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Analysis of operating conditions and modes of locomotive traction motors

Abstract. *Traction motors are a key element of locomotive drive systems, the safety and efficiency of transportation depend on the reliability and stability of their operation. Under intensive operating conditions, motors are exposed to variable mechanical, electrical and thermal loads. Additionally, their operation is affected by environmental factors – temperature, humidity, dust, vibrations. An important component of increasing efficiency is the implementation of modern methods of diagnosing, monitoring and predicting the condition of motors using the Internet of Things and cloud computing. The object of research is the physical processes that occur in locomotive traction motors during their operation in different modes and under different operating conditions. The article analyzes the conditions and operating modes of locomotive traction motors with detailed consideration of the influence of temperature conditions, insulation quality, load modes, operating conditions, electromagnetic interference, and modern cloud monitoring technologies. The features of thermal processes in windings, methods of monitoring the condition of insulation and diagnostics, as well as the implementation of remote monitoring systems are considered. The need for a comprehensive approach to assessing the technical condition of traction motors, based on a combination of traditional control methods with the analytical capabilities of cloud services, is substantiated. The results of the analysis showed that the efficiency and reliability of locomotive traction motors are significantly influenced by external factors. The greatest threats are climatic conditions, electricity quality, vibration levels, electromagnetic interference, and maintenance organization. Their negative impact can be reduced by using modern diagnostic monitoring systems. This, in turn, will help increase motors efficiency, reduce operating costs, and extend the service life of locomotives.*

Keywords: *traction motor, locomotive, heating temperature, cooling, insulation, vibrations, operating modes, electric machine, electromagnetic interference, cloud technologies.*

Relevance of the research topic.

The efficiency of locomotives is largely determined by the condition of their traction motors. Traction motors, as a key element of electric traction, are particularly sensitive to changes in operating conditions, characterized by a wide range of factors that can reduce the efficiency of motors, reduce the service life of their components, and increase the risk of accidents. Therefore, conducting an analysis of the conditions and operating modes of locomotive traction motors with detailed consideration of the influence of temperature conditions, insulation quality, load modes, operating conditions, electromagnetic interference, and modern cloud monitoring technologies is important for increasing the reliability and efficiency of rail transport.

Introduction.

The traction motor is certainly the main and most important component of a locomotive, and the temperature management of electric motors is attracting increasing attention from both industry and the academic community. This is because the traction motors in modern locomotives need to be more powerful and competitive, so effective temperature management becomes important to maintain the efficiency, durability and safety of the motors. A thermal management failure can lead to demagnetization of magnets, aging of insulating materials, reduced efficiency, shortened service life, and even burnout of motors.

Locomotive traction motors operate in extremely difficult conditions that are significantly different from the operating conditions of stationary electric machines. Therefore, it is necessary to take into account a number of specific features of their operation. Thus, the ambient temperature during motor operation and idling can vary in the range from –50 to +50 °C with relative air humidity up to (95±3) %. Under such conditions, the mechanical strength of individual structural elements decreases. At low temperatures, most insulating materials become brittle, with cracks appearing on their surfaces. In the summer, the operation of traction motors is complicated by deteriorating cooling conditions, drying out of insulation, and increased dustiness of the air. Increased humidity, especially during precipitation in the form of rain or snow, contributes to corrosion of metal parts and worsens the condition of insulation.

The traction motor housing is periodically, and in some cases, constantly exposed to accelerations that exceed the acceleration of free fall by 10–20 times. Such dynamic loads acting on traction motor elements can cause various damages: breaks in wires and windings (especially in soldering areas), cracks and insulation destruction, accelerated wear of axles and bearings, as well as disruption of the normal functioning of elastic elements.

The design of the motor and the conditions for its installation on the locomotive [1–3] must provide convenient access to:

– plain bearings with liquid lubricant – to control the sufficiency of the lubricant supply during autonomous lubrication and to check the circulation of lubricant through the bearings during forced lubrication;

– grease-lubricated rolling bearings – for partial replacement or replenishment of grease without the need to disassemble the bearing assembly;

– brush apparatus of DC motor collectors or slip rings of AC motors;

– bolts that fix the main and additional poles of DC motors to the frame;

– air coolers;

– terminal boxes of motor winding ends of all types of current;

– heavy elements – in order to ensure the possibility of using mechanized means for their maintenance and repair.

In some cases, motors are operated on locomotives in enclosed spaces with limited ventilation and no air exchange. Such conditions lead to contamination of the motor with coal dust from the brushes, deterioration of commutation, and increase the risk of arcing from the collector to the housing.

And vice versa: sometimes during movement, traction motors are blown by an oncoming air flow containing dust particles with abrasive properties. These particles damage the insulation of traction motors, impair the operation of bearings, and form conductive paths that can cause short circuits.

The efficiency and reliability of locomotive traction motors depend to a large extent on the electromagnetic environment in which they operate. During the operation of rolling stock, numerous electromagnetic interferences arise, which negatively affect the operation of electrical machines, control systems, and auxiliary equipment [4, 5].

Some of these conditions contradict the basic requirements for locomotive traction motors. For example, to ensure minimal dimensions, the active core of the motor must operate at a high utilization rate, which leads to increased operating temperatures that reach the limit values allowable for heat-resistant insulation. A similar situation is observed with regard to mechanical stresses and structural elements, which, due to increased motor speed, also reach high, and in some cases, maximum permissible levels.

The creation of new, more advanced and reliable motors, as well as their effective operation, is possible only with a deep understanding of the physical processes occurring in similar operating motors [6]. Such processes include wear, relaxation and fatigue of metals, corrosion and erosion of structural elements under the influence of fluid flows, aging of lubricants, thermal destruction of electrical insulation, dusting, as well as prolonged exposure to repetitive overloads, vibrations and other factors [7, 8]. All these phenomena appear only after prolonged motor operation, therefore, reliable information about wear can only be obtained on the basis of a systematic analysis of the experience of operating equipment in real conditions of moving vehicles.

Analysis of recent research and publications. References [9] present a comprehensive collection of heat transfer mechanisms for various heat removal methods used in traction electric motors. They provide an overview of different cooling concepts in existing and future traction motors, and compare cooling approaches. Geometric calculation formulas for various cooling heat transfer mechanisms used in motor technology have been collected and general heat transfer phenomena occurring in traction electric motors have been considered. Various specific aspects are analyzed, including rotor shaft cooling, different spray cooling concepts, different air convection phenomena, bearing heat transfer, and stator-housing contact. Thermal analysis and comparison of various cooling methods were carried out. The issue of economic feasibility of applying the proposed approaches to cooling traction motors was left out of consideration.

The paper [10] presents the current state of the art of various thermal management methods for traction motors, including air cooling (natural and forced, air impingement cooling) and liquid cooling (water/oil jacket, jet impingement, spray, immersion, forced convection in slotted channels) for the stator, winding and rotor. However, hybrid thermal management technologies for dealing with extreme conditions have not been fully considered.

The review article [11] mainly focuses on different types of effective thermal design methods that analyze the thermal performance of traction motors. It presents a brief overview of the comparison of different thermal design and analysis methods for different types of traction motors with the aim of showing how improved thermal design can be achieved through optimal electromagnetic and structural design characteristics for different traction motor geometries.

In [12], an analysis of the operating conditions of traction drives of electric locomotives with asynchronous traction motors was conducted. It was found that during operation, defects may occur in the output converter of an asynchronous motor, which leads to asymmetric modes of its operation. Models of the traction drive of an electric locomotive with asynchronous motors with scalar and vector control of the output converter, which take into account asymmetric operating modes, are proposed. As a result of the simulation, the starting characteristics of the traction drive were obtained for various control methods in both normal and emergency modes of operation of the drive. Comparison of the simulation results showed that in emergency modes of the traction drive, the torque pulsations on the motor shaft in the drive with vector control are 13 % smaller, and with scalar control, the phase current asymmetry coefficient is 22 % smaller. Among the shortcomings of the study, it is worth noting that it does not take into account the impact of digital technologies and Smart Grid systems on the development of electric drives.

In the article [13], the operating modes of the traction asynchronous drive of a diesel locomotive are optimized according to the efficiency criterion and the optimal control modes of the autonomous voltage inverter at different temperatures of the traction motor windings are identified. In addition, the optimal operating modes of the traction drive of a diesel locomotive and a tram were analyzed, which allowed us to establish the differences in the location of the transition point from space-vector to single-phase PWM depending on the motor temperature. The disadvantage of the article is that it does not present a comprehensive approach to the analysis of the system «asynchronous motor – converter – load – control system».

Publications [14, 15] are devoted to determining additional heat losses from higher harmonics in the windings of electric motors. And materials [16, 17] consider the influence of higher harmonics of rotating electric machines on the operating modes of active-adaptive networks and their power equipment. This influence depends on the energy level of higher harmonics and the operating modes of active-adaptive networks. A method is proposed that allows determining the levels of slot harmonic components in the phase windings of electrical machines. The calculation of the energy level of higher harmonics was carried out taking into account the electromagnetic asymmetry of rotating electrical machines and asymmetric operating modes of three-phase electrical networks using the phase coordinate method.

In [18], a thermal model is presented that can be used to estimate the resulting temperatures in PMSM components for different operating points and duty cycles. The model is used to compare two cooling systems for electric motors: frame cooling and direct winding cooling. Both systems can be equipped with additional rotor cooling. It is claimed that direct winding cooling instead of frame cooling provides significant advantages in terms of resulting continuous torque and power at the assumed manufacturing costs. A limitation of the work is the insufficient attention to the adaptability and self-updating of the proposed thermal model.

The publications [19, 20] consider the application of the finite element method for thermal calculations of electrical equipment of diesel locomotives. A solid-state model of an asynchronous traction motor was built using the SolidWorks program. The developed finite element model of the elements of an asynchronous traction motor allows determining the thermal state of the elements of the rotor and stator of the electric machine of a diesel locomotive. The disadvantage of the study can be considered the limited feasibility of the experimental conditions.

In [21], a practical approach to modeling and analyzing transient thermal effects in air-cooled traction motors is presented. The developed thermal modeling method allows for accurate estimation of the temperature in critical parts of the motor, including the winding and bearing. In addition, the developed model provides an opportunity to study the effect of stator and rotor air duct clogging on the thermal characteristics of the motor, which is a common cause of failures in traction systems during operations in a polluted environment. A limitation of the study is the insufficient consideration of spatial and temporal temperature gradients.

The study [22] is devoted to the improvement of the method of protection of traction motors based on the use of programmable logic controllers. In addition to the voltage and current parameters, the proposed method involves monitoring the magnetic field. It also provides the possibility of adjusting the protection response time. As a result, in the event of overload, short circuit and other non-standard situations, the improved method provides the system with the ability to make more accurate and reliable decisions. However, little attention has been paid in the work to the influence of operating conditions on the performance of traction motors.

In [23], an innovative system combining a machine learning model with Internet of Things (IoT) technology for real-time diagnostics of the technical condition of traction motors is presented. This allows for rapid monitoring of changes in the motor condition. The developed system generates recommendations on the appropriate time for maintenance based on actual motor performance indicators. This approach allows you to move from traditional scheduled maintenance to predictive maintenance based on real-time diagnostic results. As a result, reliability is increased and motor service life is extended, as well as the number of unplanned downtimes is reduced. However, the issue of interaction of the system presented in the work with motor control systems or SCADA in order to provide remote monitoring and control of its operation through integration with IoT technology is not fully disclosed.

Defining the purpose and objectives of the research.

The purpose of the article is to conduct a comprehensive analysis of the conditions and operating modes of locomotive traction motors, which, under the conditions of implementing an integrated approach to the issue of effective operation of traction motors, which includes monitoring the temperature state and insulation of windings, adaptive control of operating modes, protection against electromagnetic interference, the use of cloud monitoring and diagnostic technologies, etc., will contribute to increasing reliability, extending the life of motors and reducing operating costs. To achieve the goal, the following tasks were set:

– analyze the heating and cooling processes of traction motors, identifying the main causes of motor overheating;

– consider the effect of heating temperature on the aging of motor insulation;

– identify the main causes of traction motors vibration;

– to review the nominal operating modes of traction motors;

– to investigate the effect of electromagnetic interference on the operation of locomotive traction motors;

– to learn about the use of cloud technologies in traction drives control systems.

The main part of the research.

Analysis of heating and cooling processes of traction motors. The operation of locomotive traction motors is accompanied by the conversion of electrical energy into mechanical energy, which is always associated with the appearance of energy losses in the form of heat. Heating and cooling processes determine the thermal state of the machine, which directly affects the reliability, durability and efficiency of the traction motor. Therefore, their analysis is a necessary component in the design, operation and diagnostics of traction rolling stock.

The load capacity of electric motors mainly depends on their heating conditions, since it is the temperature increase that is the main factor limiting the motor power under both long-term and short-term loads. As the load increases, energy losses increase and, accordingly, the amount of heat released. With excessive load, the temperature of individual elements, especially insulation, may exceed permissible values.

At the beginning of operation, the temperature of the electric motor practically coincides with the ambient temperature. At this stage, all the heat released in the motor is spent on heating its parts. Gradually, the intensity of heat transfers to the environment increases. After some time, the motor heats up to such an extent that the amount of heat released by it per unit of time is completely balanced by the amount of heat transferred to the environment. At this point, the temperature increase stops, and thermal equilibrium is established, in which all the heat generated in the motor is dissipated through its surface.

The motor heat balance equation has the form:

$$C\frac{dT}{dt} = P_{losses} - k \cdot \left(T - T_{cm}\right), \quad (1)$$

where C is the heat capacity of the motor;

T is the current temperature;

T_{cm} is the temperature of the cooling medium;

P_{losses} is the total power losses;

k is the heat transfer coefficient.

Equation (1) describes the change in temperature over time under the influence of internal heat sources and external cooling.

An electric machine consists of many elements (windings, parts of the magnetic circuit, structural parts) that differ in thermal conductivity, heat capacity, and cooling conditions [24]. As a result, the temperatures of individual parts of the machine also differ. Despite the complexity of the distribution of heat flows inside the motor and the limited accuracy of thermal calculations based on this approximation, it is possible to identify general patterns of temperature changes in the processes of heating and cooling the motor. The temperature of the traction motor during heating and cooling changes according to an exponential law. During heating, the temperature rise of the motor above the ambient temperature gradually increases and asymptotically approaches a value corresponding to a certain current level. This behavior is observed with increasing power losses (load) of the motor or a decrease in its cooling efficiency [25].

By increasing the cooling intensity or reducing the load current, the temperature rise decreases to a new steady-state level corresponding to the changed current values. After disconnecting the motor from the mains, the load current becomes zero and the motor gradually cools down to ambient temperature.

During sufficiently long operation, the temperature rise reaches an almost constant level. In this state, the motor is in a practically stable thermal mode, which is called continuous.

The main reasons for overheating of electric motors can be as follows:

– motor contamination and dust deposition on the windings and active steel of the machine, which leads to deterioration of heat transfer;

– the fan with inclined blades rotates in the wrong direction, which causes it to supply insufficient air to the motor and the cooling system to operate inefficiently;

– increased ambient temperature (over +35 °C), at which the motor heating temperature exceeds permissible values;

– reduction of the armature or rotor speed below nominal, which causes reduced air circulation and poor motor cooling;

– interturn short circuits in the motor windings, as a result of which an electromotive force is induced in the short-circuited circuit, and due to the low resistance of this circuit, significant short-circuit currents flow through it, which cause the motor to overheat;

– reducing the armature rotation frequency, due to which, to ensure the nominal voltage, a current of a greater magnitude than the nominal is supplied to the excitation winding in order to create a more powerful magnetic flux, which leads to overheating of the excitation winding.

Motor overheating can also be caused by increased bearing temperature, which is usually caused by insufficient lubrication or an overly tight belt.

In DC motors, collector overheating occurs when there is strong sparking under the brushes, which occurs due to poor commutation, the use of brushes that are too hard, or excessive pressure on the collector.

In synchronous generators, the rotor excitation winding overheats at low power factor. This is because to compensate for the demagnetizing effect of the armature reaction, the current in this winding must exceed the nominal value when the generator is operating at rated load.

For asynchronous motors, in addition to the causes of overheating common to all electric machines, an additional temperature increase can occur for the following reasons:

– increasing the voltage in the network above the nominal value leads to increased losses in the steel;

– operation of the motor on only two phases while maintaining the rated load causes the rated current in these phases to exceed approximately $\sqrt{3}$ times;

– a decrease in voltage at the motor terminals causes its current overload under rated load conditions;

– connecting the stator windings in a “delta” instead of a “star” configuration leads to a significant excess of the rated current in the stator windings.

To maintain an acceptable thermal regime in locomotive traction motors, various cooling systems are used, depending on the type of motor and operating conditions:

– natural (self-cooling) – used in low-power or auxiliary machines. Heat is removed through convection and thermal conductivity from the surface of the housing to the environment;

– forced air cooling is the most common method for DC and AC traction motors. The air flow is supplied by fans or turbines built into the motor or locomotive design [26]. The system can be open, when air is drawn from the environment, closed, when recirculation flow through heat exchangers is used;

– liquid cooling – used in powerful traction motors of modern electric and diesel locomotives. Water, oil or antifreeze are used as a coolant, which circulates through the cooling jackets of the body and windings;

– combined systems – combine air and liquid cooling for different components (e.g. winding – liquid, collector – air).

To ensure optimal thermal conditions of traction motors, the following technical measures are used:

– use of materials with increased thermal conductivity for housings and winding elements;

– optimization of aerodynamic channels in the motor design to improve cooling air flow;

– use of modern heat-resistant insulating materials of classes *F* and *H* (up to 155–180 °C);

– the use of intelligent temperature control systems that provide automatic adjustment of fan or pump speed depending on the load;

– periodic cleaning of channels and checking the condition of cooling systems during maintenance.

For heating and cooling analysis, thermal equivalent models are used, where individual parts of the motor are represented as elements of an electrical circuit:

– thermal resistances – as an analogue of electrical resistances;

– heat capacities – as capacities;

– heat sources – like current generators.

Solving such models allows you to determine the dynamics of temperature changes under different loads and cooling modes, as well as evaluate transient processes after start-up, stop, or short-term overloads.

Effect of heating temperature on motor insulation aging. The operating temperature is one of the determining factors affecting the durability and reliability of the insulation systems of locomotive traction electric motors. During operation, motors operate in difficult conditions characterized by variable loads, high humidity, vibrations, and the effects of electromagnetic fields. The combination of these factors causes accelerated aging of insulating materials, especially when the permissible temperature limits are exceeded: mechanical strength decreases, insulation becomes brittle, cracks form [27]. The presence of cracks in insulation reduces its electrical strength. The main causes of insulation aging include the following:

– high temperature;

– large temperature differences between individual motor parts;

– electric field;

– high humidity;

– mechanical loads.

An increase in temperature causes an intensification of physicochemical processes in the structure of insulating materials, such as [28]:

– oxidation of organic compounds, which leads to loss of elasticity, formation of microcracks and reduction of dielectric strength;

– evaporation of plasticizers and moisture, as a result of which the insulation becomes brittle and less resistant to mechanical stress;

– acceleration of polymerization and thermal degradation processes, which change the molecular structure of the material and worsen its operational properties.

Increased temperature leads to oxidation of the components of the insulating varnishes. Therefore, to ensure the specified service life of the traction motor, the heating temperature of individual components must not exceed the permissible values. Thus, the maximum permissible operating temperature of the motor is determined by the thermal resistance of the insulation used. At the same time, increasing the permissible temperature of motor parts allows for increased load, but at the same time accelerates the aging processes of insulation and reduces the service life of the machine [29]. Electrical insulating materials used in electric motors are classified by the level of thermal resistance into seven classes, the temperature limits of which are given in Table 1.

Table 1 – Thermal resistance classes of electrical insulating materials used in electric motors

Insulation class	Y	A	E	B	F	H	C
Permissible overheating temperature, °C	80	105	120	130	155	180	Above 180

The most vulnerable to the effects of elevated temperatures are materials based on cellulose, paper, silk and similar substances, which are used in class *A* and *E* insulation. In class *B* insulation, the binding components and impregnating varnishes are primarily subject to oxidation when heated. Class *F* and *H* insulation, like class *B*, is made using mica, asbestos and fiberglass, but they use binders that are more heat-resistant. Class *C* insulation, made of ceramic and mica, is resistant to high temperatures.

The duration of insulation aging (in years) under the influence of temperature can be roughly calculated using the following expression:

$$t = e^{-\alpha\theta}, \tag{2}$$

where α is a coefficient depending on the insulation class;

θ is temperature, °C.

From expression (2) it is clear that with increasing temperature the aging process of insulation is significantly accelerated. For example, for class *A* insulation at a temperature of 95 °C its service life is about 16 years, at 110 °C it decreases to 4 years, and at 150 °C it is reduced to only a few days. In approximate calculations, the so-called «eight degree rule» is usually used: each increase in insulation temperature by 8 °C above the permissible level reduces the service life of class *A* insulation by half. For class *B* insulation, the temperature dependence of service life is similar, but reduced by approximately 20 °C towards higher temperatures. Therefore, the above patterns and the eight-degree increment can be applied to other types of insulation. Although it is difficult to practically determine the actual overheating of the insulation, it is always necessary to consider its effect on the durability of the electrical machine.

Table 2 shows the maximum permissible temperature excesses of some parts of electric machines of rolling stock, the service life of which is 8–15 years.

Table 2 – Overheating of electric machine elements

Parts of an electric machine	Maximum permissible temperature, °C				
	Insulation classes				
	A	E	B	F	H
Armature windings connected to the collector and AC windings	60	75	80	100	125
Multilayer excitation windings of DC and AC machines	60	75	80	100	125
Single-row excitation windings with bare surfaces	65	80	90	110	135
Cores and other steel elements in contact with insulated windings	60	75	80	110	125
Collectors and slip rings	60	70	80	90	100

In locomotive traction motors operating in severe conditions with frequent starts, braking, and short-term overloads, the winding temperature often exceeds the nominal values. This leads to accelerated aging of impregnating varnishes, resins, and insulating tapes, and subsequently to interturn short circuits or insulation breakdowns on the housing.

The maximum permissible winding temperature is determined by adding the maximum permissible temperature rise to the nominal ambient temperature, which is assumed to be 40 °C. If the actual ambient temperature is higher than this limit, the permissible winding temperature rise must be reduced so that the actual winding temperature does not exceed the set limit.

If the ambient temperature is lower than the standard, then during operation it is allowed to proportionally increase the maximum permissible excess of the winding temperature, but not more than by 10 °C compared to the value established by standards or technical specifications. When operating the machine in areas where low barometric pressure reduces heat transfer efficiency, it is necessary, on the contrary, to slightly reduce the permissible temperature excesses.

In some cases, for special-purpose electric machines, their service life is reduced by allowing higher insulation heating values than those specified in Table 2. This allows for increased power with the same dimensions or to produce a machine of the required power with a smaller mass and dimensions.

The average excess of the winding temperature over the temperature of the cooling medium is usually determined based on the change in the resistance of the winding or conductor:

$$r_2 = r_1 \cdot \left[1 + \alpha \cdot \left(\theta - \theta_0\right)\right], \quad (3)$$

where r_1 and r_2 is the active resistance of the winding in the cold and heated state, respectively, Ohm;

α is the temperature coefficient (for copper $\alpha = 0{,}004\ K^{-1}$);

θ is the winding temperature, °C;

θ_0 – is the ambient temperature, °C.

To minimize the negative impact of temperature on insulation in traction motor designs, the following technical solutions are used:

– use of heat-resistant materials of heat resistance classes *F*, *H* or higher;

– implementation of efficient cooling systems (forced ventilation, liquid or combined cooling);

– monitoring the temperature state of windings using temperature sensors and automatic control systems;

– preventive cleaning of ventilation ducts to ensure proper heat exchange.

The main causes of traction motors vibrations. During operation of traction motors, their parts vibrate, which is called vibration. Vibration leads to disruption of connections in the motor, increased wear and overheating of bearings [30–32]. Vibration is considered permissible if the doubled amplitude of vibrations does not exceed the limits specified in Table 3.

Table 3 – Permissible vibration limits

Motor revolutions per minute	Permissible vibration, mm
750	0.12
1000	0.10
1500	0.08
3000	0.05

The occurrence of vibration of traction motors is caused by various factors of both mechanical and electrical nature [33–35].

The main mechanical causes of traction motor vibration include the following:

– rotor imbalance – occurs due to uneven mass distribution or wear of parts, which leads to the appearance of centrifugal forces during rotation;

– shaft or rotor deformation – even a slight shaft distortion can cause beating and vibrations;

– rotor and stator misalignment – misalignment during installation or operation leads to an uneven gap in the air gap;

– wear or damage to bearings – increased backlash, misalignment or destruction of separators cause vibrations and noise;

– unreliable fastening of the motor to the locomotive frame – loose bolts, deformation of supporting elements or metal fatigue cause additional vibrations.

Electromagnetic causes of traction motor vibration are:

– unevenness of the magnetic field in the gap – may be a consequence of winding asymmetry or stator displacement;

– electromagnetic forces that vary with the network frequency – in DC or AC traction motors they can cause periodic torque pulsations;

– poor commutation (for DC motors) – sparking on the collector creates pulsed electromagnetic disturbances;

– power asymmetry or winding defects – unequal current in the phases causes electromagnetic imbalance.

In addition, there are also structural, operational and external factors, which should be included:

– mismatch of the geometry of the connection with the gearbox or chassis – misalignment of couplings or gears can transmit vibrations to the motor housing;

– wear of the gear teeth – causes periodic shocks and vibrations during operation;

– operation under excessive load or abnormal conditions – overloading of the rotor or stator windings increases dynamic forces;

– Insufficient or uneven lubrication – increases friction in bearings, causing vibrations;

– the impact of vibrations from wheelsets and track – especially when driving on uneven or worn track.

Thus, the main cause of vibrations of electrical origin is interturn short circuits in the windings. As a result, magnetic asymmetry occurs in the motor, due to which the attraction between the stator and rotor becomes uneven, which causes oscillations of the machine elements. Magnetic asymmetry can also occur due to eccentricity of the rotor relative to the stator, which is a consequence of bearing wear or uneven air gap between the rotor and stator. In DC motors, magnetic asymmetry rarely causes vibration, while in AC motors, even a slight asymmetry of the magnetic field can cause severe oscillations.

To determine what exactly is causing the vibration – magnetic asymmetry or a mechanical fault – the excitation is removed while the generator is running, the electric motor is disconnected from the mains and its vibration is observed while it continues to rotate by inertia. If the vibration stops after the voltage is turned off, then the cause is magnetic asymmetry. If the vibration does not disappear, then the source of the malfunction is mechanical defects.

Traction motors operating modes. Depending on the characteristics of load changes, locomotive traction motors can operate in different nominal modes: long-term, short-term, repeated short-term, and others, which mainly take into account frequent starts, braking, reverses, and intermittent operation [36–38].

Long-term mode. A continuous motor operation mode is considered to be a mode in which the motor operates at a constant load for a sufficiently long time for the motor temperature to reach a set value that exceeds the ambient temperature. This means that for a given cooling surface size and cooling intensity, the electric motor can only operate at a power level at which losses do not exceed the level corresponding to the maximum permissible heating. The amount of permissible overheating is determined by the thermal resistance of the winding insulation used in this type of motor.

The power at which the overheating limit temperature is set (rated power or continuous power) is the main indicator that determines the ability of a traction motor to operate under load in continuous mode. In order for the motor temperature to not exceed the permissible limit at a given load, it is necessary that the dimensions of the cooling surface are large enough. If the cooling area is given, the permissible overheating temperature can be ensured by increasing the cooling intensity.

The characteristic features of long-term motor operation are that:

– the temperature of the windings and magnetic core reaches a constant (nominal) value;

– stability of parameters (resistance, torque, current) is ensured;

– mode promotes reliable and safe operation if permissible temperatures are not exceeded;

– insulation wear is minimal, which increases motor life.

An example of a long-term motor operation is the movement of a locomotive along a flat section of track at a constant speed.

Short-term mode. In short-time operation, the electric motor operates at a constant load, alternating periods of operation with shutdowns. In this case, the time of operation under load is not long enough for the motor temperature to reach the set value, and the pauses between switching on are long enough for the motor to cool completely to ambient temperature. For general-purpose electric motors, the standards provide for the following values for the duration of the operating period: 10, 30, 60 and 90 minutes.

Prolonged motor operation in overload mode is unacceptable and should be limited in time. As the power output increases, and therefore losses, motor overheating increases – the temperature rises more and more intensively as it heats up. Therefore, as the motor load increases, the operating time before reaching the limit overheating temperature decreases.

During short-term overloads lasting 2–3 minutes, it can be assumed that the heating process proceeds without heat transfer, that is, adiabatically.

An example of a short-term motor operation mode is the movement of a heavy train or movement on a short slope.

Repeated short-term mode. In rolling stock, electric motors often operate in a repetitive short-term mode. In this mode, intervals of motor operation under load alternate with pauses when the motor is off, as a result of which the entire operating time is divided into regularly repeating cycles. At times of load, the motor temperature does not reach a stable value, and during periods of pauses the motor does not cool down to ambient temperature. The cycle duration in this mode of operation should not exceed 10 minutes. The characteristic of the repeated short-term mode is given by the fraction of the on-time, expressed as a percentage of the total cycle duration.

During the operating cycle, the motor temperature increases according to its heating curve, and during pauses it decreases according to the cooling curve. In repeated short-term operation, higher loads are possible compared to long-term operation. The ratio of power losses in the motor in repeated short-term and long-term modes, which ensure the same temperature excess, depends on the duration of switching on.

An example of repeated short-term motor operation is frequent stops and starts during maneuvering or driving in urban conditions.

Intermittent mode. In this mode, short periods under load (working intervals) alternate with periods of idling (pauses). The intermittent mode is defined by the relative duration of the load, expressed as a percentage, the standard values of which are 15, 25, 40 and 60 %. The duration of one cycle is usually taken to be 10 minutes. The nature of the changes in parameters in this mode is similar to the changes observed in the repeated short-term mode. During the operating period, the motor temperature and the temperature rise do not have time to reach the set values.

Additional nominal modes. In addition to the main nominal operating modes, additional (recommended) modes are established in which the load is cyclic in nature:

1) repeated short-term mode with frequent starts and a duty cycle of 15, 25, 40 or 60 %;

2) repeated short-term with frequent starts and electric braking with a duty cycle of 15, 25, 40 and 60 %;

3) interspersed with frequent reverses and electric braking;

4) interleaved with two speeds.

The following parameters are set for additional nominal modes:

– for modes 1) and 2) – standard number of starts per hour;

– for mode 3) – number of reverses per hour;

– for mode 4) – the number of cycles per hour is 30, 60, 120 and 240.

Work under variable load. During the operation of electric motors, modes may occur that differ from those listed earlier. The most characteristic is the mode with a rapidly changing load, similar to repeated short-term, in which the temperature of the motor parts practically does not change during the cycle. If an electric motor operates continuously but under varying loads, different power losses occur at different times. The equivalent current method is usually used to assess the motor's ability to withstand a given load schedule. It is based on the assumption that the variable losses in the machine are proportional to the square of the load current.

Operation under alternating current load. When operating traction motors, operation in modes other than those specified above is possible. Such machines are characterized by conditions with rapidly changing current and power. If the motor operates for a long time at constant power, but with currents of different magnitude, then the thermal process in it should be considered as not steady, since a change in current leads to a change in losses.

The influence of electromagnetic interference on the operation of locomotive traction motors. The operation of modern locomotives is closely related to the widespread use of powerful traction motors [39, 40], semiconductor converters [41, 42], microprocessor-based control systems [43–45], and numerous auxiliary electronic devices. Under such conditions, a complex electromagnetic environment arises in which electromagnetic interference can significantly affect the operation of traction motors and related systems.

Electromagnetic interference is unwanted electrical or magnetic influences that cause electrical current or voltage parameters to deviate from their nominal values. Their occurrence is caused by both internal and external factors.

The main internal sources of electromagnetic interference in locomotive traction drives are:

– switching processes in power circuits (operation of thyristors, transistors, contactors, relays);

– sparking on the collector-brush assembly of the traction motor;

– operation of power frequency converters, rectifiers and inverters;

– inductive and capacitive coupling between power and signal circuits.

External sources of electromagnetic interference include:

– electromagnetic influences from the contact network;

– interference from other locomotives or electric vehicles;

– lightning pulses and other natural electromagnetic phenomena.

As a result of the action of electromagnetic interference in the power supply circuits of traction motors, short-term overvoltage pulses occur, which can significantly exceed operating values. This leads to:

– partial or complete breakdown of the insulation of the stator and rotor windings;

– accelerated aging of insulating materials;

– the appearance of local partial discharges that destroy the insulating coating;

– the occurrence of eddy currents in ferromagnetic parts of the motor, which increases heating and power losses.

Particularly dangerous are high-frequency pulses of short duration that act adiabatically – without heat removal, which causes a local increase in temperature and can lead to insulation degradation.

Modern locomotives are equipped with microprocessor control systems that are highly sensitive to electromagnetic interference [46, 47]. Electromagnetic interference can cause:

– distortion of signals from measuring sensors (current, voltage, temperature, speed);

– false triggering of automatic control and protection systems;

– controller software failures;

– disruption of data exchange between system units via CAN or RS-485 interfaces.

Such deviations reduce the stability of traction modes, can cause spontaneous shutdown or incorrect operation of the electric motor, which directly affects the safety of train movement.

High-frequency electromagnetic interference causes additional energy losses in the form of eddy currents in the ferromagnetic parts of the machine (yoke, cores, housing), which, in turn, leads to local overheating of structural elements, increased bearing temperature and increased friction, reduced motor efficiency, and the possibility of resonance phenomena when the frequencies of electromagnetic interference coincide with the natural oscillation frequencies of the electric drive elements, which enhances their destructive effect. In addition, electromagnetic emissions from traction motors and converters can extend beyond the power circuits and affect locomotive systems, the contact network and adjacent tracks, creating interference for other means of transport [48, 49]. Such effects are critical because they can cause loss of communication between the driver and the dispatcher, failures in signaling, centralization and blocking systems or even incorrect indication of signals.

To ensure reliable operation of traction electric drives, it is necessary to implement a set of measures aimed at ensuring electromagnetic compatibility of systems. The main methods for reducing the impact of electromagnetic interference include:

1) electromagnetic shielding and filtering:

– application of high-pass filters in power circuits;

– use of metal screens and grounded cable sheaths;

– separation of signal and power wires in space;

2) optimization of control and switching circuits:

– using smooth (soft) switching methods for power elements;

– limiting the rate of rise of current (di/dt) and voltage (du/dt);

– application of damping circuits and interference suppression filters;

3) improvement of the grounding system:

– correct organization of grounding of electrical equipment;

– eliminating ground loops that can act as antennas for interference;

– use of symmetrical cable routes;

4) constructive solutions:

– increasing the electrical strength of insulating materials;

– use of materials with high magnetic characteristics to reduce losses;

– temperature control and timely equipment maintenance;

5) diagnostics and monitoring:

– regular measurement of electromagnetic radiation levels;

– checking the condition of screens, filters and contacts;

– computer diagnostics of the state of control systems for the presence of interference.

Using cloud technologies in traction drive control systems. The modern development of railway transport is characterized by the widespread introduction of digital technologies [50–53], among which cloud computing occupies a special place. The use of cloud technologies in traction electric drive control systems [54, 55] opens up new opportunities for monitoring, diagnostics, condition prediction, and optimization of locomotive traction motor operating modes.

Cloud technologies involve storing, processing, and analyzing large amounts of data on remote servers accessible via the Internet. In transport infrastructure, they are used for:

– collection and analytical processing of information about equipment operation in real time;

– centralized storage of technical data and operation history;

– remote control and adjustment of electronic locomotive systems;

– implementation of the principles of «predictive maintenance».

In the context of traction motors, cloud technologies allow for the creation of an intelligent control system that integrates data from the locomotive into a single information transport network [56–58].

A typical architecture for interacting with cloud services and traction drives includes three levels:

– field level (on-board layer) – sensors, controllers and microprocessor units that directly capture data from traction motors: current, voltage, temperature, vibration, rotation speed, load, etc.;

– communication layer (edge layer) – data transmission via wireless networks (LTE, 5G, Wi-Fi, radio channel) to pre-processing servers, where information filtering, normalization and encryption are performed;

– cloud layer – an analytical platform that stores large data sets (Big Data), performs real-time analysis, models the technical condition of motors, and generates recommendations to optimize their operation.

The use of cloud technologies provides a number of advantages that significantly increase the efficiency of locomotive traction drives:

– improved maintenance – cloud systems allow for continuous monitoring of motor parameters, which allows for timely detection of deviations, prediction of malfunctions and planning of repairs based on the actual condition of the equipment;

– energy consumption optimization – data analysis in the cloud helps determine the most efficient motor operating modes depending on the load, track profile, temperature conditions and the driver's driving style;

– increasing the service life of electrical machines – thanks to precise adjustment of control parameters, peak currents, heating and mechanical loads are reduced, which has a positive effect on the durability of windings and bearings;

– remote diagnostics and software updates – updates to control algorithms and protection parameters can be carried out without physical intervention in the locomotive, via secure communication channels;

– improving traffic safety – artificial intelligence systems integrated into cloud platforms are able to predict emergency situations by analyzing historical data from numerous locomotives and issuing warnings about possible failures.

Despite significant advantages, the integration of cloud services into the traction motor control system is accompanied by a number of challenges:

– data transmission delays (latency) – the operation of a traction electric drive requires high-speed control systems, so even minor signal delays can affect the accuracy of regulation;

– dependence on the quality of communication - in the case of an unstable or absent Internet connection (especially on remote sections of the track), data exchange between the locomotive and the cloud may be disrupted;

– cybersecurity issues – data transmission over public or corporate networks requires reliable encryption and protection against unauthorized access;

– difficulty of integration with existing systems – many older locomotives do not have compatible interfaces and require modernization to connect to cloud platforms;

– increased requirements for technical personnel – the operation of such systems requires special training of engineers and drivers capable of working with digital services and remote monitoring interfaces.

In the coming years, a transition to integrated cyber-physical traction control systems is expected, where cloud platforms will be closely linked to artificial intelligence (AI) and Internet of Things (IoT) systems. Such solutions provide a complete digital model of the traction motor («digital twin»), adaptive real-time control, automatic optimization of energy consumption, synchronization of locomotives in trains («smart train» technology). As a result, cloud technologies will contribute to increasing the efficiency, reliability and environmental friendliness of the new generation of locomotives.

Conclusions.

Based on the research conducted, the following conclusions can be drawn:

– analysis of the heating and cooling processes of traction motors shows that the thermal state is one of the main factors determining their reliability and service life. Increasing the temperature of the windings beyond permissible limits leads to insulation degradation, increased electrical losses and reduced mechanical strength of the elements. Ensuring effective cooling, using modern heat-resistant materials and temperature monitoring systems can significantly increase the durability and efficiency of locomotive traction motors in various operating conditions;

– heating temperature is a critical parameter that determines the intensity of aging processes of insulating materials in locomotive traction motors. Maintaining the optimal thermal operating mode contributes to increasing the reliability, durability and energy efficiency of railway rolling stock;

– traction motor vibration is the result of a combination of factors, most often combining mechanical imbalances with electromagnetic asymmetries. To reduce it, rotor balancing, bearing and mounting inspection, motor alignment control, and winding and electrical parameter diagnostics are required;

– the influence of operating modes (long, short-term, repeated short-term, etc.) on locomotive traction motors is decisive for their reliability, durability and efficiency. Each mode is characterized by its own loading conditions, thermal processes and operating characteristics;

– electromagnetic interference is one of the most significant factors affecting the efficiency, reliability and durability of locomotive traction motors. Its impact manifests itself in the form of overvoltages, failures in control systems, increased heat losses and electrical interference in adjacent devices. To ensure stable operation of electric traction systems, it is necessary to provide for electromagnetic protection measures that comply with electromagnetic compatibility requirements at the design stage, and during operation, to carry out systematic monitoring and prevention of sources of interference;

– cloud technologies are an important direction in the digital transformation of rail transport. Their use in traction motor control systems provides a new level of intellectualization of operational processes, allowing for real-time monitoring, diagnostics, analysis, and optimization of motor operation. At the same time, the effective use of cloud solutions requires addressing cybersecurity issues, standardization of data exchange protocols, and technical compatibility with existing equipment. In the future, the integration of cloud technologies with artificial intelligence systems and the Internet of Things will become a key factor in increasing the efficiency of electric traction drives and the development of «smart railway transport».

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Нерубацький В. П. Аналіз умов і режимів роботи тягових двигунів локомотивів.

Анотація. *Тягові електродвигуни є важливим елементом систем привода локомотивів, від надійності і стабільності роботи яких залежить безпека і ефективність перевезень. В умовах інтенсивної експлуатації двигуни зазнають дії змінних механічних, електричних і теплових навантажень. Додатково на їхню роботу впливають фактори зовнішнього середовища – температура, вологість, запиленість, вібрації. Важливою складовою підвищення ефективності є впровадження сучасних методів діагностики, моніторингу та прогнозування стану двигунів із використанням Інтернету речей і хмарних обчислень. Об'єктом дослідження є фізичні процеси, що протікають у тягових двигунах локомотивів під час їхньої роботи в різних режимах і за різних умов експлуатації. У статті проаналізовано умови та режими роботи тягових електродвигунів локомотивів із детальним урахуванням впливу температурного стану, якості ізоляції, режимів навантаження, умов експлуатації, електромагнітних завад і сучасних хмарних технологій моніторингу. Розглянуто особливості теплових процесів в обмотках, методи контролю стану ізоляції та діагностики, а також впровадження систем дистанційного моніторингу. Обґрунтовано необхідність комплексного підходу для оцінювання технічного стану тягових двигунів, що базований на поєднанні традиційних методів контролю з аналітичними можливостями хмарних сервісів. Результати аналізу показують, що на ефективність і надійність тягових двигунів локомотивів визначально впливають зовнішні фактори. Найбільшу загрозу становлять кліматичні умови, якість електроенергії, рівень вібрацій, електромагнітні завади та організація технічного обслуговування. Зменшити їхній негативний вплив можна за рахунок застосування сучасних діагностичних систем моніторингу. Це, зокрема, сприятиме підвищенню коефіцієнта корисної дії двигунів, скороченню експлуатаційних витрат і подовженню строку служби локомотивів.*

Ключові слова: *тяговий двигун, локомотив, температура нагрівання, охолодження, ізоляція, вібрації, режими роботи, електрична машина, електромагнітні завади, хмарні технології.*

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