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# New Approaches to Assessing State of Insulating Material of Traction Electric Motors of Electric Locomotives

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## ABSTRACT

*Increasing the efficiency of functioning of railway transport in the field of cargo and passenger transportation, reducing operating costs are immediately related at present to the cost of maintaining and restoring traction rolling stock. Optimization of operating costs is possible on the basis of the transition from a scheduled preventive system of repair of traction rolling stock, based on assessment of the average statistical level of its technical condition without considering peculiarities of the operating range, to a system of repair and maintenance based on the actual technical condition, objectively determined on the basis of creation and implementation of onboard, portable and stationary means of technical diagnostics of units and assemblies, of development of a data bank on the current state of electric locomotives and their units.*

*Power plants belong to the basic elements and units of traction rolling stock structures. The reliability and service life of traction electric motors of electric locomotives, especially winding insulation, does not meet modern requirements, and the existing systems for diagnosing the state of winding insulation do not allow providing the required level of failure detection at an early stage. To qualitatively determine the wear category of the insulating material, new approaches have been developed. They are based on the method of IR spectrophotometry based on relative rate of transmittance of electromagnetic radiation in a gas atmosphere removed from the traction motor winding. This is the basis for development and implementation of onboard system for automated monitoring of the current state of the electric motor insulation and assessment of the residual resource.*

*Keywords:* *railway, electric locomotive, traction motors, assessment of the current state, insulating material, reliability growth.*

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Railway transport plays a crucial role for the stable, progressive development of the industrial economics, and is the basis for implementation of programs for long-term development of national economic potential. Today one of the most urgent tasks is to create conditions for increasing efficiency of railway transport in the field of cargo and passenger transportation, reducing operating costs, and increasing labour productivity.

The issues of increasing the efficiency of functioning of railway transport, optimizing the use of various types of traction, considering prospects for development of cargo transportation, are considered in work [1]. The authors, in the context of the main topic of the research, emphasize the relationship between the efficiency of functioning of railway transport, its progressive development, and adaptability of rolling stock, considering specific operating conditions.

The decisive factor in increasing efficiency of railway transport in modern conditions is linked to improvement of technological processes of operation and repair of traction rolling stock, to solution of the problems of increasing reliability, reducing operating costs.

These approaches are implemented on Russian railways, are subject to wide discussion and implementation on the railways of Europe and other regions. In [2], the authors consider ways to increase the efficiency of power units using the examples of locomotives 2M62 and TEP-70, increasing their reliability, reducing operating costs through the introduction of a system for monitoring the parameters of the traction motor.

Priority areas for improving the Russian domestic system of maintenance and repair of electric locomotives currently comprise repair and maintenance according to technical condition, for this it is necessary to assess both the current and the residual resource of basic elements and assemblies. The most promising measures for implementation of the program aimed at improving efficiency of traction rolling stock operation are creation and implementation of diagnostic systems based on the use of on-board, portable and stationary means of technical diagnostics of units and assemblies; development of a data bank on the current state of electric locomotives and their units in order to ensure transition to a system of maintenance and repair of locomotives, considering their actual, current state.

The results of economic analysis of functioning of traction rolling stock fleet indicate a significant dependence of the prime cost of all types of transportation on the costs of technical maintenance and repair of traction rolling stock. The structural analysis of the costs of railway transport shows that the share of operating costs reaches 18–20 % of the total cost of transportation [3]. At present, with the existing system of technical maintenance and repair of traction rolling stock, the cost of maintenance for the period from beginning of operation to setting of the locomotive for overhaul is 3,5–4,0 times higher than its initial cost [4]. About 1700 locomotives on the railway network daily underwent all planned types of repair and maintenance (excluding TM-2 [technical maintenance of type 2]), including about 100 locomotives that were undergoing factory repairs. Thus, up to 13,5 % of the operated fleet of JSC Russian Railways was diverted daily for maintenance and repairs.

Currently, the preventive maintenance system for traction rolling stock of JSC Russian Railways is based on assessment of the average level of its technical condition. Often, the assessment of the current technical condition of structural elements and determination of the required type and volume of repair work depends on qualifications of employees, technical equipment, and availability of required diagnostic equipment. As a result, defects are detected by external signs (increased backlash, noise, vibration, heating, wear, etc.).

The basic elements and units of the structure of traction rolling stock include power plants, running gear, etc. The statistical analysis of assessment of the current state indicates that reliability and service life of traction electric motors (TEM) of electric locomotives, particularly of winding insulation, does not meet modern requirements. Existing systems for diagnostics of the state of insulation of windings of traction electric motors do not allow to provide the required level of failure detection at an early stage.

As practices have shown, the system for maintaining reliability of insulation using mileage indices is not optimal. The operating conditions of traction electric motors are not the same for different regions of the country, therefore, insulation aging is not the same, and not every motor with a mileage of 1600 thousand km necessarily needs to be replaced with a winding. Sometimes a cheaper average repair of traction electric motors is sufficient, i.e. cleaning, impregnating and drying the winding insulation. Thus, an objective assessment of the real state of insulation will ensure extension of its service life without reducing reliability of operation but at a lower cost.

The *objective* of the research was to study the application of IR spectrophotometry method based on relative rate of transmittance of electromagnetic radiation in a gas atmosphere removed from the traction motor winding as a basis for development and implementation of onboard system for automated monitoring of the current state of the electric motor insulation and assessment of the residual resource, while the *methods* of structural economic analysis, statistical analysis, and experimental methods of spectrophotometry were used.

**Results**

In operation, insulation of traction rolling stock electrical equipment is exposed to a wide range of impacts. These include temperature of winding, vibration amplitude and frequency, electrical overvoltage, electrodynamic effects from electric current, air humidity, presence of corrosive vapors and dust in the environment. They initiate complex processes in insulation, the result of which is a gradual deterioration of its electrical properties, called aging [5]. Under the influence of various factors and loads, physicochemical processes occur in dielectric materials, which lead to destruction of the insulating material and subsequent failures of the insulation of windings of electrical machines in the form of electrical breakdown and turn-to-turn short circuits. However, in most cases, the effects of aging can be eliminated by restoration of the insulation [6].

Aging processes limit the service life of insulating structures [7; 8]. Therefore, in development, manufacture and operation of high voltage equipment, measures should be taken to reduce the aging rate of insulation to such a level that ensures the required service life of insulating structures which is of 20–30 years or more [9; 10]. The main patterns of aging of insulation and methods of its preventive testing are considered in [11–13].

During operation, following the transmission of various types of energy to electrical insulation, a significant change in its initial properties occurs. There are the following types of insulation aging: electrical, mechanical, and thermal aging. Besides, the current state and intensity of aging processes can be significantly influenced by the external environment, high humidity, and pollution.

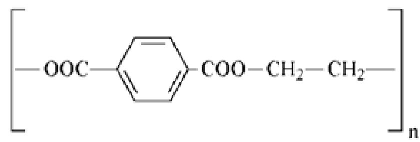
It is known that electrical breakdown of solid dielectrics occurs mainly for the following reasons [13]:

1) *mechanical – mechanical destruction, namely development of microcracks that weaken dielectric strength*. In order to increase operational reliability of TEM, high mechanical properties of insulating materials of the pole and armature windings must be ensured, which are necessary to maintain the dielectric strength of the insulation, frost resistance and heat resistance both during manufacture of TEM and during long-term operation, when windings are exposed to the influence of contrasting temperatures, significant centrifugal and electrodynamic influences, shaking, vibrations and shocks [14];

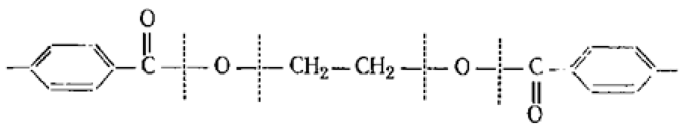
b) *thermal – a change in properties and structure of a dielectric, an increase in thermal conductivity*. Thermal processes play a decisive role in changing the properties and features of elements, in the process of their destruction and aging. The rates of thermal aging of insulation are determined by the rates of chemical reactions, depending on temperature. The service life of dielectric exposed to thermal aging is generally believed to be inversely proportional to the rate of chemical reactions, which are related to temperature by the Arrhenius equation. This results in the Montzinger rule (the rule of eight degrees) [14].

c) *electrical – impulse overvoltage, ionization followed by the process of ejection of electrons from atoms, molecules, and ions*. When the dielectric material is in a high-temperature field, partial decomposition of the material occurs, which is the more intense, the higher is the temperature. Over time, there is a gradual increase in porosity of the insulating material. This leads to appearance of local electrical inhomogeneities, which affect the change in the local dielectric constant (permittivity), which, in turn, leads to occurrence of local overvoltage when an alternating electric field is applied to the insulating material [14].

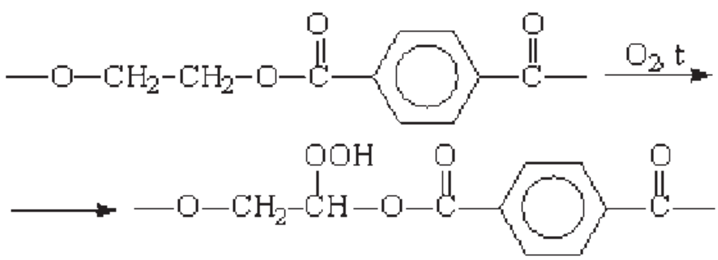
Analysis of data on TEM failures showed that thermal aging during operation has the



Pic. 1. Structural formula of polyethylene terephthalate polymer film.



Pic. 2. Homolytic (radical) rupture of C-O bonds of a film made of polyethylene terephthalate polymer.



Pic. 3. Thermal oxidative destruction of polyethelene terephthalate.

greatest negative effect on strength of the turn insulation of windings. In works [15; 16] the authors point out that «many physicochemical processes associated with occurrence of failures in coil insulation are thermally activated processes, i.e. intensity of processes increases with increasing temperature». At the same time, destruction of TEM insulating material through appearance of porosity and cracking, is due to the effect of mechanical loads, in particular, vibration.

Considering the mechanisms of decomposition of the electrical insulation material of traction electric motors of NB-418K6 type, it was found that the cause of electrical breakdown of traction electric motor windings is thermal and thermal oxidative destruction, leading to mechanical destruction of electrical insulation with formation of cracks in it and to carbonization (charring) of electrical insulation, which is accompanied by a sharp drop in its electrical resistance.

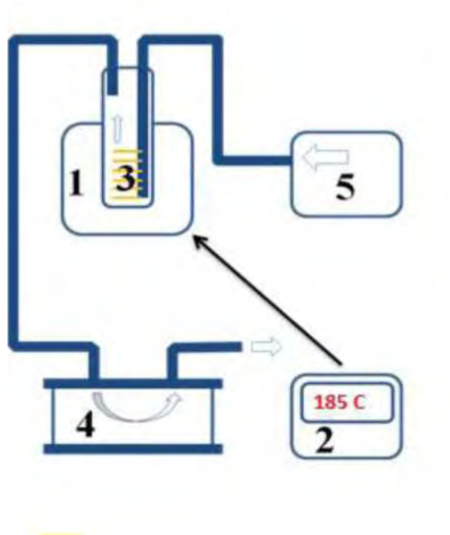
Electrical insulation of Elmikaterm-524019 type, used in NB418-K6 traction motors, is a composition consisting of mica paper (28 % by weight), glass fiber cloth and polyethylene terephthalate film (together 32–52 % by weight), glued together and impregnated with electrical insulating varnish or a compound (20–40 % by weight). Its organic component suffers first of all in case of its thermal and thermal oxidative destruction.

The basis of Elmikaterm-524019 electrical insulation is a film made of polyethylene terephthalate (lavsan) polymer (Pic. 1).

During heating, there is mainly a homolytic (radical) rupture of C-O bonds, as the least strong (Pic. 2).

The process of thermal oxidative destruction of polyethylene terephthalate proceeds intensively at temperatures of 170–220°C. The presence of air contributes to significant destruction of insulation, which is accompanied by yellowing and intense release of such gaseous products as acetaldehyde, carbon monoxide and carbon dioxide (Pic. 3).

The IR spectrum of the emitted volatile products contains compounds with C-O bonds – ethers and esters, acids, aldehydes, acetals. It is the appearance of these compounds




***Pic. 4. Temperature-controlled attachment for the study of gaseous products from an insulating material with a calibration cuvette.***

in the IR spectrum that indicates beginning of destruction of polymer electrical insulation, and their disappearance shows its complete destruction. Studies have shown that compounds with such groups during thermolysis of the considered electrical insulation can be observed in the IR spectrum in the following wave number ranges:

• C=O (ester, acidic) – 1770–1680 $cm^{-1}$ (a system of overlapping peaks is observed in this area);

• C-O (ethers and esters, acids, acetals) – 1300–1000 $cm^{-1}$ (peaks are observed at 1038, 1065, 1125, 1155, 1169, 1241, 1295);

• deformation vibrations of C–C bonds of aromatic rings – 2000–1667 (a system of weak peaks is observed) and 900–690 $cm^{-1}$ (740, 812, 877);

• compounds with bonds, H-C = (for example, ethylene) – 1000–800 $cm^{-1}$ (there is a peak at 937 $cm^{-1}$);

• compounds with C = C bonds – 1500–1700 $cm^{-1}$ (at the early stages of heating, there are series of intense peaks).

Based on the results of the analysis of the currently existing technical means, it has been established that there are currently no simple optical sensors for acetaldehyde, methyl-dioxolane and other indicated compounds operating under conditions of a dense background of vapors of other organic compounds. The service life of existing industrial electrochemical sensors will be extremely short as a result of a chain of specific chemical reactions in the atmosphere of a gas released from the heated insulation of a traction motor that operates in real conditions of pollution from decomposition of petroleum products, which contributes to their intensive failure.

Thus, it is advisable to proceed with the analysis of the IR spectrum of emitted volatile products during thermal and thermooxidative destruction of electrical insulation using a specialized infrared IR interferometer tuned to frequency from within the set of the above analytical vibrations, and adapted also to sampling.

Based on the results of the studies carried out, the required selectivity of analysis in the IR wavelength range was established. In all experiments with analytical tasks, an identical measurement technique was used, which provides for introduction of a gaseous sample into a gas cell, after its preliminary pumping with clean air for 30 minutes. This made it possible to avoid the influence of the atmosphere from previous measurements on subsequent series of experiments.

The device began each new measuring in the same starting state. This state was monitored by a test recording of the IR spectrum of an empty cuvette with air pumping through the empty reactor of the furnace. When the result of initial control of the cuvette atmosphere was satisfactory, a sample was introduced into the reactor chamber (Pic. 4), and a series of spectra were recorded.

The spectra were recorded in the mid-IR range of 5000–350 $cm^{-1}$, which is the most informative for studying the molecular structure of organic compounds. The selected spectral resolution of 2 $cm^{-1}$ is standard for most studies of this type and is determined to be optimal in trial measurements.

Based on the results of the measurements obtained during the described studies, it was found that thermal decomposition of organic compounds that make up the considered insulating material, accompanied by parallel thermolysis of substances contaminating the outer shell of TEM windings, has a rather complex kinetics with formation of a large number of different products in the gas phase. It is advisable to determine wear category of the insulating material by the method of IR spectrophotometry according to relative transmittance of electromagnetic radiation in the gas atmosphere, removed from TEM winding. The research results confirmed that measurements can be carried out according to the developed method, the analytical part of which is based on assessment of relative intensity of the absorption peak with a maximum in the range of 1150–950 $cm^{-1}$, corresponding to excitation of simple vibrations C-O in the most important thermolysis products of polymer electrical insulation which are ethers and esters, carboxylic acids, acetals.

To determine the effect of the degree of wear of the insulation of TEM NB-418K6 windings on intensity of the total volume of gas emissions, including carbon dioxide emissions, samples of insulating material from the main poles of different NB-418K6 traction motors of electric locomotives were studied, Samples comprised K-20 lavsan film and Elmicatherm mica film with dimensions 0,1 x 20 and 0,13 x 30.

Based on the spectra of all samples, it was concluded that emission of carbon dioxide following heating sequentially increased due to initiation of the oxidation process of organic compounds included in all samples. In this case, the lower is the degree of insulation wear, the greater is the total volume of gas emission. It should be noted that a large amount of water vapor was released by the material of all samples at the operating temperature, and it corresponded to spectral regions with a large number of narrow lines with centers near 3800 $cm^{-1}$, 1600 $cm^{-1}$.

To identify the characteristic control component, experiments were carried out to determine composition of contaminating inclusions in emanating gases of the insulation of TEM windings. When comparing the results of measurements of samples of contaminated samples and a sample with working insulation from a new engine, it was found that the main regularities in the change in intensities of lines and absorption bands are stably maintained. However, appearance and growth of intensity of new absorption lines is noted, primarily in the range of 740–1000 $cm^{-1}$, which is associated with appearance of substituted benzene derivatives in the gas phase during thermolysis of hydrocarbons that are part of lubricating oils. The products of insulation and dirt thermolysis, similar in chemical nature, do not make it possible to use the 740 $cm^{-1}$ area as an analytical one, i.e. the 740 $cm^{-1}$ band is not suitable for assessing the insulation service category under real conditions.

The conducted experimental studies allowed to reveal that only a wide multicomponent band in the region of 1150–950 $cm^{-1}$ with a maximum near 1090 $cm^{-1}$ is the most informative and resistant to overlapping with absorption lines of dirt in the applied frequency range of IR radiation. The shape of this band is far enough away from the parasitic intense absorption lines associated with appearance of pollution.

The analysis of relative intensity of the absorption band of a gas atmosphere at 1090 $cm^{-1}$ from insulation samples with different degrees of wear indicates that the position of the maximum of this band and its intensity indicate the state of the material. In the new material, relative intensity of this band is maximal, and its center is slightly shifted to the low-frequency region, to a value of 1070 $cm^{-1}$. If there is a fault in the insulation, intensity of this band is low and it is hardly distinguishable at the background level, i.e. it is absent. In the spectrum of a sample with pre-breakdown or contaminated insulation, intensity has a similar relative intensity, but gets a slightly different ratio of the right and left components – 1080 and 1120 $cm^{-1}$. Based on the analysis of experimental data, it was found that the intensity of the absorption band of gas atmosphere can be used to identify an engine which is not a new one but is still in working condition.

**Conclusions**

Thus, based on the results of measurements obtained during performance of the described studies, it can be concluded that thermal decomposition of organic compounds that make up the insulating material, accompanied by parallel thermolysis of substances contaminating the outer shell of TEM windings, has a rather complex kinetics with formation of a large number of different products in the gas phase. For qualitative determination of wear category of the insulating material, it is advisable to use the method of IR spectrophotometry based on relative transmittance of electromagnetic radiation in the gas atmosphere removed from TEM winding. An informative measurement should be carried out according to the developed method, the analytical part of which is based on assessment of relative intensity of the absorption peak with the maximum in the range of 1150–950 $cm^{-1}$, corresponding to excitation of simple vibrations C-O in the most important thermolysis products of polymer electrical insulation which are ethers and esters, carboxylic acids, acetals.

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