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Development and Investigation in MATLAB of an Autonomous Induction Generator Model with the Inverter in Rotor Circuit for a Wind Turbine

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Abstract

The work presents the development and investigation in MATLAB of a model of an autonomous self-excited induction generator with a rotor circuit inverter for a wind turbine. The system employs a scalar-controlled inverter with an independent power supply, and the nonlinear magnetization curve of the induction generator is taken into account. Voltage and frequency regulation are separated. The developed model made it possible to study the self-excitation mode for different rotor supply frequencies. During the simulation of the self-excitation process of the autonomous induction generator, it was found that the optimal parameters for stable self-excitation were achieved at a rotor frequency of 1.8 Hz and a rotor supply voltage of 20 V. The study also examined the effect of applying an active-inductive load and the system's response to changes in the drive shaft speed. When a 40% load of the rated value was connected, a slight voltage drop accompanied by an increase in the rotor phase current was recorded; however, the system remained stable without the need for additional control measures. By increasing the inverter voltage, the generator terminal voltage was restored to its initial level. When the drive shaft speed was suddenly reduced by 10%, a minor voltage decrease and a corresponding increase in rotor current were also observed. This mode remained stable, and the voltage and frequency were successfully leveled again by means of the inverter.

Keywords: model; autonomous induction generator with a wound rotor; inverter; wind turbine.

1. Definition of the problem to be solved

At present, the growing penetration of renewable and distributed energy sources requires the development of reliable and efficient generator systems capable of operating in variable-speed regimes. Among the existing solutions, asynchronous (induction) generators remain attractive due to their simple construction, robustness, low cost, and reduced maintenance requirements. However, their performance under non-standard operating conditions, especially in variable-speed applications, is significantly affected by the control method applied to the rotor circuit. The use of power electronic converters, particularly an inverter connected to the phase rotor winding, makes it possible to control the generator's electromagnetic processes, improve efficiency, and provide stable operation under different load conditions.

Despite the practical significance, comprehensive studies of such systems are still limited. A key challenge is the nonlinear interaction between the machine, the inverter, and the grid or autonomous load. Analytical approaches are often insufficient to capture all transient processes and parameter variations. Therefore, simulation tools are essential for analyzing dynamic behavior and verifying control algorithms. MATLAB Simulink, and in particular the SimPowerSystems (Simpower) library, provides a flexible environment for accurate modeling of electrical machines and power electronic interfaces.

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Developing a reliable model of an induction generator with a rotor-side inverter allows for the investigation of steady-state and transient modes, evaluation of energy efficiency, assessment of control strategies, and prediction of stability margins. Such research is highly relevant for modern energy systems, including wind power plants, microgrids, and autonomous energy complexes, where flexible and efficient generation sources are required.

2. Analysis of the recent publications and research works on the problem

Over the past three decades, a significant number of studies have appeared in periodical literature and conference proceedings devoted to grid-connected and stand-alone doubly-fed induction generators (DFIGs), their modeling, excitation methods, conversion schemes, and control strategies – ranging from classical theoretical works to modern experimental investigations and MATLAB/Simulink-based developments. Below is a detailed review of key sources selected to build the foundation for modeling an autonomous generator and its associated conversion and control systems.

In [1], an experimental analysis of a self-excited induction generator (SEIG) for small autonomous applications is presented. The authors systematically investigated the influence of three critical parameters – excitation capacitance, load and frequency (speed) – on the electrical characteristics of the SEIG. The practical experiments and measurement results in this work are highly valuable for validating MATLAB/Simulink models, as they demonstrate how real nonlinearities and condition variations affect generator behavior and highlight the need for experimental verification of simulation models.

In [2], an "impedance reshaping" approach for DFIG systems is proposed, focused on compensating rotor current dynamics to influence system behavior. This study is important for understanding how controlled inverters and their regulators interact with rotor mechanics and how these interactions should be considered when designing stable configurations for stand-alone operation or during mode transitions.

In [3], the issue of capacitor voltage synchronization in systems where a wind generator fully supplies power through an inverter is considered. The work demonstrates a synchronization control approach and analyzes transient and fault conditions, which are directly relevant to stand-alone systems with fully electronic interfaces where reactive power control and voltage matching are key.

Reference [4] presents a classical review of DFIGs for wind energy systems. The authors emphasized the advantages of a bidirectional converter in the rotor circuit for independent control of active and reactive power and discussed both grid-connected and stand-alone operation capabilities. This work often serves as a theoretical foundation for designing systems with rotor-side inverters.

Reference [5] proposed a detailed model and control strategy for a DFIG, including stand-alone modes under different load conditions. This work is valuable as a methodological resource for building Simulink models with detailed state equations and analysis of excitation and reactive power compensation.

In [6], the dynamic behavior of DFIGs during three-phase voltage dips is analyzed. The results are important for evaluating stand-alone system performance under severe disturbances and for designing protection and recovery strategies.

In [7], the authors presented a real-time analysis of voltage and frequency regulation for a small 2.2 kW SEIG with a dual-loop control structure. The work demonstrates a practical control architecture for a small autonomous system and provides testing scenarios for evaluating transient responses under load conditions.

In [8], a closed-loop ramp-comparison current regulator for an induction machine with a PWM voltage-source inverter is proposed. Although this study concerns motor control, its current control methodology and analysis of PI regulators in closed loops are applicable to controlling a rotor-side inverter in generator systems and help in selecting appropriate current regulation and protection algorithms.

The review shows that the referenced sources cover a wide range of aspects – from classical DFIG architectures and theoretical foundations to modern experimental and simulation implementations of SEIG and DFIG systems with high-performance inverters.

Thus, the necessity of developing a model of an induction generator with a rotor circuit inverter in MATLAB/SimPower Systems can be summarized as follows. First, it provides realistic reproduction of physical processes. The SimPower Systems-based model is not limited to transfer functions or simplified equations but directly simulates electrical and mechanical subsystems (windings, inverter, load, excitation source). This makes it possible to account for magnetic saturation, nonlinear losses, harmonics, and transient effects that cannot be adequately described by linear transfer functions. Second, the integration of the inverter in the rotor circuit enables independent control of active and reactive power in stand-alone operation. Modeling this subsystem in Simulink allows the study of: the influence of various control algorithms; output voltage and current quality (THD, frequency stability); behavior under variable speeds and loads; and the effectiveness of protection algorithms during fault conditions. Third, it enables analysis of the less-studied stand-alone operation mode. Unlike grid-connected operation, stand-alone mode requires the generator to independently maintain voltage and frequency without a "stiff" grid source. The SimPower Systems model allows investigation of self-excitation conditions, load-change stability, as well as power and stability limits of the system.

3. Formulation of the goal of the paper

The combination of an induction generator with an inverter in the phase rotor circuit and modeling in SimPower Systems makes it possible to integrate the classical theory of electrical machines with modern approaches to power conversion technology. This enables the study of operating modes that are difficult to describe analytically, such as harmonic interactions, fast transients, and the influence of control algorithms on real-time stability. MATLAB/Simulink allows for rapid adjustment of machine parameters, excitation circuits, inverter structures and load configurations – something that is practically impossible in a real experiment.

The objective of this work is to develop and investigate in MATLAB a model of a stand-alone induction generator with an inverter in the phase rotor circuit and self-excitation for a wind power installation. The study involves using a two-level inverter with independent power supply and taking into account the nonlinear magnetization curve of the induction generator. In addition, it is necessary to design an active-inductive load block, as well as a voltage regulator of inverter type in the rotor circuit with adjustable transistor firing angle. The investigation should be carried out in self-excitation mode for different rotor supply frequencies. Besides the self-excitation mode from the rotor side at various frequencies, it is also necessary to study the effect of applying an active-inductive load and the system's response to changes in the drive shaft speed.

4. Model Development and Investigation.

The first stage of constructing the MATLAB model of a stand-alone induction generator with self-excitation and an inverter involves selecting and configuring the main generator parameters. Figure 1 shows the induction generator along with data acquisition channels used to monitor key characteristics. This model enables the recording and analysis of parameters such as rotor speed, electromagnetic torque, as well as stator and rotor currents, and the active and reactive power of each individual phase. The figure also illustrates how measurement blocks are integrated into phase A, clearly showing the connection method and data acquisition process. The collected data provide the ability to monitor and adjust the generator's performance, allowing subsequent optimization of the self-excitation process and rotor inverter frequency to ensure stable output voltage.

A 37 kW induction machine was chosen as the main component for modeling. All technical characteristics of this machine were predetermined, allowing for accurate tuning and calibration of the model. Detailed parameterization includes entering such parameters as rated voltage, frequency, number of poles, stator and rotor winding resistances and inductances, as well as other characteristics that determine the dynamic behavior of the machine during operation. This approach allows the model to closely approximate real operating conditions and ensures correct generator performance during start-up, self-excitation, and subsequent loaded operation.

The main feature of the stand-alone induction generator (IG) model is the inclusion of the nonlinear magnetization characteristic, shown in Fig. 2. This characteristic is crucial for accurately reproducing generator operation, as it reflects the real physical properties of the materials used in its construction and directly influences the electromagnetic processes within the machine.

At the next stage, a model of a three-phase active–inductive load was built, allowing the simulation of various operating modes that affect the terminals of the stand-alone IG. This model makes it possible to simulate both purely active loads and combined active–inductive types. Additionally, it provides the ability to connect the load at a specific moment in time using electronic switches that emulate ideal transistors. The diagram shown in Fig. 1 presents the structure of the three-phase active–inductive load with a delayed connection function, enabling control over the timing of load connection to the system. The active resistance in the system is 10 Ω, and the load inductance is 0.001 H, which corresponds to an impedance of 0.314 Ω at the network frequency of 50 Hz. This approach allows for optimal load adjustment, providing effective simulation of various operating modes of the stand-alone generator.

The study implements scalar control of the induction generator through the rotor circuit. The scalar control module of the induction generator is based on maintaining a constant voltage-to-frequency ratio (*V*/*f* or *V*/Hz). The scalar control module determines the voltage applied to the rotor based on the specified reference frequency f_s. The calculation is performed using the following equation:

$$V_s = \left(\frac{V_n - V_{min}}{f_n - f_{min}}\right) \cdot (f_s^* - f_{min}) + V_{min}, \quad (1)$$

where V_n is rated inverter output voltage; V_{min} is minimum inverter output voltage; f_{min} is minimum frequency; f_n is rated frequency.

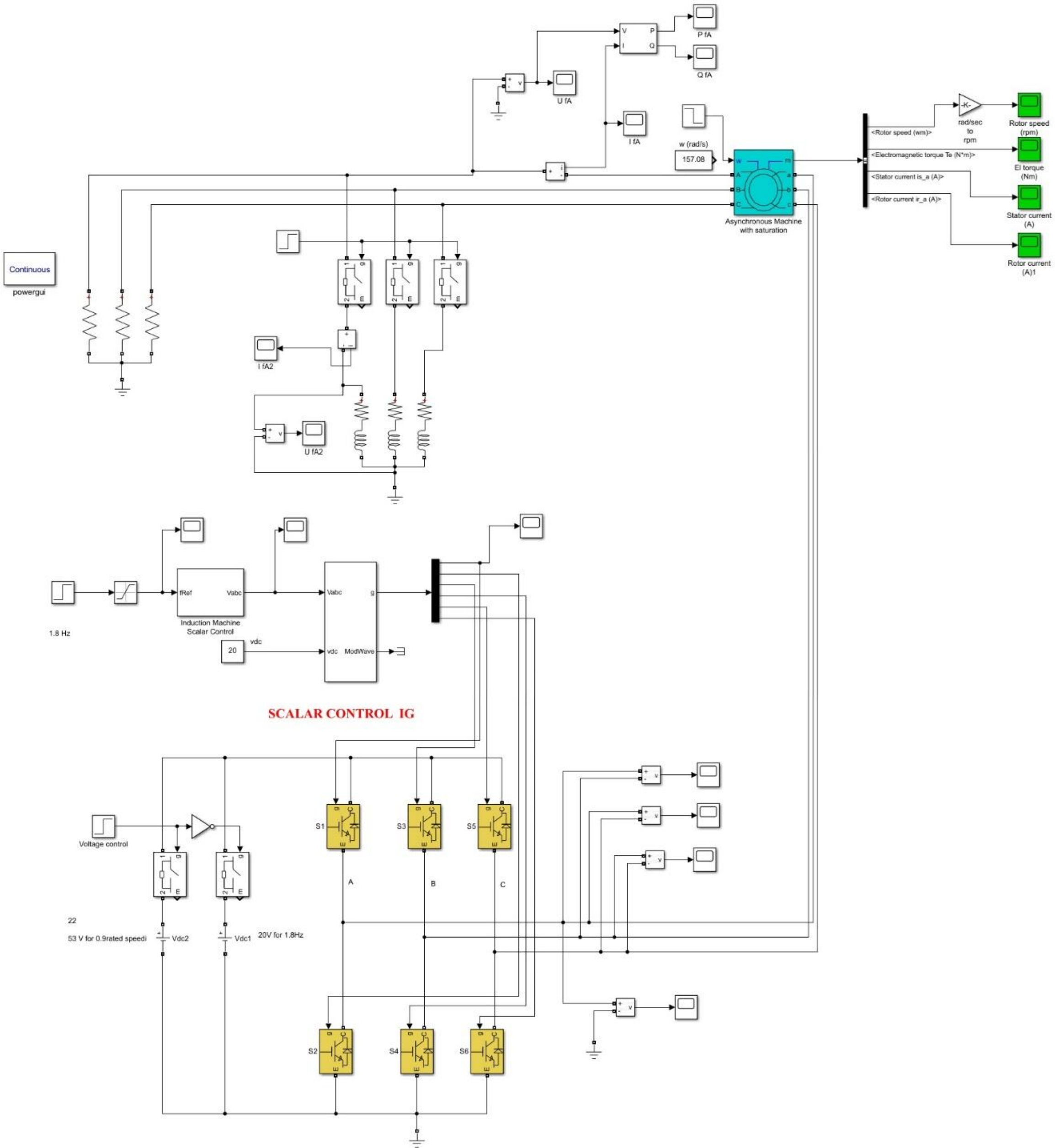

Fig. 1. Model of the stand-alone induction generator with self-excitation and an inverter in the phase rotor circuit.

The scalar control module uses voltage components in a stationary coordinate system. It then computes the phase voltages by performing an inverse Clarke transformation. The inverter is assigned the required frequency f_s, which is used to obtain the desired voltage value in accordance with the *V*/*f* principle. The calculated voltage is then transformed into the α–β coordinates. The next step is the conversion from the orthogonal α–β coordinate system to the three-phase abc system, implemented through the inverse Clarke transformation.

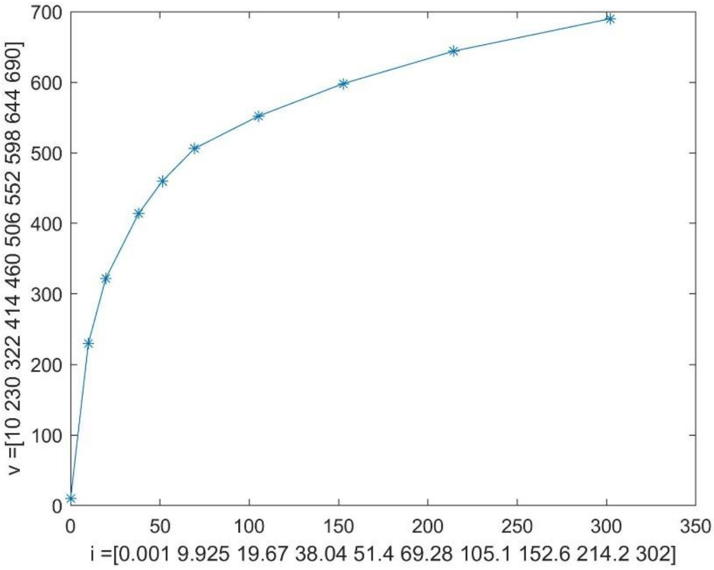

Fig. 2. Nonlinear magnetization curve for the 37 kW induction generator.

The next step after voltage transformation is the generation of a pulse-width modulation (PWM) signal. For this purpose, a specialized PWM generator must be designed. It functions as a three-phase, two-level PWM generator that forms the output signals used to control the inverter. The main task of the PWM generator is to manage the switching of the keys in the three-phase, two-level inverter (also known as a power converter). It determines the switching moments of the transistors based on the input control signals. In addition, the generator forms three sinusoidal reference voltages, each corresponding to one phase of the system. One of the key input parameters is the DC bus voltage, which affects the system's stability. At the output, the PWM generator produces six pulse signals used to control the power transistors of the inverter. Corresponding modulation signals are also generated to shape the desired output characteristics.

A specialized module is used to generate the pulse signals for transistor control. This module receives as input the formed three-phase voltage system V_{abc}, as well as the rectified DC voltage V_{dc}, which can come either from a rectifier or from a battery. To determine the precise switching instants of the transistors, the module uses an integrated MATLAB function that allows for accurate synchronization of the power switches, thereby maximizing the overall efficiency of the conversion system. This method not only provides voltage level control but also optimizes transistor operation, reducing energy losses and increasing the converter's efficiency. As a result, thermal stress on the power components is minimized, ensuring more stable system operation.

Based on the obtained values for the switching periods, the PWM control module generates gating pulse signals for each of the six inverter power transistors. These pulses determine the exact on/off instants of the transistors, ensuring proper operation of the three-phase inverter. This approach enables precise control of switching processes, allowing the inverter output voltage and current levels to be maintained within the desired limits. Such precise control is essential to guarantee the stable and efficient operation of the induction generator or any connected load. The method also contributes to improved energy efficiency and reduced thermal losses, positively affecting the overall system performance.

Fig. 1 presents the schematic diagram of the power inverter, which includes six high-power transistors. This block can be powered either from a three-phase independent rectifier or from a DC battery with a rated voltage of 560 V. This voltage level corresponds to the rectified output voltage generated by a three-phase bridge rectifier. The inverter, powered by a DC voltage source, acts as the key component for converting the DC voltage supplied by the battery or rectifier into a three-phase AC voltage. This enables effective control of the output voltage at the generator terminals and maintains stability under varying load conditions.

Fig. 1 also shows the complete MATLAB model of a household stand-alone induction generator with a phase-wound rotor and self-excitation provided by an inverter in the rotor circuit. The model integrates all the necessary components to ensure reliable power generation and voltage regulation for domestic consumers.

This integrated MATLAB model makes it possible to analyze in detail the operation of the stand-alone induction generator under various operating conditions. In particular, the model allows investigation of the influence of different load types on the generator's performance, evaluating voltage and frequency stability under changes in the active and inductive components of the load. It also enables the analysis of the reactive power compensation system implemented through the rotor-circuit inverter, which maintains the required level of reactive power for optimal generator operation. Thanks to the MATLAB simulation environment, it becomes possible to perform in-depth studies of system dynamics, transient responses, and steady-state performance with high precision.

Advantages of modeling in MATLAB. Creating such a model in MATLAB environment allows one to: conduct multiple simulations of different operating scenarios without the need for physical equipment, significantly reducing research costs; optimize system settings by analyzing generator behavior under various parameter values, thereby improving system efficiency; study the effect of the inverter on reactive power stability, which enables timely detection and correction of possible instabilities under real operating conditions.

For a detailed analysis of the operation of a household autonomous self-excited induction generator with an inverter in the rotor circuit, modeling was carried out based on the developed model. The simulation was performed in MATLAB environment to evaluate system performance under different load conditions and parameters. The purpose of the study was to examine the dynamic characteristics and verify the stability of the system under real operating loads.

The first scenario under investigation is the self-excitation mode. In this mode, the induction generator achieves self-excitation through the use of an inverter connected to the rotor circuit. The rotor circuit voltage frequency is 1.8 Hz, and the inverter voltage is 20 V. The drive shaft rotates at a constant speed of 157 rad/s.

To better understand the dynamics of self-excitation and the stability of the autonomous generator, a series of graphs were constructed to illustrate the transient processes of the system's main electrical parameters. Figure 3,*a* shows the transient graph of the instantaneous values of the phase voltage of the induction generator in phase A during the self-excitation process. This graph illustrates how the voltage rises during the transient state and reaches a stable value of 310 V in instantaneous values. Figure 3,*b* presents the transient process of the reactive power in phase A of the stator. Figure 3,*c* shows the transient process of the active power in phase A. Figure 3,*d* depicts the dynamics of the electromagnetic torque of the induction generator in the self-excitation mode. Figure 3,*e* presents the transient process of the phase current in the rotor, phase A. Measuring the current in the rotor circuit is important for understanding the influence of the inverter on the generator's operation under self-excitation conditions. Figure 3,*f* shows how the instantaneous value of the inverter output phase voltage in phase A changes during the self-excitation process.

Thus, during the study, the optimal self-excitation mode was determined – it occurs when the inverter operating frequency in the rotor circuit is set to 1.8 Hz, which ensures the required voltage levels at the stator terminals. The inverter voltage is 20 V. The reactive power is not drawn from the stator side.

In the no-load mode, the generator receives reactive power from the rotor and consumes a small amount of active power that compensates for its internal losses, including friction and cooling. In this state, the electromagnetic torque is minimal since there is no mechanical load on the shaft. As a result, the power factor is low because most of the energy corresponds to the reactive component.

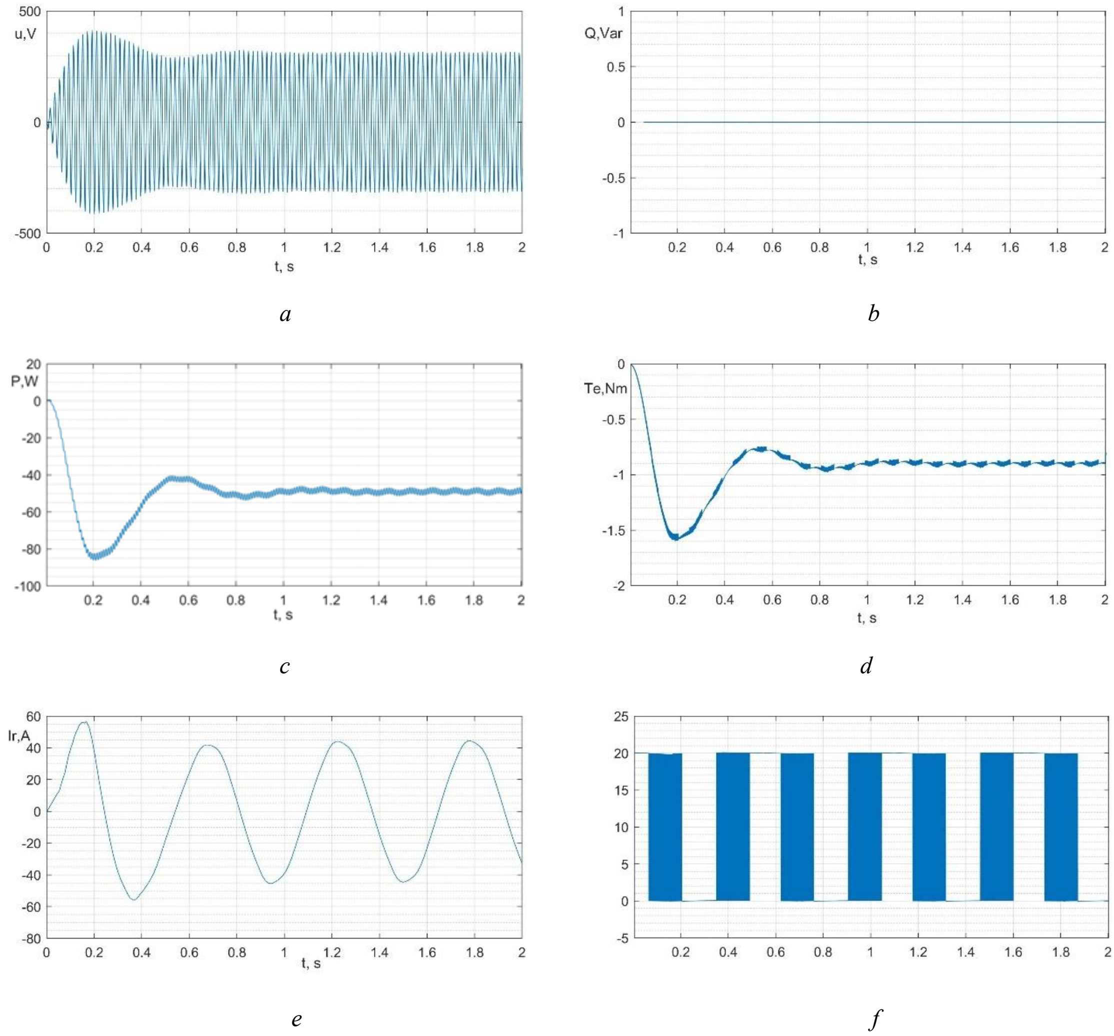

Fig. 3. System diagrams in the self-excitation mode for a rotor circuit voltage frequency of 1.8 Hz.

The next stage of the study involves modeling the operation of the autonomous induction generator under a sudden load application. This mode is critical for assessing the reliability and adaptability of the system to real-time load variations. The simulation was performed for a time interval between 2 and 3 seconds, during which an additional load is connected to the generator.

In this scenario, the rotational speed of the drive shaft is set to 157 rad/s and remains stable throughout the load application. The inverter frequency in the rotor circuit is maintained at 1.8 Hz, ensuring the necessary voltage level during the self-excitation process. The inverter voltage is 20 V. Despite the system being subjected to significant loading between 2 and 3 seconds, the drive shaft speed remains unchanged. At 2.5 seconds, the inverter voltage increases to 22 V to raise the terminal voltage to its nominal value. The 0.5-second delay in increasing the inverter voltage is due to the need to analyze the natural stability of the system.

Figure 4,*a* shows the transient graph of the instantaneous values of the phase voltage of the induction generator in phase A for the time interval from 0 to 3.5 s. Figure 4,*b* presents the transient process of active power in phase A. Figure 4,*c* depicts the dynamics of the electromagnetic torque of the induction generator. Figure 4,*d* illustrates the transient process of the rotor phase current in phase A. Figure 4,*e* shows how the instantaneous value of the inverter output phase voltage in phase A changes. Figure 4,*f* presents the waveform of the instantaneous phase voltage values in phase A for the time interval from 3.4 to 3.46 s.

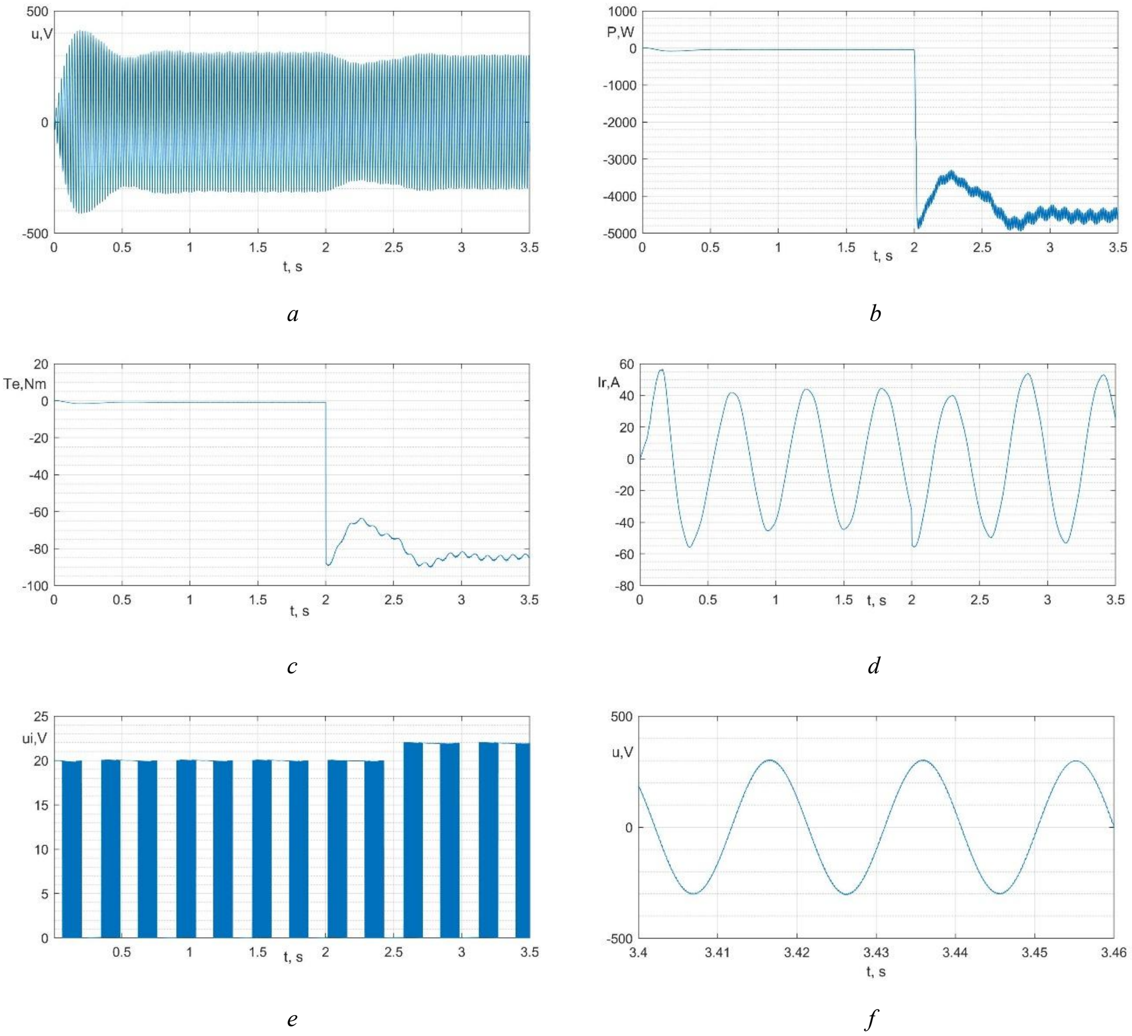

Fig. 4. System diagrams in the load connection mode.

In the load connection mode, a slight voltage drop accompanied by an increase in phase current was recorded (Figure 4,*a*); however, the system remained stable without the need for additional control measures. By increasing the inverter voltage, the generator terminal voltage parameters were restored to their initial level.

This simulation demonstrates the ability of the autonomous induction generator to maintain stable operation during sudden load changes under the condition of independent inverter supply, even for an open-loop system. As a result, the generator retains self-excitation stability, which is crucial for ensuring efficient and uninterrupted power supply to consumers. The obtained results make it possible to evaluate the generator's performance under various operating scenarios and confirm the feasibility of using an autonomous generator for supplying power to household and industrial loads under unstable conditions.

The next stage of the study involves simulating the operation of the autonomous induction generator under a sudden 10% reduction in the drive shaft speed. This mode is also critical for evaluating the reliability and adaptability of the system to real-time variations. The simulation was conducted for the time interval from 2 to 3.5 s.

The inverter operating frequency in the rotor circuit was set to 1.8 Hz to ensure the required self-excitation conditions. The inverter voltage was 20 V. In this mode, as before, the generator relied solely on the inverter for self-excitation. At 2 seconds, the rotational speed of the drive shaft abruptly decreased by 10%, reaching 141.37 rad/s. At 2.5 seconds, the inverter voltage was increased to 53 V to restore the generator terminal voltage to its nominal level. The 0.5-second delay in increasing the inverter voltage was introduced to analyze the natural stability of the system.

This simulation demonstrates the ability of the autonomous induction generator to maintain stable operation under sudden variations in the drive shaft speed, provided the inverter is independently powered, even in an open-loop configuration. Hence, the generator retains self-excitation stability, ensuring effective and continuous power supply. The obtained results confirm the correct system configuration for stable self-excitation and readiness for further experiments under various operating modes. Stable generation of reactive power ensures voltage maintenance within acceptable limits, even under changing load and drive speed conditions.

Figure 5,*a* shows the transient graph of the instantaneous values of the phase voltage of the induction generator in phase A for the time interval from 0 to 3.5 s. Figure 5,*b* presents the transient process of active power in phase A. Figure 5,*c* depicts the dynamics of the electromagnetic torque of the induction generator. Figure 5,*d* illustrates the transient process of the rotor phase current in phase A. Figure 5,*e* shows how the instantaneous value of the inverter output phase voltage in phase A changes. Figure 5,*f* presents the waveform of the instantaneous phase voltage values in phase A for the time interval from 3.4 to 3.46 s.

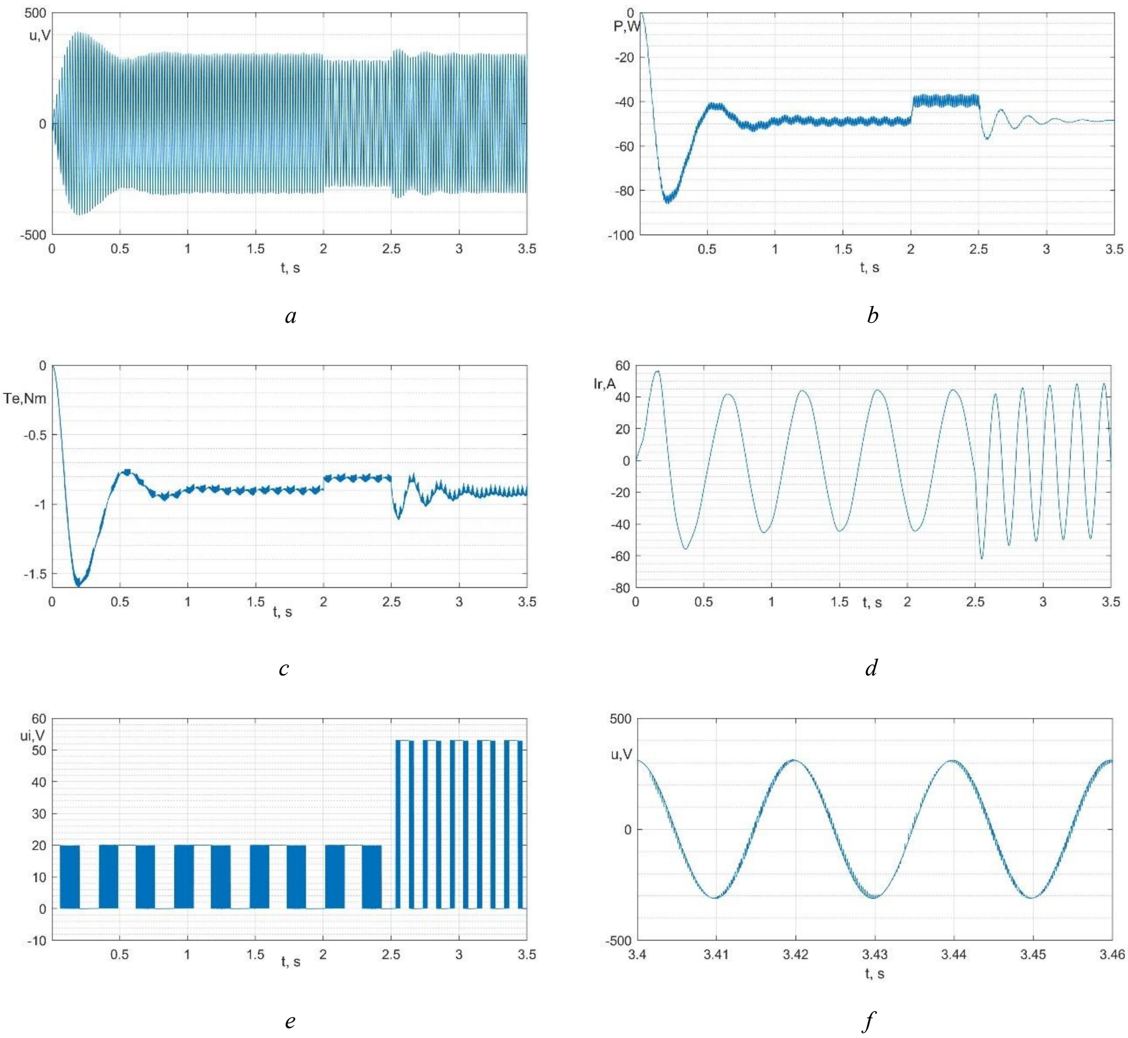

Fig. 5. System diagrams under a sudden speed reduction mode.

When the motor speed was reduced, a slight decrease in voltage and an increase in current were also observed. The system remained stable, and the voltage was restored by the inverter. This simulation confirms the ability of the autonomous induction generator to maintain stable operation during sharp variations in the drive shaft speed under independent inverter supply, even for an open-loop system.

The results indicate that the system configuration ensures stable self-excitation and readiness for further studies. The stable generation of reactive power maintains the voltage within permissible limits, even under variable load and drive speed conditions.

5. Conclusion

In this work, a MATLAB-based model of an autonomous induction generator with a rotor circuit inverter and self-excitation for a wind turbine application was developed and investigated. Voltage and frequency regulation are separated. The implementation of a two-level inverter with an independent DC supply and consideration of the nonlinear magnetization curve of the induction generator significantly improved the model's accuracy.

The developed model enabled the study of self-excitation behavior at different rotor supply frequencies. During the simulation of the self-excitation process, it was found that optimal parameters for stable operation were achieved at a rotor frequency of 1.8 Hz and an inverter voltage of 20 V. As a result, the generator terminal voltage reached 310 V (instantaneous), corresponding to 220 V RMS, which ensures reliable system operation.

The study also investigated the impact of active–inductive load application and the system response to drive shaft speed variations. In the load connection mode (40% of nominal load), a slight voltage drop and an increase in rotor phase current were observed, but the system remained stable without additional regulation. By increasing the inverter voltage, the generator terminal voltage parameters were restored to their nominal levels. Under a sudden 10% reduction of drive shaft speed, a minor voltage decrease and a current increase were recorded, yet the voltage was again stabilized by the inverter.

The developed model serves as a universal tool for: designing autonomous power sources (wind, diesel, or hybrid systems); optimizing control systems for rotor inverters; educational demonstration of induction generator principles for students and engineers.

Developing such a model is crucial for the design of autonomous power supply systems, especially under variable load conditions or in remote areas where connection to the centralized grid is not possible. This approach enables further optimization of system parameters and testing of different operating scenarios in autonomous mode. Therefore, the created model of the autonomous induction generator provides the ability to simulate and analyze its behavior under variable load conditions while ensuring accurate and efficient control of output voltage and frequency.

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Розроблення та дослідження в MATLAB моделі автономного асинхронного генератора з інвертором у колі ротора для вітрової установки

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Анотація

В роботі розроблена та досліджена в MATLAB модель автономного асинхронного генератора з інвертором у колі фазного ротора та самозбудженням для вітрової установки. В системі застосований інвертор зі скалярним керуванням та незалежним живленням, а також врахована нелінійна крива намагнічування асинхронного генератора. Регулювання напруги та частоти розділене. Розроблена модель дозволила провести дослідження в режимі самозбудження для різних частот живлення ротора. У ході моделювання процесу самозбудження автономного асинхронного генератора було встановлено, що оптимальні параметри для стабільного самозбудження досягалися при частоті ротора 1,8 Гц та напрузі живлення ротора 20 В. В роботі здійснено дослідження впливу накиду активно-індуктивного навантаження та реакцію системи на зміну швидкості приводного вала. У режимі підключення навантаження 40 % від номінального значення було зафіксовано невелике зниження напруги разом зі зростанням фазного струму ротора, однак система залишалася стабільною без потреби в додаткових засобах регулювання. За допомогою підвищення напруги інвертора параметри напруги на затискачах генератора були повернуті до початкового рівня. При раптовому зниженні швидкості приводного вала на 10 % також спостерігалося незначне зменшення напруги та збільшення струму ротора. Цей режим генератор пройшов стабільно, а напругу і частоту знову вдалося вирівняти завдяки інвертору.

Ключові слова: модель; автономний асинхронний генератор з фазним ротором; інвертор; вітрова установка.