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INDIRECT TEMPERATURE PROTECTION OF AN ASYNCHRONOUS GENERATOR BY STATOR WINDING RESISTANCE MEASUREMENT WITH SUPERIMPOSITION OF HIGH-FREQUENCY PULSE SIGNALS

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The article deals with the indirect methods for calculating the temperature of asynchronous generators with the introduction of a pulse component in the power supply circuit of the stator windings of asynchronous generators with squirrel-cage rotor. The relevance of this issue is determined by the need to improve asynchronous energy converters to increase their reliability and safety.

The object of the study is an asynchronous generator with squirrel-cage rotor, which consume 40 % of the total electricity generated, and are the most affordable. One of the dangerous modes of asynchronous generators is their overheating as a result of increased currents and temperatures.

The thermal protection of the stator winding of asynchronous generators relies primarily on measuring or determining the winding temperature.

An indirect method for determining temperature based on measuring the resistance of the stator of an asynchronous generator with squirrel-cage rotor is proposed. The method is based on superimposing pulse signals of small amplitude and high frequency of 600 Hz on an alternating sinusoidal voltage with a frequency of 50 Hz. A simulation model for a 3 kW asynchronous generator has been developed. There were given the simulation results. The estimated values of the active resistances of the stator can be used to indirectly determine the temperature of the windings in thermal protection devices of asynchronous generators, as well as for control, monitoring and diagnostics of the technical condition. The research results confirm the possibility of indirect temperature determination and the creation of a thermal protection system for asynchronous energy converters based on the use of estimation methods

Keywords: asynchronous generator, indirect thermal protection, simulation model, stator resistance, constant current components

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1. Introduction

To ensure efficient and reliable operation of asynchronous energy converters, is necessary to timely identify and eliminate the overload and overheating of the generator. It is known that up to 80 % of failures of electrical machines, including generators, occur due to insulation breakdown, primarily due to its overheating.

The existing technical solutions for the protection of asynchronous generators have a common disadvantage, which is that various heat sink options in generators are not taken into account due to operating conditions, including ambient temperature, and have a large error. It can also be noted that these methods control the amount of current flowing through the power contacts of the contactors, but not the heating of the generator. Thus, the listed disadvantages make it urgent to create generator protection systems based on indirect methods that take into account both heat dissipation and heat dissipation.

In this regard, research on the development of indirect thermal protection of a squirrel-cage rotor asynchronous generator is relevant.

2. Literary review and problem statement

In the article [1], there is proposed an engine overheating protection device based on using the effect of changing the geometry of a bimetallic plate as a function of the temperature of the stator of an electric motor.

It should be noted that the proposed device does not take into account the ambient temperature and the intensity of forced cooling.

In this work [2], a technical device for protecting an electric motor from overheating of its windings is proposed.

The proposed device is based on the use of thermosensitive resistance. The thermosensitive element must have a negative temperature coefficient of resistance.

The disadvantages of this device include the need to change the design of the electric motor, which will allow for heat exchange of thermosensitive resistance with the structural elements of the electric motor.

The authors of the article [3] performed an analysis of the methods for determining the value of the active resistance of the windings of an asynchronous motor. The works consider methods based on disconnecting energy from the stator windings with subsequent measurement of the resistance value, as well as indirect methods of current control.

In the work [4], theoretical studies of the method for evaluating the active component of the complex resistance of the stator windings of an asynchronous electric motor are conducted using the addition of a direct-current component to the electric motor power supply system.

The use of this method provides a sufficiently high accuracy of the current control of the value of the active resistance of the stator windings. For electric motors with a capacity of several megawatts, the use of this method is economically impractical, since in order to obtain an error of less than 10 %, the power of the direct current source in the stator winding circuit must be several kilowatts. Additionally, the constant voltage source, in accordance with the requirements of safety regulations, must have an appropriate insulating strength.

The authors of the article [5] conducted experimental studies with various cooling systems: the proposed IC3A1 cooling system containing a system of air filters and air channels in the front parts of the generator and the traditional dual-circuit IC6A1A6 cooling system.

In the course of experimental studies, the higher efficiency of the developed cooling system has been confirmed. The proposed cooling system reduces the temperature of the stator windings and insulated bearings of type 6330, structurally located in the frontal parts of the generator. It should be noted that the proposed cooling system requires a fundamental change in the design of the generator. Temperature sensors on the bearings and on the stator windings were installed on the asynchronous generator [6]. The insulation class of the generator stator windings is F, while the maximum permissible temperature should not exceed 155 °C. During the experimental studies, the temperature of the stator windings and bearings was controlled. When working with a semiconductor converter, high-frequency harmonics are present in the current of the stator windings, which lead to an additional increase in temperature in the stator windings of the asynchronous generator. The bearing temperature should not exceed 100 °C when operating in the field. The results of the experiments show that the observed temperature increased to 110.4 °C [7].

Temperature rise can affect the insulation and other components of the generator. Overheating can be the result of prolonged operation at high loads or the lack of a proper cooling system, all this can lead to short circuits, insulation failure or other electrical failures inside the generator, leading to possible damage, additionally overheating can be caused as a result of the generator operating under conditions exceeding the rated power [8]. In order to prevent emergencies, the asynchronous generator must be equipped with a device for current temperature control of the stator windings of the asynchronous generator of the wind turbine installation.

In the case of using thermistor temperature sensors, structural changes in the housing of the asynchronous generator are required. An additional difficulty is the transmission of reliable information from the temperature sensor, structurally located in the generator housing, to the information control unit, which is located at a considerable distance from the generator structure. The lack of current temperature control of the stator windings of the generator leads to the destruction of insulation due to overheating. One of the ways to solve the issue of increasing the reliability of wind power generators is to develop a system for current temperature control of the stator windings of the generator.

The authors of the article [9] carried out theoretical studies of the method of indirect determination of asynchronous machine parameters. The paper substantiates the relevance of using the method of indirect determination of the temperature of an asynchronous electric motor in order to improve its energy characteristics. The method of indirect parameter determination is a software product that is structurally unrelated to an electric motor and can be located in the controller of the control and protection system for the operation modes of an asynchronous machine.

Thus, the currently existing methods of protecting asynchronous generators with a squirrel-cage rotor against overheating in most cases have a number of disadvantages, since they either do not take into account various options for heat removal in generators due to operating conditions, or do not provide the required accuracy of temperature control.

The above allows justifying the feasibility of conducting studies on the development of a thermal protection system for an asynchronous generator based on the indirect method of determining the temperature of its stator winding.

3. The aim and objectives of the study

The aim of the study is to develop and confirm the effectiveness of indirect thermal protection method for a squirrel-cage rotor asynchronous generator based on a method for determining the temperature of its stator winding by measuring its resistance with the superimposition of high-frequency pulse signals on the sinusoidal voltage of the generator.

To achieve this aim, the following objectives are accomplished:

– based on the mathematical model of an asynchronous generator with a squirrel-cage rotor, to develop a simulation model of an indirect thermal protection sensor for a generator based on the method of determining the temperature of the stator winding by measuring its resistance;

– to develop an algorithm for determining the temperature of the stator winding by measuring its resistance with superimposing high-frequency pulse signals on the sinusoidal voltage of the generator;

– to perform simulation experiments with a simulation model of an indirect thermal protection sensor of the generator based on the method of determining the temperature of the stator winding by measuring its resistance with the superimposition of high-frequency pulse signals on the sinusoidal voltage of the generator;

– to conduct bench experimental studies of the proposed method of indirect thermal protection in order to confirm its effectiveness.

4. Materials and methods of research

The object of the study was a squirrel-cage rotor asynchronous generator of the 4A series with nominal parameters: a power of 3 kW and a rotation speed of 1500 rpm, which was supposed to develop, and subsequently experimentally confirm its effectiveness, a method of thermal protection based on the method of indirect determination of the temperature of its stator winding by measuring its resistance with the superimposition of pulse signals on a sinusoidal voltage of the generator.

Analytical methods of the theory of electrical machines and electrical engineering, simulation methods, bench experiments and comparative analysis were used to solve the tasks.

The simulation modeling was performed in the MATLAB R2019a /SIMULINK 9 application software package.

In the course of the research, there was developed an algorithm for determining the resistance of the stator winding of the generator, based on the imposition of an additional pulse signal of small amplitude on the phase voltage, followed by measurement of the stator current and determination of the stator resistance.

The effectiveness of the developed method was tested at the “Wind Energy System Based on an Asynchronous Generator” bench shown in Fig. 1.

Bench experiments were carried out on a squirrel-cage rotor asynchronous generator of the 4A series (rated power is 3 kW and rated rotation speed is 1500 rpm).

The tests were carried out in modes with CDF=50 %, the duration of each cycle is 30 minutes. In total, 10 experiments of 10 cycles were performed.

During each pause, the generator was disconnected from the power supply, and the active resistance of the stator winding was measured using an E7-8 digital LCR meter. The resistance of the stator winding was measured at a temperature change in the range from +20 °C to +140 °C with a discrete step of 30 °C.

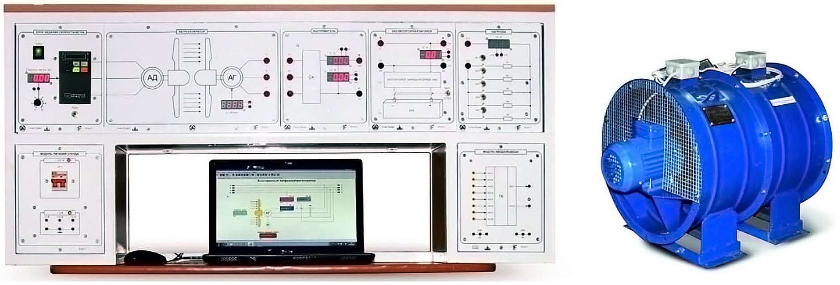

Fig. 1. Layout of the stand “Wind power system based on an asynchronous generator”

5. Results of the study of a squirrel-cage rotor asynchronous generator

5. 1. Development of a simulation model of asynchronous generator with a sensor for indirect temperature measurement of the stator windings

The most widely used in the tasks of analyzing various modes of operation of SCR AG are classical electromechanical models in the state space in a fixed coordinate system α-β, where the stator current vector and the rotor flow coupling vector are taken as state variables [10, 11], which has the following form:

$$\begin{cases} u_{s\alpha}=\left(L_S+\dfrac{L_m^2}{L_R}\right)\left(\dfrac{1}{T_S}i_{s\alpha}+\dfrac{di_{s\alpha}}{dt}\right)- \\ -\dfrac{L_m}{L_RT_R}\psi_{r\alpha}-p\omega\dfrac{L_m}{L_R}\psi_{r\beta}; \\ u_{s\beta}=\left(L_S+\dfrac{L_m^2}{L_R}\right)\left(\dfrac{1}{T_S}i_{s\beta}+\dfrac{di_{s\beta}}{dt}\right)- \\ -\dfrac{L_m}{L_RT_R}\psi_{r\beta}+p\omega\dfrac{L_m}{L_R}\psi_{r\alpha}; \\ 0=-\dfrac{L_m}{T_R}i_{s\alpha}+\dfrac{1}{T_R}\psi_{r\alpha}+\dfrac{d\psi_{r\alpha}}{dt}+p\omega\psi_{r\beta}; \\ 0=-\dfrac{L_m}{T_R}i_{s\beta}+\dfrac{1}{T_R}\psi_{r\beta}+\dfrac{d\psi_{r\beta}}{dt}-p\omega\psi_{r\alpha}; \\ J\dfrac{d\omega}{dt}=p\dfrac{L_m}{L_R}\left(\psi_{r\alpha}i_{s\beta}-\psi_{r\beta}i_{s\alpha}\right)-M_L, \end{cases} \quad (1)$$

where $U_{s\alpha}$, $\mathrm{U}_{s\beta}$ – the components of the vectors of the real and complex part of the stator voltage; $i_{s\alpha}$, $i_{s\beta}$ and $\psi_{r\alpha}$, $\psi_{r\beta}$ – the components of the stator current and rotor flow coupling vectors, respectively; ω – the angular velocity; M_L – the moment of load on the shaft; J – the moment of inertia of the rotor; p – the number of pole pairs; R_S, R_R – active resistance of the stator and rotor; L_R, L_S – inductance of the rotor and stator; L_m – mutual inductance; T_S, T_R – time constants of the stator and rotor windings.

System of equations (1) is the basis for the subsequent development of a simulation model of an AG indirect thermal protection system with a short-circuit protection system based on the method of determining the temperature of the stator winding by measuring its resistance.

In the course of theoretical research, there were determined the characteristics of a method for indirectly determining the temperature of the stator windings for a squirrel-cage rotor asynchronous generator in the generator mode of operation of the 4A series with the following technical characteristics (Table 1).

Table 1

Passport data and parameters of the asynchronous machine of the 4A series

Passport data	Designation, unit of measurement	Value
1	2	3
Rated power	*W*, Wt	3,000
Phase voltage	U_f, V	220
Phase current	I_f, A	7
Network frequency	*f*, Hz	50
Number of pairs of poles	*P*	2
Stator resistance	*Rs*, ohm	3.28
Rotor resistance	*Rr*, ohm	1.167
Stator inductance	*Ls*, Hz	0.0039
Rotor inductance	*Lr* Hz	0.0039
Mutual inductance	*Lm*, Hz	0.1671
Moment of inertia	*J*, kg·m^2	0.0058

For the selected type of asynchronous machine, a simulation model of the sensor for indirect temperature measurement of the stator windings in the MATLAB (Massachusetts, USA) application software package has been developed [12].

Fig. 2 shows a simulation model of an indirect asynchronous machine sensor with a squirrel-cage rotor.

5. 2. Developing an algorithm of determining the temperature of the generator stator winding by measuring its resistance

The algorithm for using the method of determining the temperature of the stator winding by measuring its resistance with superposition of high-frequency pulse signals on the sinusoidal voltage of the generator is presented in Fig. 3.

The method is implemented as follows.

The U_{sum} signal is supplied to one of the phases of an asynchronous generator with a short circuit protection system, which is the sum of a pulse signal U_{imp} of low amplitude of high frequency (600 Hz) and a phase sinusoidal voltage of industrial frequency.

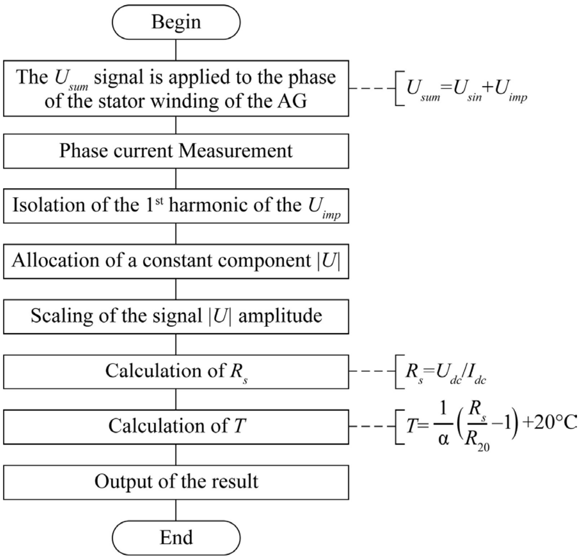

Fig. 3. Block diagram of the algorithm for the method of indirect determination of the stator winding temperature by measuring its resistance with the imposition of pulse signals on the generator voltage

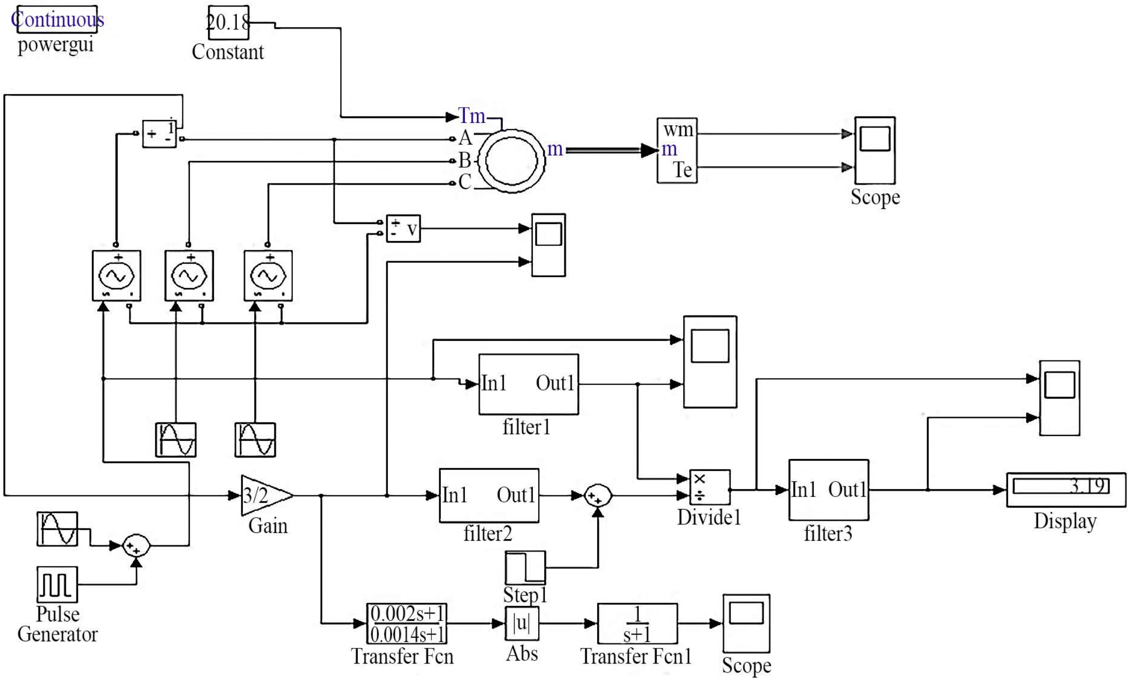

Fig. 2. Simulation model of the sensor for indirect temperature measurement of the stator windings of an asynchronous machine

The current sensor measures the phase current of the generator. The measured current of the stator winding of the generator contains a component U_{imp}. The first harmonic U_{imp} is isolated by a selective filter. At the same time, the power frequency signal is suppressed.

The next step is to isolate and to scale the amplitude of the constant component of the U_{imp} signal. The direct current component determines the load value of the electric motor. Based on the measured current and voltage values, the active resistance of the stator winding is calculated. As a rule, the stator windings of asynchronous machines are made of copper wire. In this connection, the temperature of the stator windings has a proportional dependence on their resistance.

The proposed method requires significantly less energy costs compared to the method presented in [4].

5. 3. Simulation experiments with the simulation model of the indirect thermal protection sensor of the generator

The studies were carried out on a squirrel-cage rotor asynchronous generator of the 4A series, with a power of 3 kW, a rotation speed of 1500 rpm.

The sum of a high-frequency, low-amplitude pulse signal and a sinusoidal 50 Hz high-amplitude stator power supply signal is applied to phase U (A) (Fig. 4). The phase current is measured in this phase.

The graph of the high-frequency modulated signal is given in Fig. 5.

Based on the measured values of phase currents and voltages, the resistance of the stator winding is calculated:

$$R_s = \frac{U_{dc}}{I_{dc}}, \tag{2}$$

where R_s – resistance of the stator, Ohm;

U_{dc} – constant component of the voltage, V;

I_{dc} – constant component of the current, A.

The measured currents contain pulsed components that are isolated by high and low pass filters. High-frequency pulses of 600 Hz are isolated by a high-pass filter, then the signals are fed to a low-pass filter to isolate the constant component of the current that determines the load of the electric motor, shown in Fig. 6.

The results of determining the resistance of the stator winding of a squirrel-cage rotor asynchronous generator are presented in Table 2.

The dependence of temperature on the resistance found from the expression (3):

$$T = \frac{1}{a}\left(\frac{R_s}{R_0} - 1\right) + 20\,^{\circ}\mathrm{C}, \tag{3}$$

where R_s – resistance of the stator winding, Ohm;

R_o – resistance of the stator winding at a temperature of 20 °C, Ohm;

α – temperature coefficient of resistance, 1/ °C;

T – temperature of the stator winding, °C.

Expression (3) defines the temperature of the stator winding.

Table 2

Results of determining the resistance of the stator winding

Motor	R_s, Ohm	R_s measured, Ohm	Error, %
4A100S4Y3	3.28	3.19	2.8

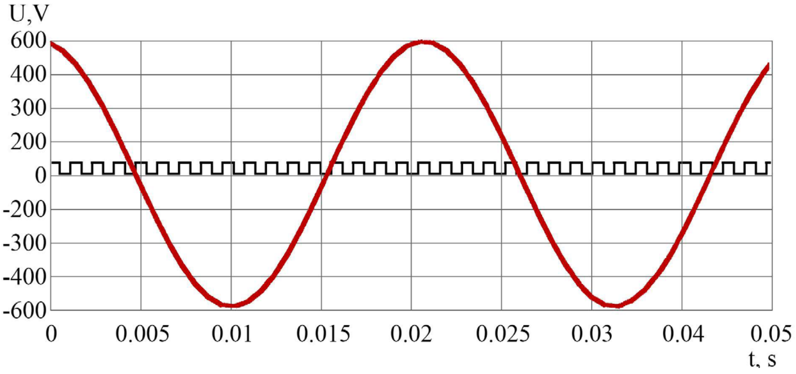

Fig. 4. Superimposition of a pulse signal on a sinusoidal voltage

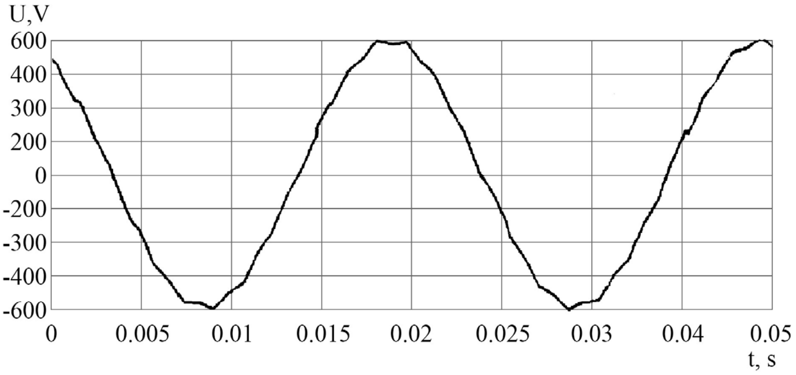

Fig. 5. Modulated high-frequency signal

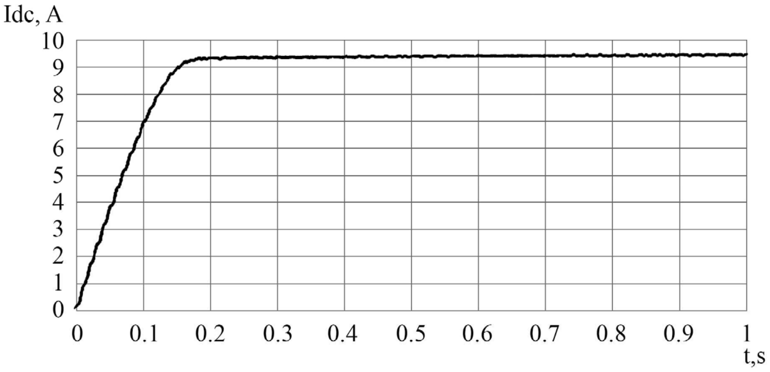

Fig. 6. Allocation of the constant component of the phase current I_{dc}

5. 4. Bench experimental studies of thermal protection

Experimental studies of the proposed method of indirect thermal protection were carried out in the laboratory of the Department of Electricity Supply of S. Seifullin Kazakh Agrotechnical Research University.

As mentioned above, the effectiveness of the developed method was carried out at the stand «Wind power system based on an asynchronous generator».

During the experiments, the temperature of the stator winding of the generator varied in the range from 20 °C to 140 °C. In total, 10 experiments of 10 cycles were performed. The averaged values of the resistance of the stator winding obtained in this case are given in Table 3.

Table 3

Results of measuring the resistance of the stator winding of an asynchronous generator for various temperature values

SCR AG of the 4A series, W=3 kW, η=1500 rpm					
T, °C	20	50	80	110	140
Reference value of the stator resistance	4,702	5,377	5,904	6,505	7,106
Measured values of stator resistance on a real AG	4,703	5,401	6,022	6,624	7,313

The dependence of the measured resistance of the stator winding on temperature was compared with the data obtained during simulation experiments. The results are shown in Fig. 7.

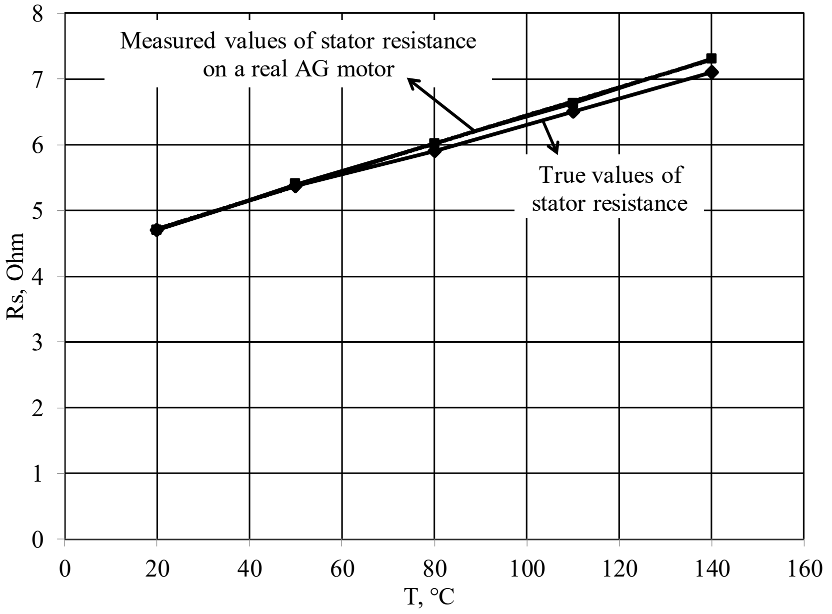

Fig. 7. Dependence of the stator winding resistance on temperature

6. Discussion of the results of developing an indirect thermal protection method for a squirrel-cage rotor asynchronous generator

The aim of the study is to develop and confirm the effectiveness of indirect thermal protection method for a squirrel-cage rotor asynchronous generator based on a method for determining the temperature of its stator winding by measuring its resistance with the superimposition of high-frequency pulse signals on the sinusoidal voltage of the generator.

The paper studies the efficiency of the method of determining the temperature of the stator winding by measuring its active resistance with superposition of high-frequency pulse signals on the sinusoidal voltage of the generator.

Reliability of the results obtained during simulation experiments is confirmed by experimental bench tests that are presented in Fig. 7. The obtained dependence graphs are linear in nature over the entire temperature range – from 20 °C to 140 °C. The average error did not exceed 5 %.

The peculiarity of the proposed indirect method of thermal protection of an asynchronous generator differs from existing methods of thermal protection by the fact that it takes into account heat generation and heat dissipation.

Currently, there are known methods for determining the temperature of the winding of SCR AG during its operation by measuring the active resistance of the stator winding. With an increase in the temperature of the winding of SCR AG, the amount of current flowing through it increases. However, the value of the current flowing through the winding reflects only heat dissipation, but does not take into account the heat sink, determined by various factors. In addition, an alternating electric current containing active and reactive components flows through each phase of the stator winding [13].

In the work [14], the temperature protection of SCR AG is considered. The disadvantage of such protection is its complexity, since temperature sensors must be integrated into the phase windings of the stator of SCR AG.

Protection using the integral dependence of the stator current as a function of time, does not allow controlling the heating temperature of the stator windings of the SCR AG, as well as turning off the generator in case of overheating of the windings caused by multiple starts in a row [15, 16].

Based on the analysis of methods and means of measuring and determining the temperature of AG [17], it is found that contact sensors and devices installed directly on the accessible parts of the stator winding have the highest accuracy in determining temperature. However, the use of these devices in the operating conditions of machines and mechanisms is difficult for a number of reasons: the complexity of these devices, the need to intervene in the design of electrical machines, limited possibilities in implementing the basic requirements for these measuring devices. All these disadvantages make it difficult to determine the temperature of the generator winding during its operation.

At the moment, the most preferred method for determining temperature is the sensorless method based on the use of a high-speed microprocessor system [18]. The main direction can be indirect, which determines the temperature by measuring the active resistance of the stator.

The proposed indirect method of temperature control of the stator windings of an asynchronous electromechanical converter in generator mode is preferably used in the power range of electric machines in generator mode up to 10 MW.

Thus, the effectiveness of the proposed method of thermal protection of a squirrel-cage rotor asynchronous generator based on an indirect method for determining the temperature of its stator winding by measuring its resistance with the imposition of high-frequency pulse signals on the sinusoidal voltage of the generator has been confirmed.

The developed method of thermal protection of an asynchronous generator will increase the reliability of a squirrel-cage rotor asynchronous generator, as well as reduce its wear and increase the life of the equipment.

It should be noted that in this study, the use of indirect thermal protection is limited to an asynchronous electric machine of the 4A series of relatively low power (3 kW) and the possibilities of its use for the other, including promising types of generators are not considered.

In addition, the disadvantage of the method is that the optimal frequency of the pulse component of the superimposed signal on the characteristics of the generators has not been determined. It is proposed to use a matching transformer for galvanic isolation of the pulse signal with the power circuit. The mass-dimensional parameters of the matching transformer and, as a result, the cost of the device depend on the frequency of the pulse component. This disadvantage can be eliminated by optimizing the frequency of the pulse signal in the power function of the electric machine.

A promising area for the further work is manufacturing a prototype of an indirect thermal protection device with structural and circuitry connection to the wind generator with subsequent industrial testing.

7. Conclusions

1. To conduct simulation studies, there has been developed a simulation model of a generator thermal protection sensor based on an indirect method for determining the temperature of the stator winding by measuring its resistance using the Matlab application software package in the Simulink software environment. The mathematical model of a squirrel-cage rotor asynchronous generator in a fixed coordinate system was used as a basis.

2. There has been developed an algorithm of determining the temperature of the stator winding of a generator by measuring its resistance based on the application of an additional high-frequency pulse signal with low amplitude to the phase voltage of the generator, followed by isolating the stator current and determining the stator resistance.

3. Simulation experiments have been carried out with a simulation model of a generator thermal protection sensor based on an indirect method for determining the temperature of the stator winding by measuring its resistance. The results of simulation experiments showed that the model works quite correctly.

4. In the process of experimental bench studies, the error of theoretical studies was estimated in the temperature range of the stator winding of the asynchronous machine from +20 °C to +140 °C. At a temperature of +20 °C, the error value is less than 1 %, and the maximum modeling error at a temperature of +140 °C does not exceed 5 %.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research 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 when creating the current work.

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