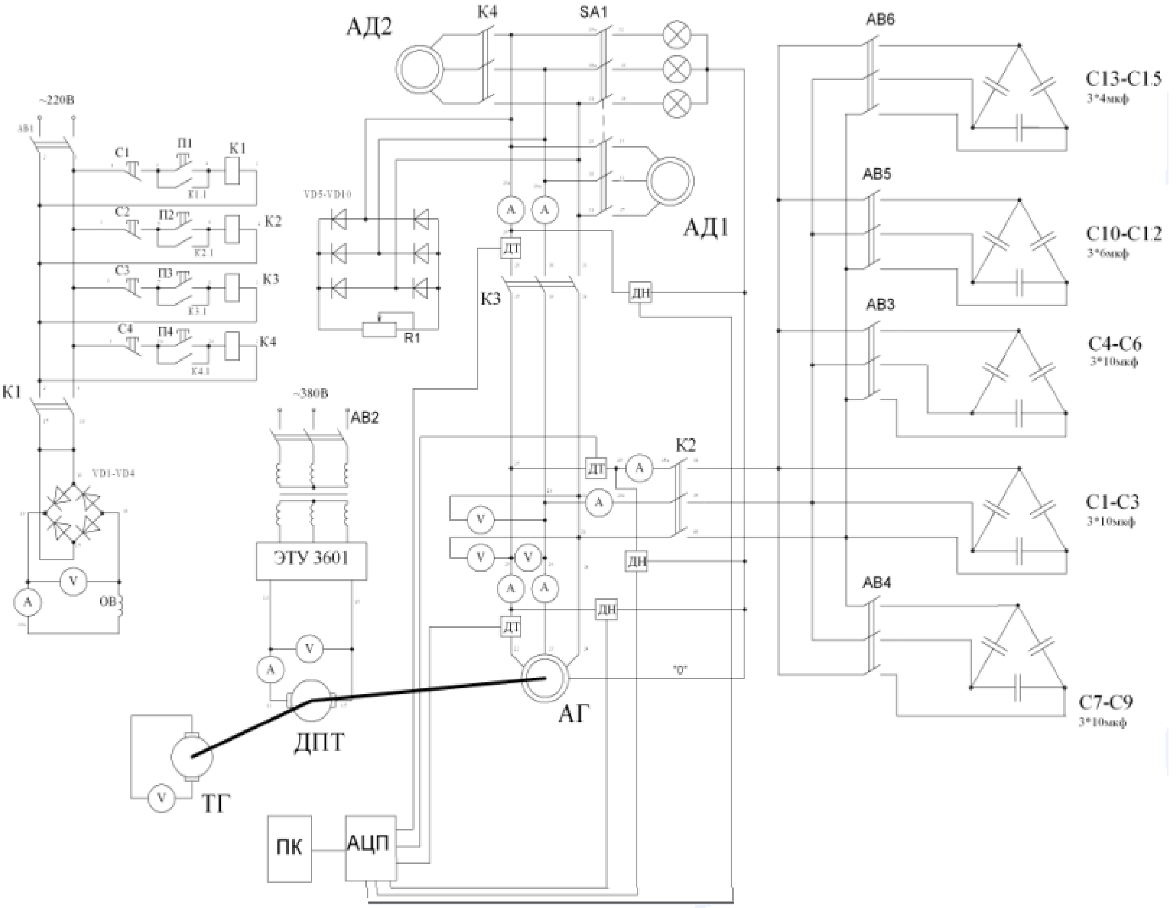

Fig. 6. Schematic electrical diagram of the experimental laboratory setup

The results of the experimental investigations are presented in Figs. 7–10. For clarity, all values of the investigated parameters are given in per-unit values (with respect to their rated values). The rated values were taken as the rated rotational speed of the induction motor operating in generator mode, the line voltage (U_{1N})) and phase current (I_{1N}) when its stator windings were connected in a star configuration. The rated resistance was taken as the total impedance (Z_N) corresponding to the rated parameters of the induction motor, where ($R=r_N/Z_N$).

Figs. 7 and 8 show the dependences of the line voltage, load current, phase current, and induction generator rotor speed on the value of the active load resistance. Curves 1–4 were obtained for different initial no-load line voltages (U_{10}), equal to 360, 300, 220, and 180 V, respectively. An identical pattern of variation can be observed for all curves 1–4. As the load resistance decreases, the voltage decreases nonlinearly. Within the load range from ($8Z_N$) to ($2.5Z_N$), the voltage at the terminals of the induction generator decreases by approximately the same amount, ($\Delta U = 0.15U_{1N}$), regardless of the initial value of (U_{10}).

Analysis of the characteristics presented in Fig. 8 showed that, as the ohmic load resistance decreases, the load current increases nonlinearly until it reaches a critical (maximum) value, after which it drops sharply. This behavior is typical of self-excited induction generators operating near the boundary of their stable operating region and reflects the complex interaction between the excitation system, the magnetic circuit of the machine, and the connected electrical load.

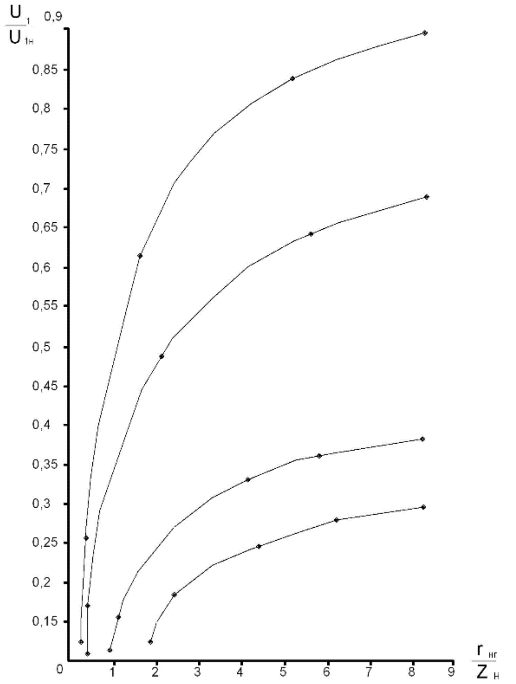

Fig. 7. Induction generator line voltage as a function of active load resistance

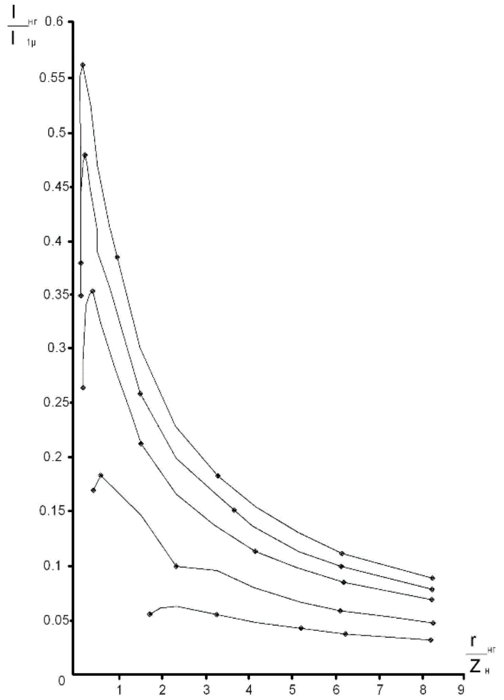

Fig. 8. Induction generator load current as a function of active load resistance

At relatively high values of load resistance, the generator operates in a stable mode, maintaining sufficient excitation and an acceptable terminal voltage level. Under these conditions, a decrease in resistance results in an increase in load current and output power delivered to the consumer. However, the relationship between current and resistance is nonlinear due to the combined influence of magnetic saturation, variations in generator slip, and changes in the frequency of the generated voltage.

As the load resistance continues to decrease, the load current gradually approaches its maximum attainable value, indicating that the generator is reaching the limit of its load-carrying capability. At this operating point, the excitation system can no longer provide sufficient reactive power to maintain the required magnetic flux in the machine. Consequently, voltage stability deteriorates, and the generator becomes increasingly sensitive to further changes in load conditions.

When the load resistance falls below the critical value, the generator enters the so-called “pull-out” or instability mode. In this region, even a small decrease in resistance causes a significant deterioration in operating conditions. Both the load current and the terminal voltage decrease abruptly instead of continuing to increase as expected. This phenomenon occurs because the capacitive excitation system is unable to compensate for the growing reactive power demand of the load and sustain the magnetizing current necessary for normal operation.

The observed behavior indicates a loss of excitation in the induction generator. Under these conditions, the generated voltage collapses rapidly, stable operation becomes impossible, and the generator effectively loses its ability to supply electrical power to the connected load. Therefore, the obtained characteristics clearly demonstrate the existence of a critical load resistance that determines the stability limit, overload capability, and maximum permissible loading of the autonomous self-excited induction generator.

For comparison purposes, the experimental and calculated characteristics of the induction generator under load conditions are presented in Figs. 9 and 10. The experimental results are depicted by solid lines, while the calculated characteristics obtained using the proposed method are shown by dashed lines.

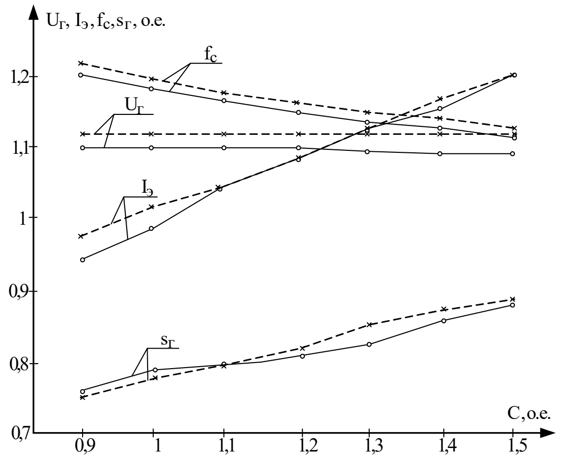

Fig. 9. Characteristics of the induction generator at constant generator voltage (Ug=const) and load resistance R_L=95 Ω.

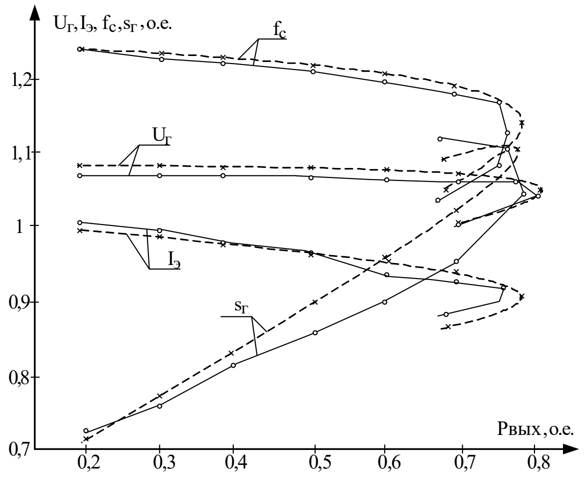

Fig. 10. Induction generator characteristics as a function of output power and excitation capacitance ($C=C_N$).

Conclusions. Based on the obtained results, an improved mathematical model of a self-excited autonomous induction generator with capacitive excitation has been developed and investigated. Unlike conventional approaches, the proposed model takes into account variations in the frequency of the generated voltage depending on load conditions. The developed method enables the simultaneous determination of the generator magnetizing reactance and the relative frequency of the output voltage, thereby improving the accuracy of calculating the steady-state characteristics of low-power autonomous induction generators.

The conducted calculations demonstrated that neglecting variations in the generated voltage frequency leads to significant errors in the determination of external characteristics, overload capability, and stability limits of the generator. It was shown that for an induction generator based on the AIR80A4SU2 squirrel-cage induction machine with a rated power of 1.2 kW, consideration of frequency variations is essential for obtaining reliable results, particularly under active-inductive loading conditions.

The investigation of the capacitive excitation system parameters revealed that increasing the excitation capacitance from 30 μF to 50 μF improves the stiffness of the external characteristics and enhances the overload capability of the generator. At the same time, excessive capacitance may result in magnetic saturation of the machine and therefore should be carefully considered during the design and selection of the excitation system.

It was established that a reduction in the load power factor significantly deteriorates the operating characteristics of the generator. When the load power factor decreases from cosφ = 1 to cosφ = 0.8, the overload capability of the generator is reduced by more than three times, while the terminal voltage becomes considerably more sensitive to load variations. These results confirm the necessity of applying additional reactive power compensation devices and automatic voltage regulation systems when supplying inductive consumers.

Experimental verification carried out on a laboratory test bench confirmed the adequacy of the proposed mathematical model and calculation methodology. A comparison of simulation and experimental results showed that the discrepancy between theoretical and measured data does not exceed 4–6%, which confirms the high accuracy of the developed approach and its practical applicability for the design and optimization of autonomous power supply systems based on self-excited induction generators with capacitive excitation.

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МОДЕЛЮВАННЯ ТА ДОСЛІДЖЕННЯ УСТАЛЕНИХ РЕЖИМІВ АВТОНОМНОГО АСИНХРОННОГО ГЕНЕРАТОРА З ЄМНІСНИМ САМОЗБУДЖЕННЯМ

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У цій статті досліджуються усталені режими роботи автономного асинхронного генератора з самозбудженням (SEIG), оснащеного системою ємнісного збудження та працюючого за активного й активно-індуктивного навантаження. Зростаючий попит на автономні та децентралізовані системи електрогенерації на основі відновлюваних і альтернативних джерел енергії суттєво підвищив інтерес до асинхронних генераторів завдяки їхній простоті, надійності, низьким вимогам до обслуговування та відсутності окремого джерела збудження. Однак робота асинхронних генераторів із самозбудженням характеризується значними змінами вихідної напруги та частоти залежно від величини навантаження і коефіцієнта потужності, що ускладнює аналіз та проєктування таких систем.

Метою даного дослідження є розроблення та перевірка вдосконаленого методу розрахунку статичних характеристик автономного асинхронного генератора малої потужності з урахуванням зміни частоти генерованої напруги за зміни умов навантаження. На відміну від багатьох традиційних методів розрахунку, які припускають *сталу вихідну частоту або нехтують її залежністю від навантаження, запропонований підхід враховує реальний вплив змін частоти, спричинених навантаженням. Це особливо важливо для асинхронних генераторів малої потужності, які зазвичай мають більші значення номінального ковзання і тому є більш чутливими до змін режимів роботи.*

Запропонована математична модель базується на схемах заміщення як асинхронного генератора, так і асинхронного двигуна навантаження. Аналіз виконується за допомогою системи рівнянь електричної рівноваги, що описують електромагнітні процеси в системі «генератор–навантаження». Для спрощення розрахунків асинхронний двигун навантаження подано еквівалентним RL-колом з параметрами, які залежать від ковзання двигуна. Отримана математична постановка дозволяє одночасно визначати намагнічувальний реактивний опір генератора та відносну частоту генерованої напруги. Такий підхід забезпечує точне прогнозування напруги генератора, частоти та навантажувальної здатності за різних режимів роботи.

З використанням розробленої методики було розраховано статичні характеристики асинхронного генератора, створеного на базі стандартної асинхронної машини з короткозамкненим ротором типу AIR80A4SU2 номінальною потужністю 1,2 кВт. Генератор досліджувався за активного та активно-індуктивного навантаження. Результати показали, що нехтування зміною частоти призводить до суттєвих похибок під час оцінювання регулювання напруги, перевантажувальної здатності та меж стійких режимів роботи. Ці розбіжності стають особливо помітними, коли генератор живить асинхронні двигуни, що характеризуються великими пусковими струмами та змінним коефіцієнтом потужності.

Для перевірки адекватності запропонованої моделі було проведено широкомасштабні експериментальні дослідження на лабораторному стенді, до складу якого входили асинхронний генератор, приводний двигун постійного струму, регульована батарея конденсаторів та різні типи електричних навантажень. Експериментальні вимірювання включали визначення напруги генератора, струму навантаження, швидкості обертання ротора, ємності збудження та вихідної потужності. Отримані результати продемонстрували добру узгодженість із теоретичними прогнозами. Порівняльний аналіз розрахункових і експериментальних характеристик показав, що відхилення між експериментальними та теоретичними даними не перевищує 4–6 %, що підтверджує достовірність і практичну придатність розробленого методу розрахунку.

Ключові слова: асинхронний генератор із самозбудженням (SEIG); автономний асинхронний генератор; ємнісне самозбудження; батарея конденсаторів; статичні характеристики; аналіз усталених режимів; зміна частоти; регулювання напруги; характеристики навантаження; активно-індуктивне навантаження; перевантажувальна здатність.

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