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IDENTIFYING THE DYNAMIC PROCESSES OF THE INTERPHASE SHORT-CIRCUIT CURRENT OF A WIND TURBINE GENERATOR OPERATING IN STANDALONE MODE

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The object of the study is the electromechanical part of a wind turbine with a horizontally arranged gearless rotor and an AC generator with a capacity of up to 40 kW. The study solves the problem of analyzing the electromechanical processes that occur during an interphase short circuit in a wind turbine generator.

The article presents the results of theoretical studies of the short-circuit mode of the power circuit of an AC generator of a gearless type wind turbine with a capacity of up to 40 kW. The relevance of the study is due to the need to increase reliability and reduce accidents caused by interphase short circuits in wind turbines.

The choice of equations for the mathematical model of the electromechanical part of the turbine is justified; a simulation model was developed using the MATLAB package; the adequacy of the simulation model was assessed by comparing transient processes obtained theoretically and experimentally on a laboratory bench under similar initial conditions and the moments of inertia of the mechanical part of the rotating elements of the wind turbine rotor and generator; a theoretical study of transient processes during interphase short circuits has been performed.

Distinctive features: the proposed energy discharge equation and the developed model allow for the estimation of the energy characteristics of a wind turbine, taking into account the dynamic characteristics of the rotor and the generator, which increases the accuracy of the analysis of the energy characteristics in the mode of interphase short-circuit of the stator windings of the generator.

Practical significance: the research results can be used in the design, modernization, and adjustment of protection systems for wind turbine generators with a capacity of up to 40 kW

Keywords: wind turbine, generator, short circuit, mathematical model, simulation modeling, dynamic processes

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1. Introduction

To ensure the efficient and reliable operation of gearless wind turbines with a capacity of up to 40 kW, it is necessary to conduct research into short-circuit conditions in the power circuit of an alternating current generator. It is known that during the operation of wind turbines, their reliability is significantly affected by climatic conditions, including the negative factor of high dynamics of changes in ambient temperature. The presence of salt solution in precipitation in coastal areas also has a significant impact. The above factors lead to a decrease in the insulating properties and plasticity of cable products. As a result, the probability of a short circuit in the generator power circuit and the occurrence of a fire increases.

Research into the dynamic characteristics of short-circuit modes will enable the implementation of an effective short-circuit protection system for wind turbines.

Therefore, research aimed at analyzing and modelling short-circuit modes in wind turbine generators is highly relevant.

2. Literary analysis and statement of the problem

The program [1], part of the «European Green Deal» project, substantiates the relevance of green energy. Reducing environmental risks should be a priority. The paper [2] presents an analysis of the growth in the number of wind turbines in technologically advanced countries and justifies the need to improve their reliability, increase their service life and minimize the number of failures. The results of studies on the dynamic and operational characteristics of wind turbines of various capacities are presented. It has been shown that the share of energy generated by wind turbines is currently on a steady upward trend: over the past 20 years, the number of new modern turbines commissioned each year has been increasing, and the share of renewable energy sources has reached 18% in the European Union, 20% in the United States, 28% in China, and 35.9% in Australia [3].

However, there are still unresolved issues related to the operation of small-capacity wind turbines (up to 40 kW), which mainly operate in autonomous mode. The reasons for this may include: objective difficulties associated with instability of voltage and frequency at the generator output; a design feature of gearless turbines – the absence of an automatic blade angle correction system depending on wind speed; the high cost of implementing additional stabilization systems, which makes research and development of practical solutions relevant.

Ways to overcome these difficulties may include the use of inverters in the load power circuit to stabilize the voltage amplitude and frequency, but the impact of climatic factors and mechanical vibrations on the reliability of electrical equipment remains insufficiently studied. All this leads to the conclusion that it is advisable to conduct research on improving the reliability and technical and economic performance of low-power gearless wind turbines.

Wind turbines with a capacity of more than 40 kW usually operate on the general power supply system, while turbines with a capacity of up to 40 kW mainly operate in autonomous mode. Modern low-power turbines are showing a trend towards an increase in the number of mass-produced gearless types, which significantly improves their reliability and technical and economic performance. An additional design feature of such turbines is the absence of a system for automatically correcting the angle of the blades relative to the plane of rotation depending on wind speed. In this case, the frequency and amplitude of the voltage at the generator output vary depending on the wind speed, and the presence of an inverter in the load power circuit ensures their stabilization.

The paper [4] present the results of research on the design and operation of gearless wind turbines with AC generators with a capacity of up to 30 kW. It is shown that the development of such installations addresses the issues of increasing energy efficiency, reducing the negative impact on the environment, and reducing the impact of climatic factors on turbine reliability.

However, there are still unresolved issues related to ensuring the stability of the generator in transient and emergency modes, as well as increasing the durability of the electromechanical system components during long-term operation under variable loads and temperatures. The reason for this may be due to objective difficulties associated with the complexity of modelling non-stationary processes in the turbine-generator system, as well as the high cost of conducting full-scale experimental research. A way to overcome these difficulties may include the development of simulation models that allow the analysis of electromechanical processes under various operating conditions without the need for costly field experiments. An important step in conducting simulation experiments is to assess the adequacy of the simulation model.

The papers [5, 6] present the results of studies on the influence of climatic and operational factors on the reliability of wind turbines. It is shown that in coastal areas characterized by high humidity, elevated salt content in the air and significant temperature fluctuations, the reliability and trouble-free operation of wind power plants is significantly reduced. But there were unresolved issues related to assessing the combined impact of these factors on the power electrical equipment of wind turbines and developing methods to protect them from emerging emergency conditions. The reason for this may be due to objective difficulties associated with the need for lengthy operational observations and the high cost of experimental research, which makes it difficult to conduct such research in real-world conditions.

A way to overcome these difficulties may include the creation of mathematical and simulation models [7] that allow for the study of dynamic processes in wind turbines under various conditions, including emergency modes. In paper [8], a mathematical model and a modern automatic control system for a multi-motor electric drive were developed. In paper [9], a system of indirect protection against emergency mode, overheating of the stator windings with the development of a temperature sensor is considered. In paper [10], the object of research is an electromechanical system with three motors, interconnected and operating according to the "electric working shaft" system. In paper [11], a resource-saving emergency protection system is presented, the purpose of which is to protect high-voltage electric motors from external and internal short circuits. The studies conducted do not fully take into account the impact of mechanical vibrations and climatic factors on the reliability of electrical equipment and cable line insulation.

The paper [12] examines the factors that have the most significant impact on the reliability of wind turbine power supply systems, including mechanical structure vibrations, resonance phenomena at certain wind speeds, lightning strikes, and switching surges. All of the above factors lead to the destruction of cable insulation and short circuits in three-phase power transmission systems, which in some cases is accompanied by the ignition of equipment components.

All this leads to the conclusion that it is advisable to conduct research on the analysis of dynamic processes during a short circuit in the stator winding circuit of a gearless wind turbine generator. To achieve this goal, it is necessary to justify the relevance of theoretical studies of short-circuit modes, develop mathematical and simulation models of the electromechanical part of a wind turbine, evaluate the adequacy of the simulation model based on comparison with experimental data, and perform theoretical studies of short-circuit modes using the similarity method.

The paper [13] presents theoretical studies conducted on the short-circuit mode of a doubly fed wind turbine that transmits energy to the grid. The aim of this work is to present the technical implementation of a short-circuit protection device in a dual-power generator. A simplified generator model was used in the study of the dynamic characteristics of the short-circuit mode. The model is abstract, numerical values for the coefficients, and the generator power values are not presented.

In paper [14], the short-circuit mode of the output terminals of a wind turbine generator that transfers energy to the grid was studied. The research was conducted for wind turbines with a capacity of 1 to 5 MW. The paper presents an analysis of transient processes for various values of power line resistance, as well as the dynamic characteristics of short-circuit currents in the generator circuit and power in the protection circuit.

But there were unresolved issues related to lack of equations for the transfer of wind energy to the generator, as well as equations for the kinetic energy stored in the rotating elements of the wind turbine structure. The absence of a section assessing the adequacy of the mathematical model indicates the low accuracy of the results of theoretical studies.

There are theoretical studies results on of the short-circuit mode in the power transmission system of a wind park with wind turbines in the power range of 0.66 to 3 MW. The paper [15, 16] presents a simulation model on the PSS/E platform. The results of theoretical studies reflect the transient processes of a short-circuit mode in a power source with energy characteristics significantly exceeding the capacity of a single wind turbine [17, 18]. It should be noted that works [13–15] justify the expediency and adequacy of using mathematical and simulation modelling of wind turbines as the most suitable method for studying transient processes in short-circuit mode.

In previous works, much attention has been paid to the study of short-circuit modes of wind turbines with direct connection to the grid. Very few works have been devoted to the study of the interphase short-circuit mode of a standalone wind turbine generator.

3. The aim and objectives of the study

The aim of this study is to identifying the dynamic processes of the interphase short-circuit current of a wind turbine generator with a capacity of up to 40 kW operating in standalone mode.

To achieve this aim, the following objectives are being addressed:

– to substantiate a mathematical model of a gearless wind turbine, taking into account the dynamic properties of its rotor and generator;

– based on a mathematical model, to develop a simulation model of the electromechanical part of a gearless wind turbine operating in standalone mode, taking into account interphase short circuits;

– to evaluate the adequacy of the simulation model by comparing the dynamic characteristics obtained theoretically and experimentally for similar initial conditions and numerical values of the moment of inertia of the mechanical part of the rotating elements of the rotor and generator of the wind turbine.

4. Materials and methods

The object of the study is the electromechanical part of a wind turbine with a horizontally arranged gearless rotor and an AC generator with a capacity of up to 40 kW. The main hypothesis of the study is to confirm the danger of an interphase short circuit at the output terminals of a wind turbine generator.

To solve the tasks set, classical methods of mathematical and simulation modelling of dynamic processes in the electromechanical part of the wind turbine were used. The relevance and adequacy of the methods used are justified in works [13–15]. When developing the mathematical model, the basic equations of an alternating current generator and a horizontal rotor were used, allowing the interaction of the current values of the coordinates of the alternating current generator and the rotor in transient modes to be described. Simulation modelling was performed using the MatLab application package, which made it possible to investigate dynamic processes during interphase short circuits and assess the impact of generator and wind turbine parameters on the nature of transient processes.

The theoretical and experimental studies are limited by the following conditions:

– the power of the wind turbine is limited to 40 kW;

– the studies were conducted exclusively for rotors with a constant optimal angle of attack;

– the output voltage of the wind turbine generator was limited in the range of 12-48 V and the values of 220 V and 380 V of three-phase voltage.

When developing a mathematical model of a three-phase generator with permanent magnets, the following simplifications were made: the amplitude values of the generated voltages, as well as the values of the active resistances and inductances of the three phases, are identical.

It is assumed that the energy characteristics of an interphase short circuit are determined by the kinetic energy stored in the rotor and generator masses of a wind turbine.

In the course of the work, the international standard Implementation of IEC Standard Models for Power System Stability Studies was used [19].

5. Research results of dynamic processes of the interphase short-circuit current of a wind turbine generator

5. 1. Mathematical model of a wind turbine

At the first stage of theoretical research, based on known dependencies, it is necessary to obtain a mathematical model that takes into account the dynamic properties of the rotor and the electromechanical part of the wind turbine.

As is known, the equation of the aerodynamic power P_a as a function of wind speed, developed by the wind turbine rotor, is

$$P_a = C_p(z)\frac{\rho S V^3}{2}, \quad (1)$$

where $C_P(Z)$ – wind energy efficiency; ρ – air density; S – total swept area of turbine blades; V – wind speed.

The torque developed by the rotor is determined by the expression

$$M_a = \frac{P_a}{\omega}, \quad (2)$$

where ω – angular velocity of rotor shaft.

Torque balance equation on the generator shaft is presented by the following expression

$$J\frac{d\omega}{dt}=M_a-M_{em}-M_c, \tag{3}$$

where J – inertia moment; M_{em} – electromagnetic torque of the generator; M_c – the resistance (loss) torque, accounting for friction and other losses.

When developing a mathematical model of a three-phase generator with permanent magnets, the following assumptions were made, among others: the voltage amplitude values of the generated electrical energy, as well as the values of active resistances and inductance of three phases are the same.

The equation system of three-phase generator with permanent magnets looks like the following:

$$\begin{cases} U_{(A,B,C)}=e_{(A,B,C)}-R_A i_{(A,B,C)}-L_A\dfrac{di_{(A,B,C)}}{dt}; \\ e_A=k\omega\sin(2p\omega t); \\ e_B=k\omega\sin\left(2p\omega t+\dfrac{2\pi}{3}\right); \\ e_C=k\omega\sin\left(2p\omega t-\dfrac{2\pi}{3}\right), \end{cases} \tag{4}$$

where: $e(A, B, C)$ – electromotive force induced in each phase of generator winding; $i(A, B, C)$ – phase winding current of the generator; R_A, L_A – active resistance and inductance of the phase winding of the generator; $U_{A, B, C}$ – phase voltage at the generator output terminals; k – constructive constant; 2p – number of pole pairs. Thus, expressions (1)–(4) describe the dynamic properties of a wind turbine operating in standalone mode.

5. 2. Simulation model of a wind turbine

In order to carry out theoretical studies of the dynamic processes in a wind turbine, a simulation model of the electromechanical part of a direct-drive wind turbine has been developed based on equations (1)–(4). The simulation model was developed using the MATLAB (California, USA) application package (Fig. 1). The functional purpose of the wind turbine simulation model blocks is presented in Table 1.

Table 1

Functional purpose of simulation model blocks

No.	Designation of simulation model block	Functional purpose of simulation model block
1	Constant 1	Setting the wind speed value
2	Subsystem 2	Modelling of wind turbine mechanical part
3	Subsystem 1	Model of generator
4	Subsystem	Model of gearless three-phase double half-period rectifier

In the process of developing the simulation model, the following assumptions were made: when studying dynamic processes in the wind turbine electromechanical part, the speed value was constant within the entire experiment. The wind speed value was set by the Constant 1 parameters.

The dynamic changes of the rotor angular speed, voltage at the rectifier output and load current were recorded using Scope 1, Scope 5 and Scope 12 oscilloscopes respectively.

The adequacy of the simulation model was assessed in two process modes: wind turbine acceleration mode and load resistance stepwise change at the output of uncontrolled double-half-period three-phase rectifier Subsystem mode. The wind speed value was set by the parameters of the Constant 1 block.

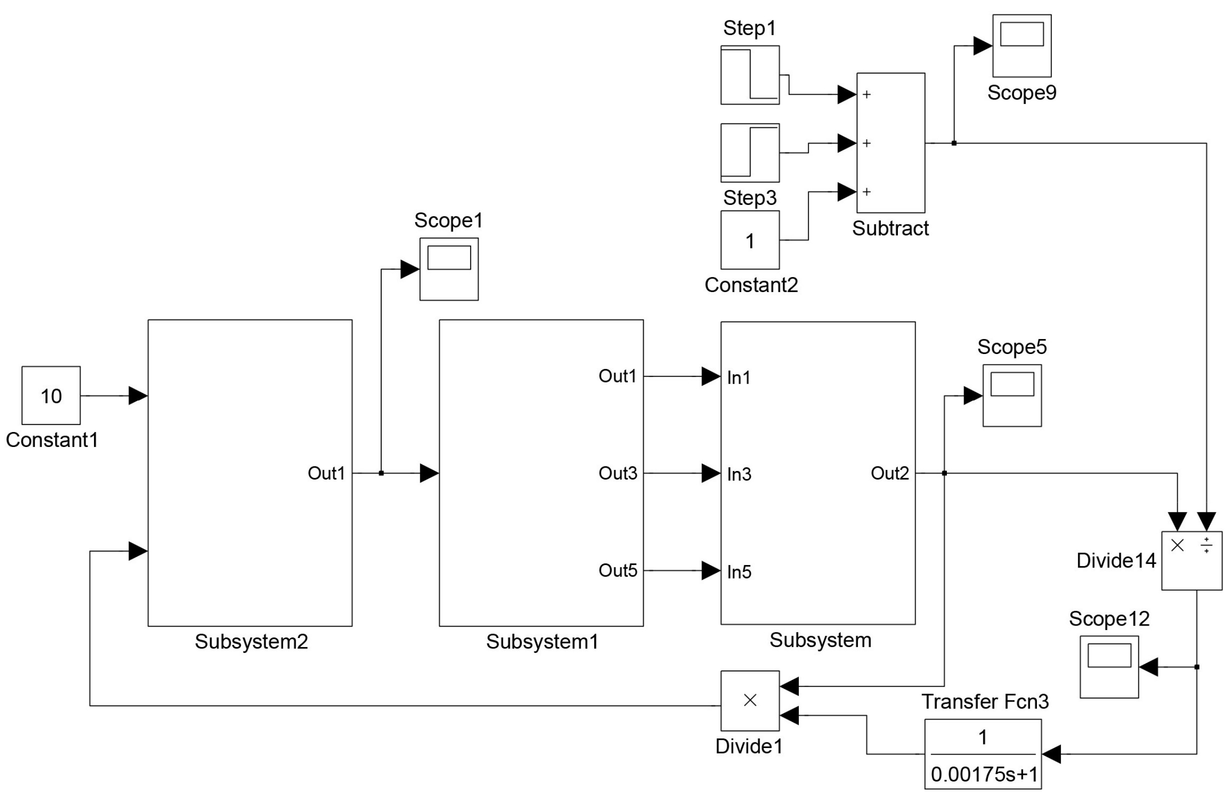

Fig. 1. Simulation model of a wind turbine

The response of the wind turbine to a step change of the generator electrical load is modeled using the Constant 2, Step 1, Step 3, and Subtract blocks. The generator load current, taking into account the load resistance, is modeled by the Divide 14 block. Using the rules for transferring functionally complete model blocks – an inertialess double-half-period three-phase rectifier and an aperiodic element modeling the inertia of each of the three phases of generator stator windings – is modeled by the Transfer Fcn 3 block. A particular feature of the double-half-period three-phase rectifier operation is its commutation properties – sequential load connection between each of the three phases of the three-phase voltage source. Due to this, the Transfer Fcn 3 aperiodic element is sequentially connected to each phase. Since the electric arc that arises during a short-circuit mode is mainly characterized by thermal processes, the load under these conditions represents only an active component. The value of the electric power consumed by the load was calculated by the Divide 1 block. The value of the active power component P consumed by the load was calculated from the expression P = Ui, where U and i are the load voltage and current of the double-half-period three-phase rectifier of Subsystem block in the generator power circuit.

In order to develop simulation model of the wind turbine mechanical part the equation (3) is presented in the integral form. The simulation rotor model is presented by Subsystem 2 block in Fig. 1.

This solves the problem of developing a simulation model of the electromechanical part of a gearless wind turbine.

After conducting simulation modelling, experimental research must be carried out on a laboratory test bench. The results of simulation and experimental tests will allow the adequacy of the simulation model to be assessed.

5. 3. Evaluation of the adequacy of the simulation model of the electromechanical part of the wind turbine

The adequacy of the wind turbine electromechanical part simulation model was evaluated by comparing the transient processes for similar model and laboratory stand parameters under identical control and disturbance inputs.

Experimental studies were conducted using a laboratory stand, the structural diagram of which is shown in Fig. 2.

By varying the control signal U2, wind speed is controlled within the range of 0 –10 m/s.

A three-phase permanent magnet synchronous generator was used in the laboratory stand as the electromechanical converter of wind energy into electrical energy. Technical characteristics of synchronic generator are presented in Table 2.

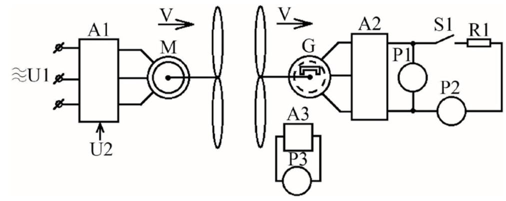

Fig. 2. Structural scheme of laboratory stand: A1 – controlled frequency converter with a DC link; M – squirrel–cage induction motor; G – AC voltage generator with permanent magnets; A2 – uncontrolled double-half-period three-phase rectifier; P1 – voltmeter; P2 – ammeter; A3 – anemometer; P3 – digital wind speed indicator; S1 – load commutator; R1 – load resistance; U2 – wind speed control signal; V – wind speed

Table 2

Technical characteristics of synchronic generator

No.	Designation of rotor and generator parameters	Numerical value of parameter
1	Nominal rotational speed, rpm	300
2	Nominal generator capacity, W	110
3	Nominal voltage at generator terminals, V	48
4	Number of phases	3
5	Stator winding resistance (R_G), Ohm	0.57
6	Stator winding inductance (L_G), H	1.01*10^{-3}
7	Generator rotor inertia moment, kg/m^2	0.00161
8	Wind turbine rotor inertia moment, kg/m^2	0.0127
9	Mechanical time constant $T_1 = J_\Sigma * \omega_n / M_n$, c	0.1408
10	Electrical time constant $T_2 = L_G / R_G$, c	0.00177

Registration of dynamic processes is implemented by means of control and indication sensors, the technical characteristics of which are presented in Table 3.

Table 3

Technical characteristics of control and indication sensors

Sensor type	Model	Manufacturing country	Technical characteristics	
Voltage sensor	LEM LV-25P	Switzerland	Input signal range, V	±0...50
			Output signal range, V	±0...4
			Current consumption, mA	15
			Absolute error, %	±0.9
			Nonlinearity of readings, %	0.2
Current sensor	LEM HX-03P	Switzerland	Input signal range, A	±0...3
			Output signal range, V	±0...10
			Frequency passband, Hz	0...50000
			Current consumption, mA	15
			Absolute error, %	±1
			Nonlinearity of readings, %	1
Wind speed sensor A3	MK-1-BEI	Russia	Wind speed measurement range, m/s	0...10
			Output signal range, V	0...10
			Current consumption, mA	200
			Accuracy, m/s	±1

The software for visualizing dynamic processes was developed in conjunction with the laboratory test bench and provides visualization of the experimental results.

The laboratory test bench is shown in Fig. 3.

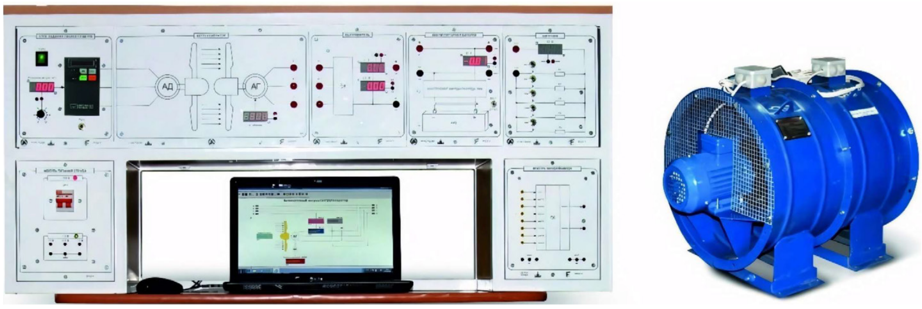

Fig. 3. External view of the laboratory test bench: 1 — assembly field for configuring various versions of the wind turbine test bench; 2 — laptop with software for visualizing dynamic processes; 3 — electromechanical part of the wind turbine

The adequacy was assessed by comparing the transient processes during the wind turbine acceleration in no-load (oscillograms 2 and 3) and under load modes (oscillograms 4 and 5), as shown in Fig. 4.

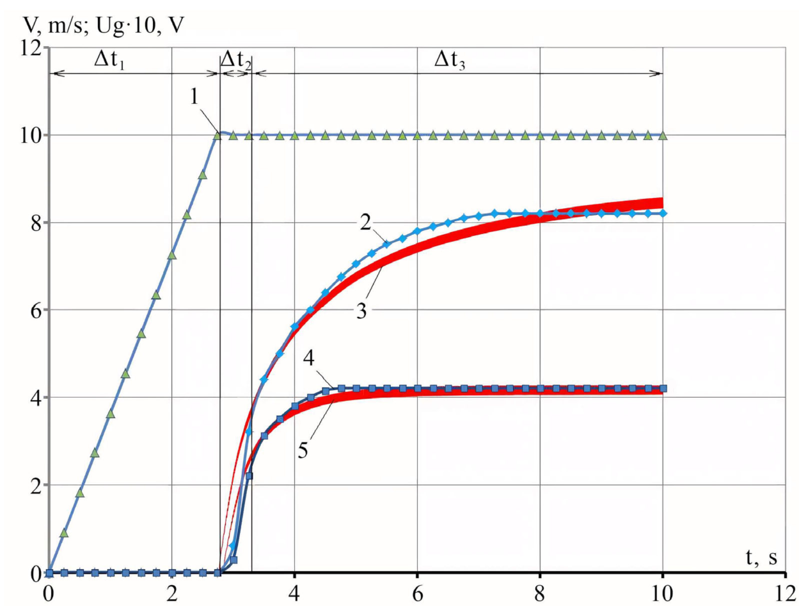

Fig. 4. Transient processes during the wind turbine acceleration: 1 — graph of wind speed versus time; 2, 3 — graphs of the transient processes of the wind turbine's acceleration at idle speed, obtained experimentally and through simulation, respectively; 4, 5 — graphs of transient processes under load, obtained experimentally and by simulation, respectively

During the time interval Δt_1, an increase in wind speed up to 10 m/s was implemented linearly using an asynchronous electric motor M and a controlled frequency converter A1. During this time interval, the wind turbine was braked mechanically. During the time intervals Δt_2 and Δt_3, the wind flow speed remained constant. After the brake was released, the wind turbine was accelerated. The transient acceleration processes of the wind turbine obtained experimentally, in no-load (position 2) and under load (position 4) modes, are presented in Fig. 4.

In order to assess the adequacy of the simulation model (Fig. 1), simulation experiments were carried out for similar wind speed and load values. The transient acceleration processes of the wind turbine, in no-load (position 3) and under load (position 5) modes, obtained during the simulation experiments, are presented in Fig. 4. During the time interval Δt2, after the wind speed reached 10 m/s, the wind turbine brake was released and the angular velocity began to increase, which correspondingly led to the rectifier output voltage increase. In this interval, the maximum transient voltage error (position 3, Fig. 4) at the terminals of the uncontrolled three-phase rectifier does not exceed 18%, and under load does not exceed 10%. The increase in error at the initial stage of wind turbine acceleration is explained by the absence in Subsystem 2 (Fig. 1) of a dependency between the wind energy utilization coefficient and the angular velocity of the wind turbine. The model uses an optimal value of the wind energy utilization coefficient. During the time interval Δt3, the modeling error does not exceed 3%, and under load, 1.5%, which fully meets the requirements for engineering calculations.

Additionally, the adequacy of the simulation model was assessed by comparing the transient processes obtained theoretically (positions 1, 4) and experimentally (positions 2, 3) during the stepwise change in load (Fig. 5).

In the interval Δt1, the wind turbine accelerated under full load (switch S1 is closed, Fig. 2). At the time t = 2s, a stepwise partial load disconnection occurred (switch S1 is open, Fig. 2). At the time t = 3.8 s, the load was connected stepwise.

When the load is disconnected at the output of the uncontrolled rectifier, a voltage increase at its output terminals is observed, following a law close to exponential. This effect is explained by the increase in angular velocity after the load is disconnected, which leads to the energy accumulation in the flywheel mass of the wind turbine rotating parts. After the load is reconnected at time t = 3.8 s, a short-term increase in current by 40% relative to the steady-state value is observed. After the complete discharge of the energy stored in the wind turbine flywheel masses, the voltage reaches a value corresponding to the time interval Δt_1. The error of the simulation results relative to the experimentally obtained results for similar input and disturbance values did not exceed 10%.

Thus, experimental studies of the wind turbine's dynamic modes were conducted, and the adequacy of the developed simulation model was confirmed.

Previous studies have presented information on the dynamic processes of electric arc development during short circuits in cable power supply systems [12]. In the initial stage of arc formation, an increase in current is observed in the interphase circuit of the three-phase power source. According to the method of A. R. Warrington, the resistance of the electric arc changes from 0.1 to 0.3 Ohms within 10 seconds.

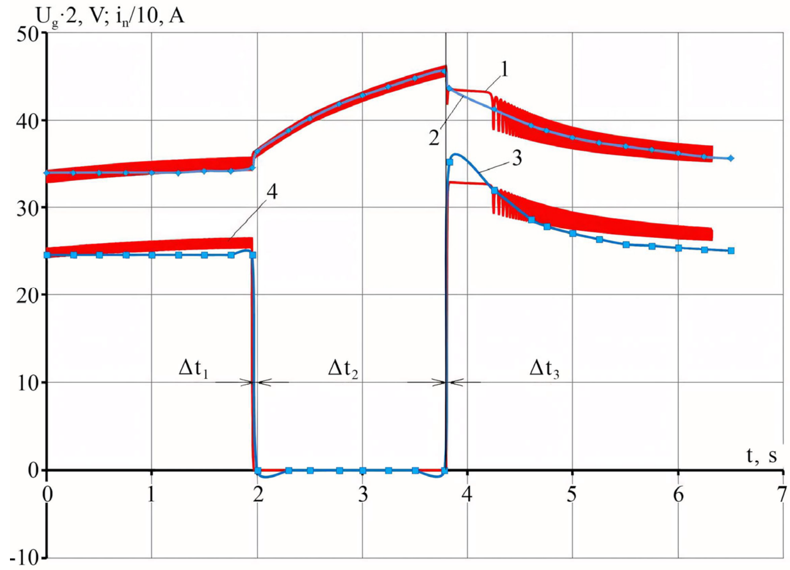

Fig. 5. Response of wind turbine parameters to stepwise load change: 1, 2 — voltage diagrams at the wind turbine generator terminals obtained, respectively, through simulation modeling and experimentally; 3, 4 — diagrams of the wind turbine generator stator current obtained experimentally and through simulation modeling, respectively

In paper [12], dynamic processes occurring in a power cable with an unlimited power source were considered.

In contrast to the studies presented in paper [12], the following characteristics of wind turbines must be taken into account in wind turbine generators:

– limited power of the energy source stored in the rotating masses of the wind turbine;

– influence of active-reactive components of wind turbine generator windings.

In wind turbines, the dynamic characteristics of the electromechanical part of the wind turbine significantly influence the energy parameters of the power source. Therefore, conducting theoretical studies of the short-circuit emergency mode in the wind turbine power supply system can be considered a relevant and important task.

This study has the following limitations:

– the object of study is a gearless wind turbine, which means that when the wind speed changes, the frequency of the voltage at the generator output terminals also changes;

– the power of the wind turbine is limited to 40 kW and, as a result, the total moment of inertia of the wind turbine corresponding to this power is also limited.

All parameters of the simulation model of the electromechanical part of the wind turbine (Fig. 2) corresponded to the parameters of the laboratory stand (Fig. 3). As a result of simulation experiments, transient processes were obtained (Fig. 6) for the angular velocity of the wind turbine and generator (position 3), the root mean square voltage at the terminals of the generator phase windings (position 3), and the root mean square current of the generator stator winding, on which a short circuit was simulated (position 1).

The simulation experiment was carried out according to the following algorithm: the rotor, and consequently the generator, was accelerated without load to an angular velocity of 14.4 rad/s, and at time $t = 0.1$ s, an interphase short circuit was simulated using a stepwise function. A characteristic feature of the angular velocity transient process (position 2, Fig. 6) is its exponential decrease after the short circuit occurs. According to the equation (4), the root means square voltage value changes according to a similar law (position 3, Fig. 6).

In Fig. 6, $\Delta t_1 = 3T_1 + 3T_2$ – time interval, characterizing transient process of energy transformation stored in the generator stator windings and the wind turbine flywheel mass energy.

On the laboratory stand, the time constant characterizing the inertia of rotating inertial masses of the rotor and generator is two orders greater than the inertia of the generator stator electrical circuit. This fact is reflected in the current rise dynamics in the stator circuit (position 1) after the short circuit occurs. The energy processes occurring in the generator stator circuit, in the case where $T_2 \ll T_1$, with sufficient accuracy for engineering calculations, can be determined using the equation for the discharge of energy stored in the wind turbine rotating parts.

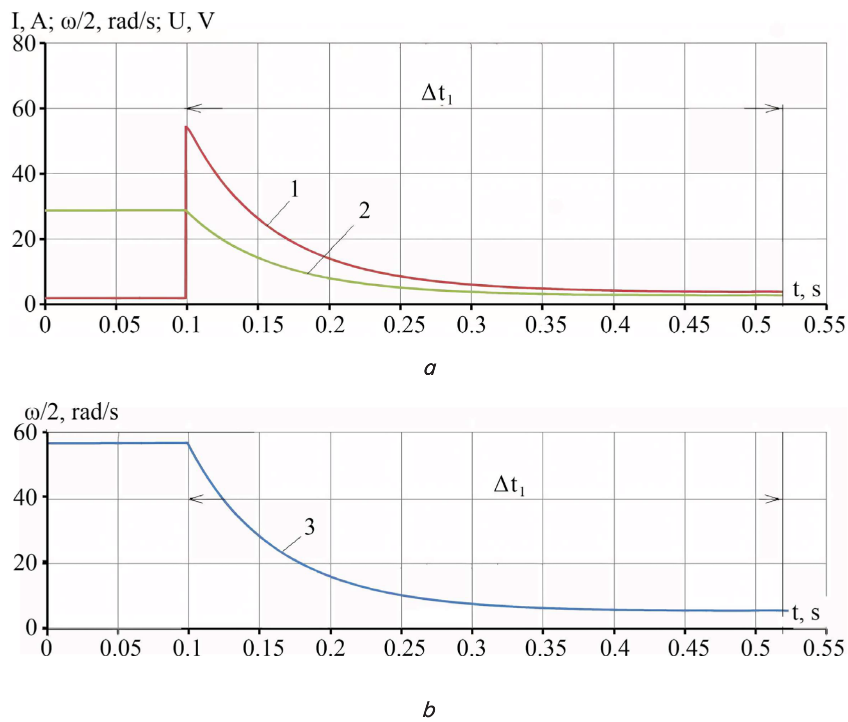

Fig. 6. Transient processes during a short circuit on the terminals of the generator phase windings: 1 — diagram of the root mean square value of the stator winding current of the generator; 2 — diagram of the root mean square voltage at the generator terminals; 3 — angular velocity diagram of a wind turbine generator

The study was conducted under the following assumption:

– in the simulation model (Fig. 1), the nonlinear relationship between the wind energy utilization coefficient and the angular velocity of the wind turbine rotor is neglected, as this introduces only a negligible error within the steady-state voltage interval at the generator terminals.

In the future, to develop an effective short-circuit protection system taking into account the dynamic features of the wind turbine, an equation was obtained for the energy characteristics of the generator stator circuit over the time interval Δt_1 (Fig. 6) during a short circuit

$$W = i_{ST} U_{IN} \int_{t_{IN}}^{t_\Sigma} \left[\left(1 - e^{-\frac{t}{T_2}} \right) e^{-\frac{2t}{T_2}} \right] \mathrm{d}t, \qquad (5)$$

where W – energy released in the wind turbine generator stator during interphase short circuit; i_{ST} – steady current value in the generator stator winding over a period of time equal to $3T_2$; U_{IN} – initial voltage value, preceding to short-circuit time; $t\Sigma$ – time period corresponding to the discharge of energy stored in the wind turbine flywheel masses, taking into account transient processes in the generator stator windings; t_{IN} – time of short-circuit mode starting; t – current time.

In the future, using the characteristics of transient processes in the electrical part of the wind turbine obtained during the research and the system of equations (1)–(4), taking into account the design features of the cooling system of the generator of the analyzed type of wind turbine, it is possible to develop a short-circuit protection system.

A potential area of application of the proposed method for determining the moment of fault development, taking into account the dynamic characteristics of the wind turbine, is the development of integrated generator protection systems.

6. Analysis of the transient processes of a wind turbine generator during an interphase short circuit

The obtained results allow to explain the dynamics of transient processes in the electromechanical part of a wind turbine during an interphase short circuit. An analysis of the mathematical model equations (formulas (1)–(4)) and simulation experiments (Fig. 1, 4–6, Tables 1–3) showed that the decrease in the rotor and generator angular velocity after a short circuit follows an exponential law, and the root-mean-square voltage at the phase winding terminals changes synchronously with the angular velocity (Fig. 6). This paper discusses the dynamic processes occurring in the power circuit of a wind turbine generator, taking into account the limited power of the energy source stored in the wind turbine's flywheels and the influence of the active and reactive components of the resistance of the generator's stator windings.

A feature of the transient process is the exponential decrease in the angular speed of the rotor and the corresponding change in the average square value of the stator voltage and current, which reflects the influence of the limited energy stored in the turbine's flywheel masses and the generator's windings. The time intervals of the transient processes allow to determine the moment when an emergency situation develops and to assess the dynamics of changes in the system parameters after a short circuit occurs.

Comparison of the simulation results with the experimental data showed that the model adequately reproduces the dynamics of transient processes: the maximum error does not exceed 18% at idle speed and 10% under load.

The obtained characteristics of transient processes allow to use this method to develop comprehensive generator protection systems that can timely prevent damage to the turbine's electromechanical components.

The proposed approach differs from existing approaches [8] in the following features:

– the limited power of the energy source stored in the rotating masses of the wind turbine is taken into account;

– integrates the influence of the active and reactive components of the generator windings;

– the simulation model implemented in MATLAB (Fig. 1) allows for the simulation of real transient processes, including step changes in load and the acceleration of a wind turbine.

Comparison with known studies shows that traditional models of short circuits in power cables [12] do not take into account the complex resistance of the generator and the energy stored in the turbine's flywheel masses. The proposed approach allows these limitations to be eliminated and the reliability of the results of emergency mode studies to be improved.

The study has the following limitations:

– the object of the study is a gearless wind turbine with a capacity of up to 40 kW; the results cannot be applied to turbines with gear transmission or a capacity exceeding 40 kW;

– the simulation model assumes a constant wind speed throughout the experiment, which limits the reproducibility of transient processes under dynamically changing wind flows;

– transient processes are only adequate within the limits of the nominal values of the rotor and generator moments of inertia, as well as the nominal load;

Prospects for further research include:

– development of an integrated generator protection system taking into account the dynamic characteristics of the wind turbine;

– extending the simulation to turbines with gearboxes and higher power ratings;

– creating adaptive protection algorithms based on the analysis of transient processes.

7. Conclusions

1. A mathematical model of the electromechanical part of a wind turbine was obtained in the form of equation system of three-phase generator with permanent magnets, taking into account the wind speed, the dynamic properties of the rotor, and the generator of a horizontal-type wind turbine.

2. Based on the mathematical model, a simulation model of the electromechanical part of the wind turbine was developed in the MatLab software environment. During the simulation, the following assumptions were made: the rotor speed was constant throughout the experiment; the parameters of the three-phase generator windings were identical.

3. The adequacy of the developed simulation model was confirmed by comparing the dynamic characteristics obtained during simulation and experimental studies during idle and load acceleration. In the operating range of the generator's rotational speed at idle, the error did not exceed 10%, and under load, it did not exceed 1.5%. In addition, the simulation error was determined during a step-by-step load change: the error did not exceed 10%.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise that could affect the study and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating the submitted work.

Authors' contributions

Gulim Nurmaganbetova: Conceptualization, Methodology, Writing – original draft; **Vladimir Kaverin:** Software, Methodology, Formal analysis; **Sultanbek Issenov:** Methodology, Formal analysis, Writing – original draft; **Gennadiy Em:** Investigation, Formal analysis, Validation; **Elmira Sarsembiyeva:** Investigation, Visualization, Writing – review & editing; **Yerlan Ualiyev:** Investigation, Formal analysis; **Zhanara Nurmaganbetova** - Formal analysis; Writing – original draft; **Zhanat Issenov:** Formal Analysis, Writing – original draft.

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