Development of the performance control algorithm of the blower motors of electric locomotives for various operating modes

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Abstract. The widespread use of electric motors in various electric drive systems and the automatic regulation of their performance are largely determined by the reliability of these machines, the failures of which cause significant material damage and are caused by significant yard time at the depot repair positions. Improving their reliability is a major scientific and technological challenge. When electric locomotives operate on the East Siberian Railway, severe climatic conditions have a direct impact on the reliability of electrical equipment, so the development of an algorithm to control the performance of blower motors for various operating modes is an urgent task. The main parameters of the entire electric locomotive energy system, which largely determine the safety of trains and the amount of throughput capacity of the sections, are the reliability of cooling machines and the algorithm of their operation in different operating modes, taking into account weather and climatic conditions. The immediate accounting and analysis of the causes of the failure of asynchronous electric motors with a short-circuited rotor in the blower drive, the use of which is justified by the simplicity of the design, was the basis for the development of the algorithm proposed in this article. The electric locomotive cooling control algorithm is focused on eliminating or minimizing snow, dust insulation of traction electrical equipment in a given range of regulation. Elimination of the unauthorized shutdown of cooling machines by locomotive crews while the train runs in the slow-down mode, as well as the elimination of the start processes of asynchronous electric motors of the blower motor actuator, will improve the reliability of the entire electric locomotive in general.

1. Introduction
The increase in the throughput and operating capacity of the transport infrastructure, caused by the increase in the volume of transport by rail, leads to physical and functional obsolescence of fixed assets, which requires their strengthening and constant control in strict operating conditions. In order to ensure the safe and uninterrupted organization of transport infrastructure facilities, special attention should be paid to the work of electrical machines, the quality of which can be presented as a set of properties that determine their suitability for normal operating conditions. Due to the fact that
reliability is the most important both technical and economic indicator, characterizing the quality of operation of any electrical machine, it allows determining its ability to work smoothly during a given period of time without changing the technical characteristics under certain operating conditions [1–4].

With a wide range of electrical vehicles in various electric drive systems and automatic regulation, production is largely determined by the reliability of these machines. The failures of electrical machines cause significant material damage, so increasing their reliability is the most important scientific and technical problem [5].

The algorithm of operation and reliability of the blower motors used directly affect the parameters of operation of the entire electric locomotive energy system and largely predetermine the safety of trains. The substantiation of the use of asynchronous electric motors with a short-circuited rotor in the blower drive is the simplicity of the design, which affects not only in reducing the time of its repair, but also the yard time of the electric locomotive in general on the positions of depot service. The long-term mode of blowers' operation determines the high requirements for the reliability of the considered electric motors in question.

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Abroad, when choosing the most profitable offer for the supply of traction rolling stock, the concept of the maintenance of the locomotive at all stages of its life cycle is increasingly used. The Japanese firm Hitachi considers the maintenance system of new locomotives to be the key to guaranteeing a high level of reliability. However, as the world experience shows, now, on average, up to 40% of the time is spent on troubleshooting, rather than on routine maintenance [6, 7].

2. Analysis of the reliability of traction electrical and auxiliary machines

The distribution of failures of assemblies and equipment of AC locomotives based on depot statistics shows that auxiliary machines account for up to 15%, and up to 30% of the total damage to traction electrical machines. It should be noted that the cost of repairing the traction electrical machines compared to other electric locomotive equipment is the most expensive. In addition, the complex process of repair, which involves rolling out the wheel-engine unit, is reflected in the time of the electric locomotive's yard time in the repair positions, bringing huge losses to the company, both temporary and financial. The reliability of the electric part of the traction electrical machines is emphasized due to the algorithm of cooling machines in operation.

The number and characteristics of failures of traction electrical machines are divided into liability categories for the companies that repair and operate them. Failures, the responsibility of which is attributed to the Russian Railways OAO, are preconditioned by the following operational violations:

- overheating of insulation due to the speed below the estimated limiting ascents with full-weight trains;
- spinning and slipping of wheel pairs, in which there may be overexertion on the traction electrical machines collector and the electric arcing;
- disabling the blower motors by locomotive crews in the slow-down mode to save power for the drive of auxiliary machines.

During the blowers' operation, excessive pressure is created in the body of the electric locomotive, which prevents dust or snow from getting on the traction electrical equipment of the electric locomotive. This is taken into account in the proposed algorithm of cooling machines. The cooling air enters the traction engine from the side of the collector, through the vent, passes through the ventilation channels in the armature and through the air gap between the armature and the main poles of the traction electrical motor. The air exits from the traction engine from the opposite collector, through a special casing, up under the body of the electric locomotive.

When the electric locomotive runs in the slow-down mode with the disconnected blowers there is a swirl of dust, snow, and a loose adjoining of the covers of the lower and upper viewing hatches, the presence of a technological hole in the frame of the traction engine and air gap lead to their ingress to
the main and additional poles, compensatory winding, collector and the brushing gear of the traction electrical machine.

It should be specially emphasized that moisture and its properties largely predetermine the life of the insulation of traction electrical equipment, as its ingress into the pores reduces not only the resistance and dielectric strength, but also leads to the emergence of leaks, partial discharges and other phenomena, the impact of which increase the probability of a breakdown. The impregnation does not always protect the material from damping, but only reduces the rate of moisture absorption [8, 9].

The presence of moisture in isolation leads to a sharp decrease in leakage resistance, which leads to an increase in dielectric losses. As a result, the heat breakdown voltage is reduced and the insulation is further heated, which leads to an acceleration of the rate of thermal aging [10]. Strong insulation damping can affect the dielectric permeability of the moisturized layers. If it can be unevenly moisturized, this circumstance can distort the electric field in insulation and reduce the disruptive voltage [11]. The use of energy-intensive calorific furnaces allows removing moisture from insulation by drying. However, this process is not only energy-intensive, but also requires a lot of yard time as part of the depot repair.

Under the influence of solid particles of dust penetrating the machine, there is an abrasive wear of the insulation of windings. When following the electric locomotive in the slow-down mode with the disabled blowers, the withdrawal of lubricants from motor-armature bearings is possible. This process causes the deterioration of insulation parameters due to the grease ingress in the frame of the traction engine. In addition, due to the small amount of lubricating material in motor-armature bearings, the armature shaft may be jammed. The thermal current relays and overload relays used do not fully protect the blower motors, as evidenced by the failure statistics of these electric motors. Based on the data obtained on the failures of the auxiliary machines of the locomotives of the East Siberian Railway, it has been established that the electrical damage account for up to 55% of the total damage to the electric motors under consideration.

3. Development of the automatic control system for the auxiliary machines of a locomotive

As part of the presented work, the authors examined the haul distance of the circulation of electric locomotives attributed to the operating locomotive depot Nizhneudinsk (Figure 1) with a total length of 2,582 km.

![Haul distances of electrical locomotives attributed to the operating locomotive depot Nizhneudinsk](image)

**Figure 1.** Haul distances of electrical locomotives attributed to the operating locomotive depot Nizhneudinsk

- “Traction” and TM mode
- Slow-down mode
According to the train driving mode charts and decryption of the registration files of the parameters of the automatic brake control system, the order of the train running on the Mariinsk-Karymskaya section in both directions in different operation modes of the electric locomotive was analyzed.

On the Nizhneudinsk-Mariinsk section, when running with down trains, the electric locomotive runs for an average of 16 hours 25 minutes and is in the slow-down mode for 3 hours 39 minutes (12%). On the Mariinsk-Nizhneudinsk section, when running with up trains, the train runs for 16 hours and is in the slow-down mode for 3 hours 40 minutes (19%).

On the Nizhneudinsk-Karymskaya section, when running with up trains, the electric locomotive runs for an average of 39 hours 50 minutes and is in the slow-down mode for 6 hours 30 minutes (16%). On the Karymskaya – Nizhneudinsk section, when running with down trains, the train runs for 31 hours 10 minutes and is in the slow-down mode for 5 hours 50 minutes (19%).

The data of the analysis allow concluding that it is advisable to control the performance of auxiliary cooling machines for traction electrical equipment in the slow-down mode.

The development of an automatic control system (ACS) for auxiliary machines of an electric locomotive with adaptation to operating conditions is aimed at eliminating the ingress of snow and dust on the insulation of traction electrical equipment. The operation of an asynchronous electric motor in a controlled electric drive on an electric locomotive is characterized by significant features, which determine the specific requirements imposed on them [12]. These features are associated with varying values of the RMS voltage and current consumption of the motor. Due to this, mathematical models of electromagnetic, electromechanical, and energy processes in steady-state and transient operating modes of motors are specific.

To technically implement the proposed microprocessor-based ACS and create a mathematical model that takes into account not only environmental parameters, but also the operating modes of the electric locomotive, it is necessary to take into account:

- limiting the minimum amount of cooling air during the slow-down mode and stops at intermediate stations to create excess pressure in the body of the electric locomotive;
- heating temperatures of the insulation of traction electrical equipment of an electric locomotive when implementing the algorithm for controlling the performance of blower motors.

The basic design principles of the developed control system for cooling machines should take into account the parameters of their operation as part of an electric drive for various operating modes, taking into account the positive aspects of the developed and operated systems, taking into account their shortcomings.

It is necessary to use a systematic approach to analyze the operation of an asynchronous motor in interaction with other elements of the power system:

- a) circuit implementation of the power part of the semiconductor converter;
- b) an algorithm for controlling traction electrical equipment cooling machines, adaptive to operating conditions;
- c) datasheet specifications of the electric motor, taking into account the design parameters of the blower wheel to estimate the output value of the system.

The elements of an electric drive should be implemented in a mathematical model, taking into account individual characteristics to implement an effective system approach when designing the system being developed. The correctness of the calculation of the parameters of the individual links of the system will make it possible to assess the adequacy of the mathematical model of the system to real physical processes. It should be noted that a change in one of the parameters of the system will affect the parameters of the output signal, which must be adequately changed depending on the steady-state value of the insulation temperature of traction electrical equipment.

Guided by the task set within the framework of the article, when developing an algorithm, it is necessary to take into account:

- providing soft start of blower motors at a reduced frequency;
- control of the amount of current in traction electrical equipment using a current sensor;
• duplicated control of the temperature mode of traction electrical equipment through the use of temperature sensors with reasonable settings for switching cooling machines from one frequency to another.

National and international experience in operating systems for controlling the performance of cooling machines for electric locomotives made it possible to determine the disadvantages of their use – low energy indicators of frequency converters PChF and SAUV. It should be noted that a threefold decrease in the performance of blower motors is reflected in the reliability of the insulating materials of the traction electrical equipment of the electric locomotive, due to the ingress of snow and dust on its surface. In addition, the frequent switching of cooling machines from one frequency to another is due to the insufficient amount of cooling air for unloaded operation.

The boundary of creating excessive pressure in the body of an electric locomotive to eliminate the ingress of snow and dust on the insulation of traction electrical equipment begins with a reduced rotation frequency of the cooling machine shaft of at least 25 Hz.

Guided by the well-known analytical dependencies, it follows that the air consumption for electric motors with a blower-type load is proportional to the power consumption. Productivity \( Q \), head \( H \) and load moment \( M \) on the shaft of the cooling machine depend on the speed of rotation of the impeller \( n \), formulas 1, 2.

\[
\frac{Q}{Q_n} = \frac{n}{n_n} \tag{1}
\]

\[
\frac{H}{H_n} = \frac{M}{M_n} = \frac{n^2}{n_n^2} \tag{2}
\]

In formulas 1, 2, the index "n" refers to the parameters of the nominal operating mode.

The calculation of the useful power \( P \) on the shaft for different modes is determined by the following relationship, formula 3.

\[
\frac{P}{P_n} = \frac{n^3}{n_n^3} \tag{3}
\]

It should be noted that the steady-state value of the temperature of traction electrical equipment in order to ensure its normal thermal mode, taking into account its current load and the temperature of the cooling air, is fundamental in regulating the performance of cooling machines.

The dependences of the required air supply on its temperature obtained in the works [13, 14] indicate the possibility of using a control system for cooling machines of an electric locomotive, since at 0 °C the supply of cooling air can be reduced by 13-38%, and at a temperature of -40 °C – by 28-60%, taking into account the parameters of the cooled equipment.

The required supply of cooling air, depending on the change in current load, in the reference literature is determined from the conditions of thermal equilibrium in the steady state, formula 4.

\[
k \cdot I^2 \cdot r = \rho \cdot c \cdot \tau_\infty \cdot Q^n \tag{4}
\]

where \( k \) is a coefficient that takes into account heat losses; \( I \) is the current strength in traction electrical equipment, A; \( r \) is the active resistance depending on temperature, Ohm; \( \rho \) is the air density, kg/m³; \( c \) is the heat capacity of ambient air; \( \tau_\infty \) is the steady-state value of the excess of the machine winding temperature over the ambient temperature, °C; \( n \) is the coefficient for power equipment.

Required air supply when the current strength is different from the nominal, formula 5.

\[
Q = Q_n \cdot \left( \frac{I}{I_n} \right)^2 \tag{5}
\]
The values of the coefficient $n$ for the main power electrical equipment are shown in Table 1.

Table 1. Numerical values of the coefficient $n$

| Electrical equipment                                      | $n$  |
|----------------------------------------------------------|------|
| traction electrical machine, reversible converter, smoothing reactor | 0.8  |
| traction transformer                                    | 0.6  |
| power resistors                                          | 0.72 |

The current load of electrical equipment of AC electric locomotives is unstable and depends on the following random factors: train weight; section profile; conditions of wheel-rail adhesion; the nature of the train environment. The ability to regulate the performance of blowers can provide a static analysis of the current loads of electric locomotives and the calculation of the total operating time in the slow-down mode.

To justify the control algorithm in the slow-down mode and stops at intermediate stations, it is necessary to take into account the permissible temperature rise of the insulation of conductive parts. The presented well-known formulas 4-5 do not take into account the modes of operation of an electric locomotive when slowing down and stopping at intermediate stations, which implies the introduction of an additional coefficient and a minimum amount of air, which will prevent snow from entering the traction electrical machine due to the shutdown of the blower motors, taking into account the magnitude of the steady-state value of the temperature rise of the traction winding machines, formulas 6, 7.

\[ k_{\omega_0} + k \cdot I^2 \cdot r = \rho \cdot c \cdot \tau_{\omega} \cdot Q^n \]  \hspace{1cm} (6)

\[ Q = Q_{\omega_0} + Q_s \cdot \left( \frac{I}{I_s} \right)^2 \]  \hspace{1cm} (7)

On the basis of the above mentioned calculations, using Matlab computer mathematics, a block diagram of the blower motors control was developed (Figure 2).

At the instant when the current in the traction electrical equipment became equal to 0A, the control algorithm of the blower motors was determined by the parameters of the technological process of the routine diagram. The proposed algorithm is possible when the train follows a favorable profile.

Based on the obtained dependences, it can be concluded that the steady-state value of the temperature regime for the presented control algorithm tends to the value of the environment. This allows drawing a conclusion about the adequacy of the mathematical model to real physical processes [14-15].
4. Conclusion
Substantiated minimum performance limit of blower motors will create sufficient overpressure in the locomotive body. The use of the proposed control algorithm for the cooling machines of the electric locomotive will allow minimizing the ingress of snow, dust on the insulation of traction electrical equipment within the entire control range. With that, the practical application of the developed automatic control system will allow eliminating the unauthorized shutdown of electric locomotive cooling machines by locomotive crews when the train is in the slow-down mode, and will also eliminate starting processes of asynchronous electric motors of the electric locomotive blower motors’ drive. The developed technical solution will reduce the number of failures of traction electrical equipment and the yard time of electric locomotives for unscheduled types of repair.

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