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INVESTIGATION OF THERMAL AND OPERATIONAL MODES OF AN INDUCTION MOTOR IN THE AGRO-INDUSTRIAL COMPLEX

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Summary. The article examines the operating and thermal modes of induction motors used in agro-industrial machinery. It shows that load conditions and duty cycles strongly affect motor temperature, reliability, and insulation life. Key heating factors and the relationship between thermal and operating parameters are analyzed, emphasizing the need to consider thermal regimes during operation and maintenance to improve efficiency and service life.

Key words: induction motor; operational modes; thermal mode; technical service; reliability of electrical machines; agro-industrial complex.

Formulation of the problem. Induction motors (IM) are the primary converters of electrical energy into mechanical energy in the systems of agro-industrial complex. Their operation occurs under stochastic loads, high dust levels, and humidity, which destabilize the thermal balance of the machines. The discrepancy between the intensity of heat generation and the conditions of heat dissipation leads to accelerated degradation of insulation materials. Exceeding the allowable winding temperature significantly reduces the operational life and increases the entropy of the technical service system due to the prevalence of emergency repairs over preventive ones. Thus, a comprehensive analysis of the interrelation between operational and thermal modes of IMs is essential for optimizing energy consumption and increasing the reliability of electric drives in the agricultural sector [2].

Basic research materials. The primary research materials include the theoretical principles of electrodynamics and thermodynamics describing energy conversion processes and the heat balance law in induction machines [3]. The technical basis of the work comprises the specifications of 4A and AIR series motors, as well as regulatory data on insulation material heat-resistance classes in accordance with all-Union State Standard (GOST). The empirical foundation consists of statistical data regarding electric drive operation under specific conditions of the agro-industrial complex, characterized by unstable power grid parameters and aggressive environmental impacts [4].

The energy balance of an induction motor in the agro-industrial complex (AIC) is determined by the efficiency of electromagnetic energy transformation into mechanical work. Total power losses are converted into heat, causing degradation of insulation systems. According to the classical theory of electrical machines, total losses are categorized as follows [3]:

1. Major copper losses in the stator (P_{cu1}) and rotor (P_{cu2}), which are functionally dependent on the square of the load current.

2. Magnetic losses in the steel core (P_{fe}), determined by the magnetic reversal frequency and magnetic induction magnitude.

3. Mechanical losses (P_{mech}) due to friction in bearings and ventilation.

4. Additional losses (P_{add}), arising from higher harmonics of the magnetic field.

A significant feature of IM operation in rural distribution grids is voltage instability. When the voltage U deviates from the nominal value, a redistribution of losses occurs [2]. A decrease in voltage leads to an increase in stator current to maintain the required shaft torque, which exponentially increases heat dissipation in the windings:

$$P_{cu} = 3\ \cdot I^2 \cdot R \cdot k_{add}$$

where k_{add} is the current displacement factor. Since the winding resistance R is a function of temperature, a non-linear self-heating process occurs in an overloaded motor.

Electrical copper losses in the stator P_{cu1} and rotor P_{cu2} are directly proportional to the square of the current I^2 and depend on the active resistance R, which, in turn, increases linearly during heating:

$$R_T = R_{20}[1 + \alpha(T - 20)],$$

where α is the temperature coefficient of resistance. Thus, a positive feedback loop occurs: higher temperature increases resistance, which raises heat losses and reduces efficiency. Here, T is the actual winding temperature, varying with load, cooling conditions, and ambient temperature.

The heat dissipation process in the active parts of the machine is described by the heat balance equation [3]:

$$P_{pot} = \ dt = C \cdot d\tau + A \cdot \tau \cdot dt$$

where C is the heat capacity of the motor, J/ºC; A is the heat transfer coefficient, W/ºC; τ is the temperature rise above the ambient environment, ºC.

Analysis shows that in agro-industrial conditions (high humidity, dust accumulation on cooling fins), the heat transfer coefficient A decreases by 15–20% [4]. This leads to a violation of the steady-state thermal regime and causes the stator winding temperature to rise above the critical level defined by the insulation class [5].

Graphical analysis of energy flows (Fig. 1) demonstrates that the structure of total losses $\sum \Delta P$ is heterogeneous. Under nominal load conditions, the dominant influence on the thermal state is exerted by losses in the stator and rotor windings, which together account for more than 60% of the total heat dissipation. This confirms the necessity of prioritizing stator current control when monitoring thermal modes in the agro-industrial complex.

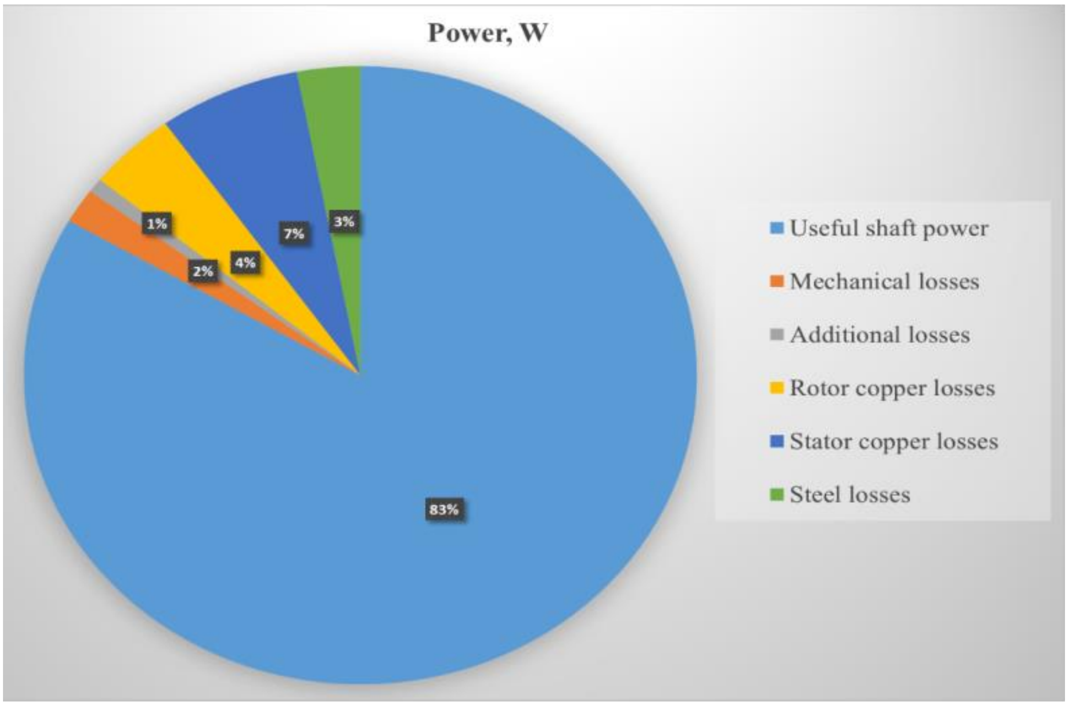

Fig. 1 – Power loss distribution diagram in an induction motor

The process of IM heating in non-steady-state modes (starting, reversing, variable load operation) is described by the differential heat balance equation:

$$P \cdot dt = C \cdot d\tau + \alpha \cdot S \cdot \tau \cdot dt$$

where P is the heat dissipation power, W; C is the motor heat capacity, J/°C; α is the heat transfer coefficient, W/(m²·°C); S is the cooling surface area, m²; τ is the temperature rise above the ambient environment, °C.

In feed mills and grain processing facilities, the cooling surface S can become coated with organic dust of very low thermal conductivity (λ≈0.05–0.1 W/(m·K)), adding thermal resistance and raising steady-state winding temperature by 15–30% even at nominal load. The analysis of losses and thermal conditions for 4A and AIR series induction motors is based on experimental data from Kumakhov A.A. and Pugachev A.A. [1,5].

Table – Analysis of loss structure and thermal state of IM (for 4A and AIR series motors)

Load mode $\beta = P/P_{nom}$	Stator current, % from I_{nom}	Copper losses, W	Winding temperature, °C	Insulation life, years
0,7 (underloading)	78	480	115	22
1,0 (nominal load)	100	850	145	15
1,2 (overload)	125	1320	170	4

The kinetics of winding heating (Fig. 2) graphically demonstrates that under starting conditions or in a locked-rotor state, the temperature reaches its critical threshold within a matter of seconds. In the context of the unstable voltage characteristic of rural power grids (with deviations reaching ±10%), there is a secondary increase in core losses. This phenomenon significantly intensifies the overall thermal load imposed on the motor frame and cooling system.

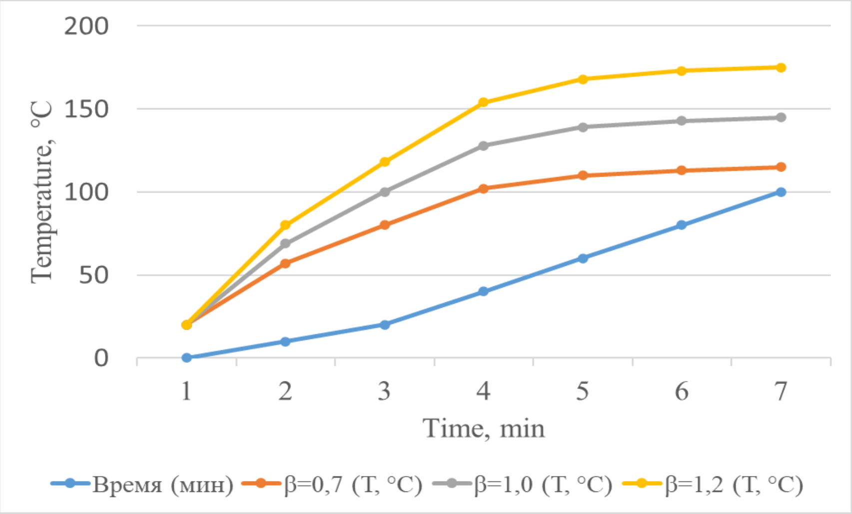

Fig. 2 – Kinetics of stator winding heating at various load factors

Research indicates that operating an induction motor with a temperature rise of just 10 °C above the rated value reduces the machine's service life from 15 years to 7-8 years. From an energetic standpoint, this is equivalent to a 3-5% increase in specific energy consumption per unit of agricultural output, resulting from a reduction in electromagnetic torque and increased slip.

High temperature accelerates insulation degradation by breaking polymer bonds. Under the “eight-degree rule,” every 8–10 °C rise above the allowable limit (e.g., 155 °C for Class F) halves insulation life. For agricultural enterprises, this causes repair costs and downtime losses. Experiments also show that overheating reduces electromagnetic torque, increases critical slip, raises reactive power consumption, and lowers overall power factor, leading to additional economic costs.

Conclusion. It has been established that the thermal regime of induction motors under agro-industrial conditions is an integral indicator of their operational reliability, depending on the quality of electric power and the state of the cooling system. It is mathematically confirmed that a thermal overload of the windings by only 10 °C reduces the insulation service life by half, leading to significant economic losses for agricultural enterprises. To enhance the energy efficiency of agro-industrial production, the implementation of continuous thermal monitoring systems within the framework of electrical drive technical service is recommended.

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