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DEVELOPMENT OF A VIRTUAL HARDWARE TEMPERATURE OBSERVER FOR FREQUENCY-CONTROLLED ASYNCHRONOUS ELECTRIC MOTORS

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One of the most common types of AC electric machines are asynchronous electric motors. Because of their simple and reliable design, they are used in many industries. In this paper, the object of research is an asynchronous electric motor with a short-circuited rotor. To ensure the normal operation of an asynchronous electric motor, the heating temperature of its active parts should not exceed the maximum permissible values, which are determined by the corresponding class of heat resistance of the insulation system used in the electric motor. In asynchronous electric motors, the stator winding is the most thermally vulnerable node, which is the first to fail when the temperature of the electric motor increases. Thermal protection devices protect an asynchronous electric motor from emergency operating modes accompanied by an unacceptable excess of the temperature of their windings.

In order to build an indirect system of protection against overheating of the stator windings, a temperature observer has been developed using already available signals in a frequency-controlled electric drive. Simulation studies were performed in Matlab/Simulink application software packages. Simulation studies were carried out on the basis of asynchronous electric motors of the 4A series with a capacity of 30, 75 and 110 kW in the temperature range from 20 °C to 250 °C. As a result of the research, it was found that the error of indirect calculation of the temperature of electric motors, taking into account the correction factor, does not exceed 1 %. The proposed temperature observer can be used to build protections for asynchronous electric drives

Keywords: asynchronous electric motor, renewable energy, temperature observer, resistance, thermal protection

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1. Introduction

The best mode of operation of any technological equipment is the nominal passport mode, while in practice, due to the peculiarities of technological processes, work in the nominal passport mode is extremely rare. This factor is of particular importance in many industries, including wind power, which are characterized by severe operating conditions, accompanied by non-stationary operating modes with frequent starts, loads varying in wide ranges and regular overloads. In the vast majority of such technological installations, an asynchronous electric drive is used as the main source of motion (asynchronous machines in wind power), and the most critical is the operation of an asynchronous electric drive with overload dividers, which causes the engine to overheat and significantly increases the likelihood of its emergency failure.

The existing technical solutions aimed at diagnosing the thermal regime of an asynchronous motor (in the wind power of a generator) differ in the principle of operation, physical implementation, speed and selectivity. At the same time, indirect methods are promising, which do not require the installation of special sensors in the design of the electric motor, but directly determine the thermal mode of the engine, and not indirect signs of temperature excess. Consequently, studies that are devoted to indirect thermal protection of asynchronous motors of a frequency-controlled electric drive, taking into account heat generation and heat sink, based on the determination of stator resistance by identification methods have are scientific relevance.

2. Literary analysis and statement of the problem

The article [1] discusses thermometric devices based on the use of thermal sensors in contact with the protected object, for example, in the form of thermocouples or thermistors, and a control unit connected to a thermal sensor. In this case, temperature sensors are placed directly on the winding of electric motors. However, these sensors can be installed in an electric motor only at the stage of its manufacture, which not only reduces the manufacturability of the design and reduces its reliability, but also does not allow this method of protection to be used for mass-produced electric motors of basic designs in operation. The significant disadvantages of temperature protection include the fact that it monitors the temperature only at the point where the temperature sensors are installed. This reduces the reliability of the thermal state of the electric motor as a whole.

The author of the article [2] cites parametric protection devices monitor the current or changes in the ohmic resistance of the winding due to its heating.

With indirect thermal protection, heat relays are included in the supply circuit of electric motor windings. The disadvantage of this method is that the protection reacts not to the temperature of heating of the windings, but to the amount of heat released without taking into account the time of operation in the overload zone and the actual cooling conditions of the electric motor. The complexity of design of thermal relays and insufficiently high reliability of protection systems based on them led to the creation of methods of current protection, which simulate the process of heating the winding of the electric motor.

Currently, the Republic of Kazakhstan is developing intelligent sensors [3]. Wireless sensors are undoubtedly promising. Moving objects distributed in space require wireless communication with their automation means, with controllers. But their disadvantage is the inadmissibility of their installation and operation in the conditions of some industries and industry [4, 5].

The authors of the article [6] propose an inductive measuring converter that monitors the temperature within the specified limits. However, this approach usually results in a percentage of the response distance and reaches about 10 % of it.

To detect and eliminate the overload mode, as well as from overheating of the asynchronous motor (for wind power, an asynchronous machine), protection is used in the function of the integral dependence of the stator current on time [7]. This method does not allow to control the heating temperature of the AM stator windings, as well as turn off the engine in case of overheating of the windings caused by multiple starts in a row.

Quite often, in manufacturing enterprises, the AD is located at a considerable distance from the starting equipment and the transmission of information from the built-in temperature sensor to the starting devices requires the use of an additional information cable [8, 9].

The disadvantage of protection is a long line of information signal from the temperature sensor, in the protected elements of the electric motor design, to the control unit located near the starting equipment, which leads to a decrease in the reliability of the protection system. In addition, the built-in temperature sensors are used only in newly manufactured AM.

In the article [10], the authors propose a method of thermal protection based on a change in the active and/or reactive components of the winding impedance due to a change in its temperature causing a corresponding change in the angle between the vectors of phase voltages and currents. The disadvantage of the method is that various options for heat removal in electric motors due to operating conditions, including ambient temperature, are not taken into account.

Thus, the currently existing methods of protecting an asynchronous motor (for wind power of an asynchronous machine) with a short-circuited rotor from overheating in most cases have a number of disadvantages, since they either do not take into account various options for heat removal in electric motors due to operating conditions, or do not provide the required accuracy of temperature control.

All this allows to assert that it is advisable to conduct research on the development of protection systems based on indirect methods for asynchronous electric motors.

3. The aim and objectives of the study

The aim of the study is to develop a method of indirect thermal protection of an asynchronous electric motor (for wind power of an asynchronous machine) with a short-circuited rotor, taking into account the processes of heat generation and heat removal.

To achieve this in, the following objectives are accomplished:

– to develop a simulation model of a temperature observer;

– to analyze the errors of the observer model;

– to develop the structure of the temperature protection system of a frequency-controlled electric drive with an asynchronous motor (for wind power of an asynchronous machine) with a short-circuited rotor.

4. Materials and methods of research

To solve this problem, it is proposed to develop a simulation model of a temperature observer based on a vector mathematical model of an asynchronous electric motor (for wind power of an asynchronous machine) with a short-circuited rotor [11, 12] and a structure of a temperature observer of an adjustable electric drive.

To create an indirect temperature protection of variable frequency asynchronous electric drive, a mathematical model of squirrel cage induction motor in a stationary coordinate system ($\omega_k=0$, $\alpha_k=0$) is used, where real axis is denoted by α and imaginary axis by β. The spatial vectors in this case are expanded along the axes: $\bar{u}_s = u_{s\alpha} + ju_{s\beta}$, $\bar{i}_s = i_{s\alpha} + ji_{s\beta}$, $\bar{\psi}_s = \psi_{s\alpha} + j\psi_{s\beta}$, and the system of nonlinear differential equations developed on the basis of the theoretical provisions of the work has the form:

$$\left.\begin{aligned} &u_{s\alpha} = R_s\left(1+\bar{\tau}'_s s\right)i_{s\alpha} - \frac{k_R}{\bar{\tau}_R}\psi_{R\alpha} - k_R p\omega\psi_{R\beta},\\ &u_{s\beta} = R_s\left(1+\bar{\tau}'_s s\right)i_{s\beta} - \frac{k_R}{\bar{\tau}_R}\psi_{R\beta} + k_R p\omega\psi_{R\alpha},\\ &0 = -k_R R_R i_{s\alpha} + \frac{1}{\bar{\tau}_R}\left(1+\bar{\tau}_R s\right)\psi_{R\alpha} + p\omega\psi_{R\beta},\\ &0 = -k_R R_R i_{s\beta} + \frac{1}{\bar{\tau}_R}\left(1+\bar{\tau}_R s\right)\psi_{R\beta} - p\omega\psi_{R\alpha},\\ &M = k_R\left(\psi_{R\alpha}i_{s\beta} - \psi_{R\beta}i_{s\alpha}\right),\\ &\bar{T}_m s\omega = M - M_L, \end{aligned}\right\} \qquad (1)$$

where $u_{s\alpha}$ is the projection of the spatial stator voltage vector on the real axis α of the fixed coordinate system (α, β); $u_{s\beta}$ is the projection of the spatial stator voltage vector on the imaginary axis β of the fixed coordinate system (α, β);

$i_{s\alpha}$ is the projection of the spatial stator current vector on the real axis α of the fixed coordinate system (α, β); $i_{s\beta}$ is the projection of the spatial stator current vector onto the imaginary axis β of the fixed coordinate system (α, β); $\psi_{r\alpha}$ is the projection of the spatial vector of the rotor linkage on the real axis α of the fixed coordinate system (α, β); $\psi_{r\beta}$ is the projection of the spatial vector of the rotor linkage on the imaginary axis β of the fixed coordinate system (α, β); R_s is stator winding resistance, Ohm; R_R is rotor winding resistance, Ohm; s is Laplace operator; M is electromagnetic torque IM, N·m; M_L is load torque on IM shaft, N·m; ω is angular velocity, rad/s; p is number of pole pairs; $\overline{\tau}'_s = x'_s/R_s$, $\overline{\tau}_R = x_R/R_R$, $k_R = x_m/x_R$ are non-dimensional coefficient; $\overline{T}_m = J\omega_b^2/M_b$, $x'_s = \omega_b L_s/R_s$, $x_R = \omega_b L_R/R_s$, $x_m = \omega_b L_m/R_s$ are relative parameter; L_s is stator winding inductance, H; L_R is rotor winding inductance, H; L_m is mutual inductance of stator and rotor windings, H; J is moment of inertia, kg·m^2; M_b is base torque on the machine shaft, N·m; ω_b is nominal value of angular velocity, rad/s.

This system of equations (1) is the basis for the development of the temperature observer of the variable frequency drive.

The system of nonlinear equations (1) has no solution in general. In order to construct an observer of the temperature of the stator windings, a numerical method for solving nonlinear differential equations by means of simulation modeling using the MATLAB software environment and the Simulink library was used.

The algorithm of operation of the temperature monitor, explains the block diagram in Fig. 1.

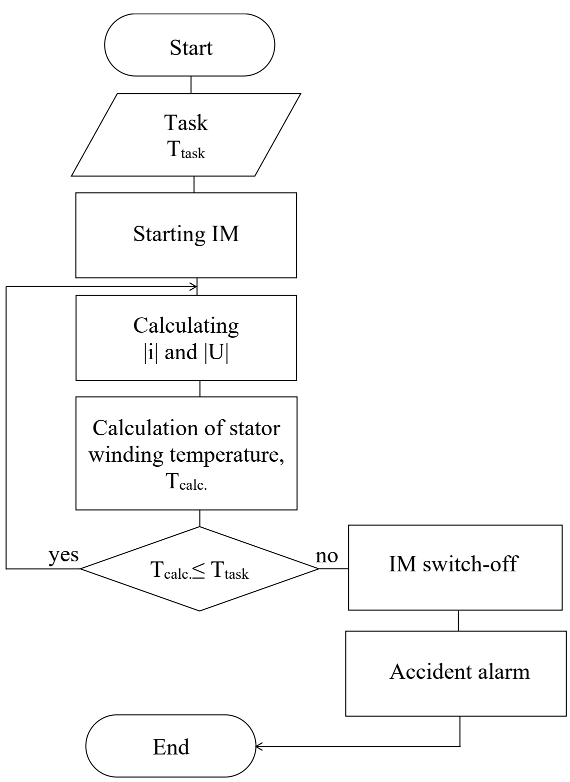

Fig. 1. Algorithm of operation of the temperature observer of stator windings of squirrel cage induction motor

Voltage and angular velocity signals from the automatic control system of the frequency converter are fed to the input of the temperature observer. To calculate the stator winding temperature, the current and voltage modulus parameters are used. The calculated temperature is compared with the set temperature, and if the temperature exceeds the signal to turn off the squirrel cage induction motor.

5. Results of the study of an asynchronous machine with a short-circuited rotor

5. 1. Development of a simulation model of a temperature observer

To study the algorithm of the temperature observer, a simulation model of squirrel cage induction motor series 4A with the motor parameters: R_s=0.219 Ohm, R_R=0.211 Ohm, stator winding inductance L_s=0.094 H, rotor winding inductance L_R=0.094 H, mutual inductance of the stator winding and rotor L_m=0.092 H, the number of pole pairs p=2, rotor moment of inertia J=0.09 kg·m^2. As a mathematical model of the motor starting process is taken a system of equations (1). The simulation model is shown in Fig. 2.

Simulation studies were performed for squirrel cage induction motor of series 4A with speed 750 rpm, and power from 3 kW to 200 kW in the temperature range of 20÷250 °C.

In the simulation model of the electric drive (Fig. 2), the temperature observer is represented as a separate Subsystem unit, the internal structure of which is shown in Fig. 3.

The working load range in the drive is limited by the maximum allowable temperature of the stator windings according to the operating conditions. For building overheating protection devices, it is possible to limit the minimum temperature to 100 °C÷120 °C. The maximum temperature value is determined by the insulation class of electric motor windings (for 4A series electric motors – 250 °C). The active resistance of stator windings changes in proportion to their temperature.

The temperature observer consists of a model of the electrical part of a squirrel cage induction motor and a block for calculating the temperature of the stator windings of a squirrel cage induction motor.

Heating of squirrel cage induction motor is related to the load parameters on the motor shaft and electromagnetic processes inside squirrel cage induction motor:

– electromagnetic interactions of stator and rotor windings;

– slip, the difference between the rotational speeds of the magnetic field and the rotor, referred to the rotational speed of the field.

The «Model of the electrical part of the IM» block calculates the current relative coordinates of the voltage and current of the electric motor using nonlinear differential equations 1.

In «Block for calculating the stator winding temperature», the calculation of the current value of the temperature of the stator windings of the electric motor is implemented on the basis of the power thermal balance equation (2).

$$\left.\begin{aligned} |U| &= \tau_1 \frac{dU_1}{dt} + U_1 + K_1, \\ |i| &= \tau_2 \frac{di_1}{dt} + i_1 + K_2, \\ T &= K_3 Ui + K_4, \\ T_1 &= \tau_3 \frac{dT}{dt} + T, \end{aligned}\right\} \qquad (2)$$

where U_i is the alternating voltage; U_1, i_1 is the voltage and current after the two-half-period rectification of the function modeled by the module and followed by the allocation of a constant component; τ_1 and τ_2 are the time constants of the filter for the allocation of a constant component of the voltage and current of the stator windings; τ_3 is the time constant of the thermal inertia of the electric motor; T and T_1 are the temperature of the stator windings without taking into account and taking into account the thermal inertia of the electric motor; K_3 is a coefficient that takes into account the heat exchange of the electric motor with the environment.

As a result of changing the sliding value, the current of the active component of the stator current changes, which determines the heating of an asynchronous motor with a short-circuited rotor.

The model of electromagnetic processes of stator windings consists of equations containing active and reactive components. To calculate the temperature of the stator windings, the parameters of the active component of current versus voltage are used.

The value of stator active resistance is considered in the aperiodic link (blocks No. 2 and 15), which is the basis for calculating the stator temperature parameter.

The input coordinates of the temperature observer are the stator supply voltage and angular velocity, which are taken from the model of the adjustable electric drive. Coordinates of the active component of stator winding current and supply voltage are reconstructed in the model of the electrical part of squirrel cage induction motor.

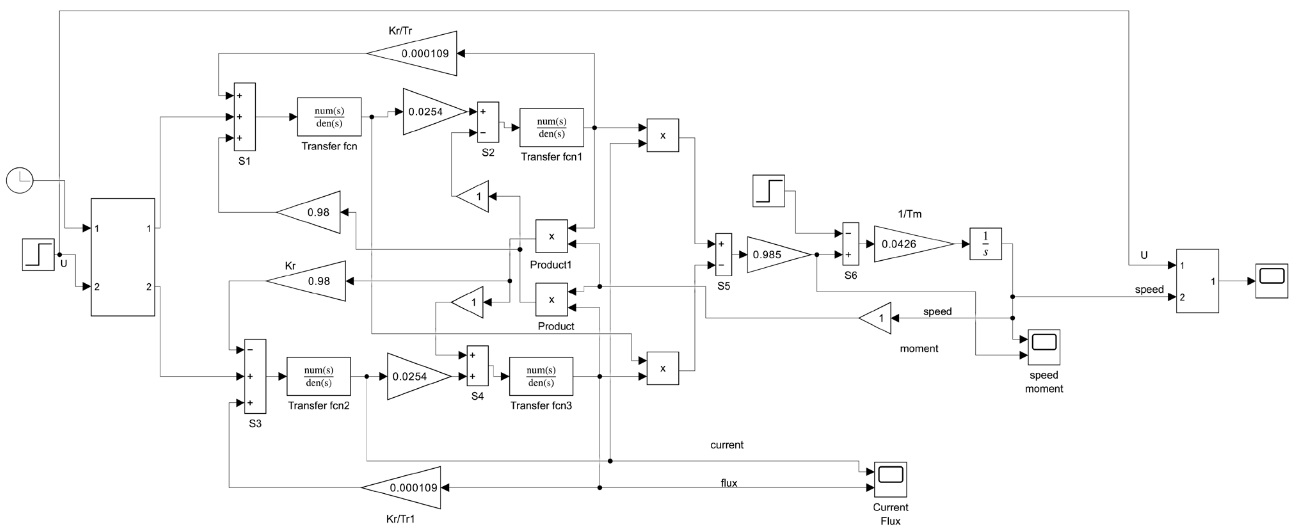

Fig. 2. Simulation model of an asynchronous electric motor with a short-circuited rotor

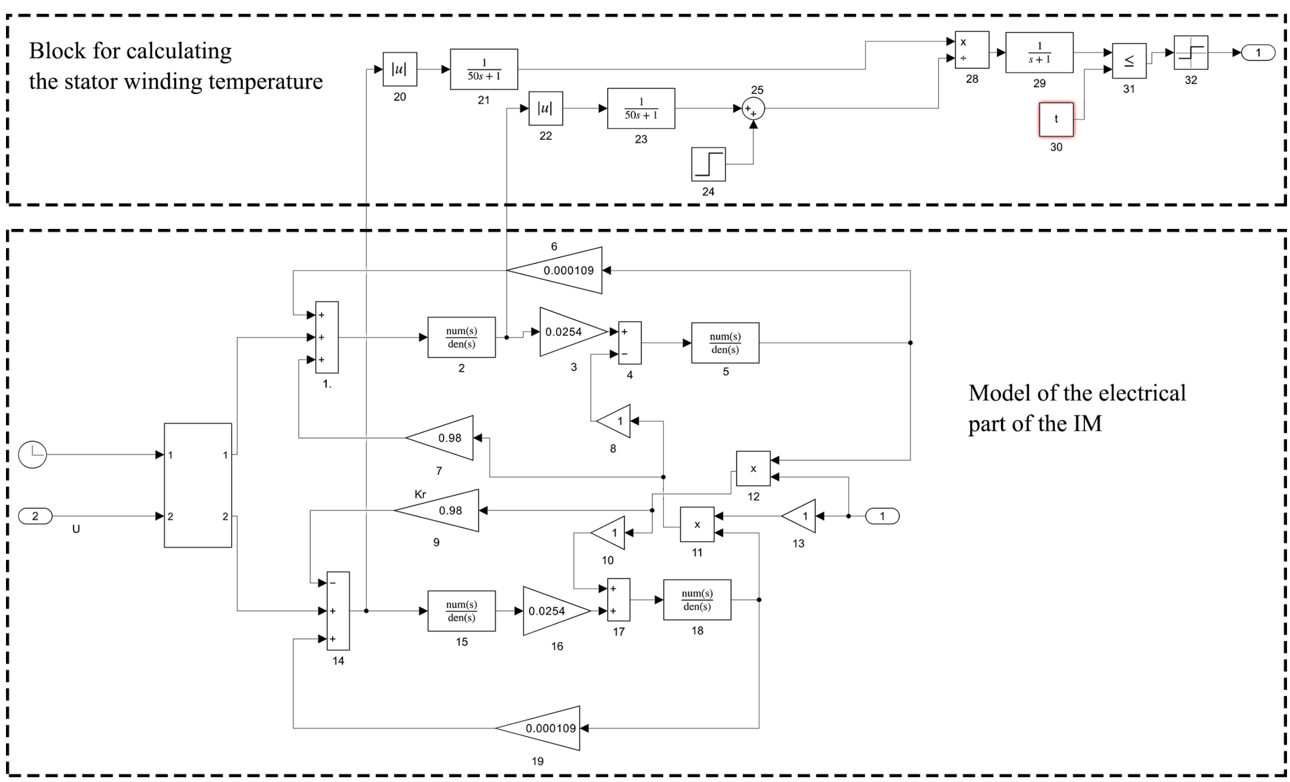

Fig. 3. Temperature observer simulation model

Signals at the output of the adder block (block No. 14) and the aperiodic link (block No. 2) have a sinusoidal form of the industrial frequency. In order to determine the stator temperature, the module values of blocks No. 20 and No. 22 are calculated. Allocation of the constant component is carried out by blocks No. 21 and No. 23 aperiodic link of the first order. To eliminate the error of division calculation by zero at the start of the electric motor an offset is entered by blocks No. 26 and No. 24. The signal proportional to the temperature of AM motor stator windings heating block No. 29 goes to the input of block No. 31 of the comparison element, where it is compared with the maximum allowable temperature of stator windings (block No. 30). When the maximum permissible value of heating temperature is reached at the output of the threshold element (block No. 32), a signal is generated to disconnect the power supply from the squirrel cage induction motor.

5. 2. Analysis of simulation experiments

The resistance of the stator winding is made of copper wire.

The resistance of copper has a proportional dependence on temperature.

Therefore, in the course of experimental studies, in order to estimate the error of the temperature observer, the resistance of the stator windings was measured, followed by the calculation of their temperature and the correction of simulation models.

For asynchronous electric motors (asynchronous machine for wind power plants) with a closed-loop rotor of the 4A series, the ranges of resistance changes of the stator windings for different power and temperature with a nominal rotational speed of 750 rpm are determined.

As an example, Tables 1–3 show the stator resistance as a function of temperature from 20 °C to 250 °C for powers of 30 kW, 75 kW and 110 kW.

Here R_s – true value of stator resistance, Ohm; $R(t)$ – calculated value of stator resistance with the help of the observer, Ohm; R_k – stator resistance taking into account the correction factor.

To calculate the stator resistance value with the observer $R(t)$, the calculation data are used, which are given in Tables 4–6 for powers of 30 kW, 75 kW and 110 kW.

Dependences of stator resistance on temperature R_s (Tables 4–6) are determined by the formula:

$$R_s = R_0 (1 + aT), \quad (3)$$

where R_s – stator winding resistance, Ohm; R_0 – stator winding resistance at 20 °C, Ohm; α – stator temperature coefficient of resistance, 1/°C; T – stator winding temperature, °C.

Table 1

Dependence of stator resistance as a function of temperature for squirrel cage induction motor with 30 kW

Squirrel cage induction motor 4A series, W=30 kW, η=750 rpm					
T, °C	20	125	170	200	250
R_s	0.2654	0.3767	0.4251	0.4567	0.5101
$R(t)$	0.2764	0.3834	0.4292	0.4598	0.5108
R_k	0.2672	0.3792	0.4279	0.4598	0.5135

Table 2

Dependence of stator resistance as a function of temperature for squirrel cage induction motor with 75 kW

Squirrel cage induction motor 4A series, W=75 kW, η=750 rpm					
T, °C	20	125	170	200	250
R_s	0.1018	0.1275	0.140	0.1480	0.1620
$R(t)$	0.0809	0.1122	0.1256	0.1345	0.1495
R_k	0.0925	0.1159	0.1273	0.1345	0.1473

Table 3

Dependence of stator resistance as a function of temperature for squirrel cage induction motor with 110 kW

Squirrel cage induction motor 4A series, W=110 kW, η=750 rpm					
T, °C	20	125	170	200	250
R_s	0.1076	0.1248	0.1335	0.1385	0.148
$R(t)$	0.0662	0.0918	0.1028	0.1102	0.1224
R_k	0.0856	0.0993	0.1062	0.1102	0.1177

Table 4

Calculation data for calculating the stator resistance of squirrel cage induction motor with 30 kW

W=30 kW, η=750 rpm							
$R(20)$	α	x_m	x_R	R_R, Ohm	R_s, Ohm	T, °C	$R(t)$, Ohm
0.254	0.004	2.2709	2.3089	0.0013	0.2751	20	0.2764
0.254	0.004	2.2709	2.3089	0.0013	0.3820	125	0.3834
0.254	0.004	2.2709	2.3089	0.0013	0.4279	170	0.4292
0.254	0.004	2.2709	2.3089	0.0013	0.4585	200	0.4598
0.254	0.004	2.2709	2.3089	0.0013	0.5094	250	0.5108

Table 5

Calculation data for calculating the stator resistance of squirrel cage induction motor with 75 kW

W=75 kW, η=750 rpm							
$R(20)$	α	x_m	x_R	R_R, Ohm	R_s, Ohm	T, °C	$R(t)$, Ohm
0.074	0.004	2.2738	2.3092	0.0003	0.0805	20	0.0809
0.074	0.004	2.2738	2.3092	0.0003	0.1118	125	0.1122
0.074	0.004	2.2738	2.3092	0.0003	0.1252	170	0.1256
0.074	0.004	2.2738	2.3092	0.0003	0.1342	200	0.1345
0.074	0.004	2.2738	2.3092	0.0003	0.1491	250	0.1495

Table 6

Calculation data for calculating the stator resistance of squirrel cage induction motor with 110 kW

W=110 kW, η=750 rpm							
$R(20)$	α	x_m	x_R	R_R, Ohm	R_s, Ohm	T, °C	$R(t)$, Ohm
0.061	0.004	2.2645	2.3095	0.0002	0.0659	20	0.0662
0.061	0.004	2.2645	2.3095	0.0002	0.0916	125	0.0918
0.061	0.004	2.2645	2.3095	0.0002	0.1026	170	0.1028
0.061	0.004	2.2645	2.3095	0.0002	0.1099	200	0.1102
0.061	0.004	2.2645	2.3095	0.0002	0.1221	250	0.1224

(4) is used to measure the resistance of copper stator windings, which accurately determines the stator winding temperature of squirrel cage induction motor:

$$R(t)=R_s+\left(\frac{x_m}{x_r}\right)^2\cdot R_R, \quad (4)$$

where x_m, x_R – relative parameter; R_R – rotor winding resistance.

According to the results of experiments, the dependences of the stator resistance on temperature for various capacities of an asynchronous electric motor (asynchronous machine for wind power plants) were determined. Fig. 4 shows the dependences of the stator resistance change as a function of temperature: dependence 1 is the true values of the stator resistance taken from the reference data for each asynchronous motor power, dependence 2 is the calculated values of the stator resistance using an observer.

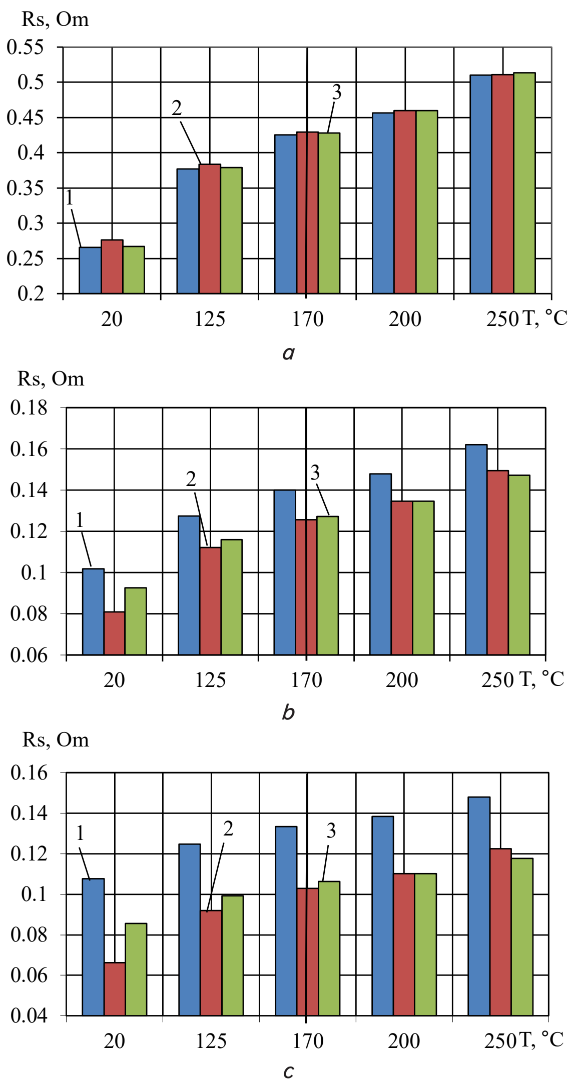

Fig. 4. Results of simulation experiments of squirrel cage induction motor: *a* — for a power of 30 kW with a rotation speed of 750 rpm; *b* — for a power of 75 kW with a rotation speed of 750 rpm; *c* — for a power of 110 kW with a rotation speed of 750 rpm

Knowing the temperature coefficient of change in the resistance of copper, the resistance of the stator from temperature is calculated. Dependence 3, obtained taking into account the correction factor, the numerical value of which for the corresponding type of electric motor is selected from the dependence shown in Fig. 5.

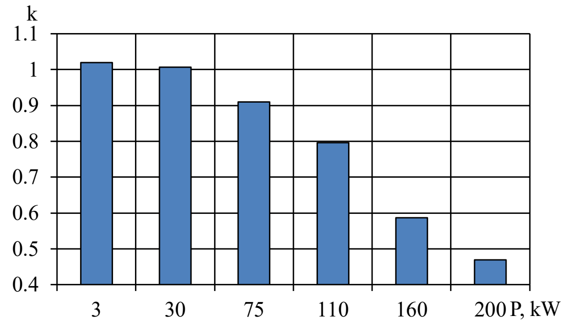

Fig. 5. Dependence of the correction factor on the capacity of squirrel cage induction motor

As can be seen from the results, there is an error between the true value of the stator winding resistance and the calculated value. It is caused with the error of the temperature observer. In order to correct the observer's errors, a correction factor is introduced, which is determined by the equation:

$$R_k=R_s\cdot k, \quad (5)$$

where k – correction factor.

Correction factor is the ratio of the calculated stator winding resistance value to the true stator resistance value:

$$k=\frac{R(t)}{R_s}. \quad (6)$$

Table 7 shows the calculations of the correction factor for different capacities of squirrel cage induction motor at 250 °C.

Table 7

Correction factor calculations for different capacities of squirrel cage induction motor

T, °C	*W*, kW	*Rs*, Ohm	*R*(*t*), Ohm	*k*
200	3	7.8744	8.0326	1.0200
	30	0.4567	0.4598	1.0067
	75	0.148	0.1345	0.9087
	110	0.1385	0.1102	0.7956
	160	0.0995	0.0584	0.5869
	200	0.0911	0.0426	0.4676

According to Table 5, there is a graph of the dependence of the correction factor as a function of power (Fig. 5).

From the obtained graph it follows that the error value decreases with the increase of squirrel cage induction motor power.

The discrepancy between the true and calculated values of the relative resistance of the stator winding, are presented in Table 8.

Table 8

Value of discrepancy between calculated and true values of relative stator winding resistance

Motor power (W, kW)	The value of the temperature observer error, %
30	0.01
75	0.02
110	0.5

As can be seen from Table 8, the error of indirect calculation of the temperature of electric motors, taking into account the correction factor, does not exceed 1 %.

5. 3. Development of the structure of the temperature observer in an adjustable electric drive

The features of the protection system of a frequency-controlled electric drive with a temperature observer are that the voltage signals of the stator windings U and the angular velocity of the electric motor ω are used, which are available in the frequency converter control system. The signal about overheating of the asynchronous electric motor (asynchronous machine) from the temperature observer enters the automatic control system of the frequency converter.

The structure of the regulated drive with a temperature observer is shown in Fig. 6.

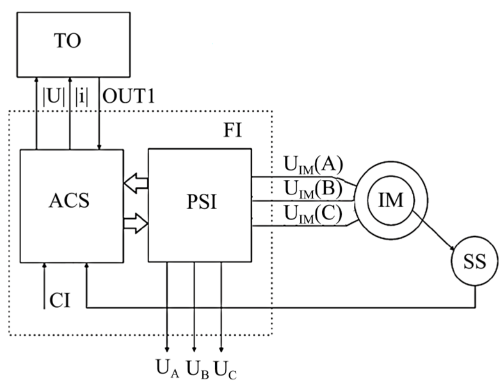

Fig. 6. Structure of an electric regulated drive with temperature observer: TO — temperature observer; FI — frequency inverter; ACS — automatic control system; PSI — power section of the inverter; IM — induction motor; SS — speed sensor; CI — control input; |U| — voltage module; |i| — stator active component current module; U_A, U_B, U_C — frequency inverter supply voltage; U_{AD}(A), U_{AD}(B), U_{AD}(C) — supply voltage of AD phases A, B, C; OUT1 — motor overheat alarm

The protection system (Fig. 6) operates as follows: a commercially available frequency converter is equipped with an automatic regulation system and the power part of the converter. The power part of the inverter contains: rectifier, filter, and inverter. The output of the power part of the inverter is connected to an induction motor. Induction motor shaft speed control is performed by the speed sensor. The signal from the speed sensor goes to the ACS of the frequency converter. For the operation of the temperature observer, the signals of the voltage of the stator windings and the angular velocity of the electric motor are taken from the automatic control system of the frequency converter. The signal of IM overheating from the temperature observer goes to the automatic control system of the frequency converter.

6. Discussion of the results of the study of the dependences of the stator resistance on temperature

Thus, a simulation model of the temperature observer has been developed, taking into account the thermal balance of the electric motor as a function of power (Fig. 3). In the process of simulation experiments, the necessity of introducing a correction factor that increases the accuracy of temperature calculation by an indirect method is justified (block 30, Fig. 3). The dependence of the correction coefficient of the temperature observer in the power function of an asynchronous electric motor is determined.

An analysis of the dependencies of the error of the model of the stator winding resistance observer for asynchronous motor with a short-circuited rotor in the power range of 3–200 kW has been performed (Fig. 4).

The peculiarity of the proposed indirect method of thermal protection of an asynchronous electric motor differs from existing methods of thermal protection in that it takes into account heat dissipation and heat sink (system of heat balance equations (2)).

In the works [13–15], thermal current protection is used, which reacts not to heat, but to current, and has a large error in determining the temperature time constants of the electric motor and the lack of ambient temperature control, which significantly reduces the protection efficiency and reliability of the electric drive as a whole. In addition, in the case of starting the engine after a prolonged overload and subsequent shutdown, when the engine has not yet had time to cool down, but the load has already reached the normal limits, such protections will not be able to prevent the operation of an overheated engine. The method in question controls the amount of current flowing through the power contacts of the starters, but not the heating temperature of the stator windings of the electric motor. It should be noted that this study does not consider the possibility of using indirect protection in modern and promising types of engines.

In addition, the method has a disadvantage in which the issues of taking into account the length of the cable connecting the frequency converter with an asynchronous electric motor were not considered. Of course, in further studies, it will be necessary to take into account the resistance of the cable line in the correction factor.

Further research will be directed to the development of temperature observer software products, taking into account the algorithms available in the automatic control system of an asynchronous electric motor.

7. Conclusions

1. Technical requirements for the protection system have been developed. Based on the mathematical model of an asynchronous electric motor and the equations of the thermal balance of the electric motor power by means of the Matlab application software package, a temperature observer model has been developed indicating qualitative or quantitative indicators of the results of the study.

2. In the system of equations of thermal power balance, a correction factor has been introduced, providing an increase in the accuracy of temperature determination and the depen-

dence of this correction factor in the power function of an asynchronous electric motor has been established, indicating qualitative or quantitative indicators of the results of the study. A method for determining the error of calculating the temperature of the stator windings of an asynchronous electric motor by an observer has been developed.

3. The structure of the hardware of an adjustable asynchronous electric drive with a temperature observer has been developed. Studies have been carried out to determine the temperature calculation error by an observer for asynchronous motors of the 4A series with a capacity of 30, 75 and 110 kW in the temperature range from 20 °C to 250 °C. As a result of the research, it was found that the maximum value of the error value did not exceed 1 %. The presence of the error is explained by not taking into account the magnetic fields of scattering and not taking into account the mechanical losses in the model of the electric motor.

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.

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