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METHODS AND MEANS OF IMPROVING THE EFFICIENCY OF TRACTION MOTOR OPERATION

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МЕТОДИ ТА ЗАСОБИ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ЕКСПЛУАТАЦІЇ ТЯГОВИХ ДВИГУНІВ

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Abstract. *The efficient operation of locomotive traction motors is one of the key factors in the reliability, energy efficiency, and cost-effectiveness of rail transport. With the growth in transport volumes, increased speeds, more complex track profiles, and an aging locomotive fleet, the issue of ensuring stable and reliable operation of traction electric machines is becoming particularly relevant. Traction motors operate in difficult operating conditions characterized by significant mechanical, electromagnetic, and thermal loads, as well as uneven operating modes, which negatively affects their service life and performance.*

The current development of power electronics, control systems, materials science, and information technology creates the conditions for the introduction of new methods and means of improving the efficiency of traction motors. At the same time, the practical implementation of such

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solutions requires a thorough analysis of the operating conditions of traction electric machines, systematization of existing approaches to energy conservation, improvement of reliability and durability, as well as assessment of the capabilities of modern means of technical diagnostics and monitoring of technical condition.

The object of the study is the operational electromagnetic, thermal, and energy processes that occur in locomotive traction motors during their operation in real operating conditions. The work reviews and summarizes methods and means of improving the efficiency of locomotive traction motors, taking into account real operating factors. The influence of load modes, thermal processes, and the nature of interaction with power converters and control systems on the operational performance of traction motors is analyzed. Modern methods of optimizing operating modes aimed at reducing electrical and mechanical losses, improving thermal conditions, and increasing efficiency are considered. Special attention is paid to reviewing technical diagnostics and monitoring tools for traction motors, in particular systems for continuous monitoring of temperature, currents, vibrations, and insulation parameters. It is shown that the introduction of such means allows to implement the concept of operation based on technical condition, to detect defects in a timely manner, to predict the remaining resource and to reduce the probability of emergency failures.

Keywords: *traction motor, locomotive, operational efficiency, electric machine, energy efficiency, resource.*

Анотація. *Ефективна експлуатація тягових двигунів локомотивів є одним із основних чинників надійності, енергоефективності та економічності роботи залізничного транспорту. В умовах зростання обсягів перевезень, підвищення швидкостей руху, ускладнення профілю колії, старіння локомотивного парку проблема забезпечення стабільної та безвідмовної роботи тягових електричних машин набуває особливої актуальності. Тягові двигуни працюють у складних експлуатаційних умовах зі значними механічними, електромагнітними і тепловими навантаженнями, а також нерівномірністю режимів роботи, що негативно позначається на їхньому ресурсі та експлуатаційних показниках.*

Сучасний розвиток силової електроніки, систем керування, матеріалознавства та інформаційних технологій створює передумови для впровадження нових методів і засобів підвищення ефективності експлуатації тягових двигунів. Водночас практична реалізація таких рішень потребує ґрунтовного аналізу умов роботи тягових електричних машин, систематизації існуючих підходів щодо енергозбереження, підвищення надійності та довговічності, а також оцінювання можливостей сучасних засобів технічної діагностики і моніторингу технічного стану.

Об’єктом дослідження є експлуатаційні електромагнітні, теплові та енергетичні процеси, що відбуваються в тягових двигунах локомотивів під час їхньої роботи в реальних умовах експлуатації. У роботі оглянуто і узагальнено методи і засоби підвищення ефективності експлуатації тягових двигунів локомотивів з урахуванням реальних експлуатаційних чинників. Проаналізовано вплив режимів навантаження, теплових процесів, характеру взаємодії із силовими перетворювачами та системами керування на експлуатаційні показники тягових двигунів. Розглянуто сучасні методи оптимізації режимів роботи, спрямовані на зниження електричних і механічних втрат, покращення теплового стану та підвищення коефіцієнта корисної дії. Окрему увагу приділено огляду засобів технічної діагностики і моніторингу стану тягових двигунів, зокрема систем безперервного контролю температури, струмів, вібрацій і параметрів ізоляції. Показано, що впровадження таких засобів дає змогу реалізувати концепцію експлуатації за технічним станом, своєчасно виявляти дефекти, прогнозувати залишковий ресурс і знижувати ймовірність аварійних відмов.

Ключові слова: *тяговий двигун, локомотив, ефективність експлуатації, електрична машина, енергоефективність, ресурс.*

Relevance of the research topic. The relevance of research in the field of improving the efficiency of locomotive traction motors is due to the growing demands for energy efficiency, reliability, and environmental friendliness of rail transport. A significant portion of the locomotive fleet is operated under conditions of increased loads and physical wear, which leads to increased maintenance and repair costs. At the same time, energy losses in traction electric machines significantly affect the cost of transportation. Modern methods of control, diagnostics, and monitoring open up new opportunities for improving the efficiency of traction motors, but require systematic analysis and generalization. In this context, a review of existing methods and tools is a necessary step in forming scientifically sound recommendations for their practical implementation.

Introduction. The effective functioning of rail transport is directly related to the technical condition and operational characteristics of locomotives, which ensure the implementation of the transportation process. Managing the technical condition of a locomotive covers all stages of its life cycle (Fig. 1).

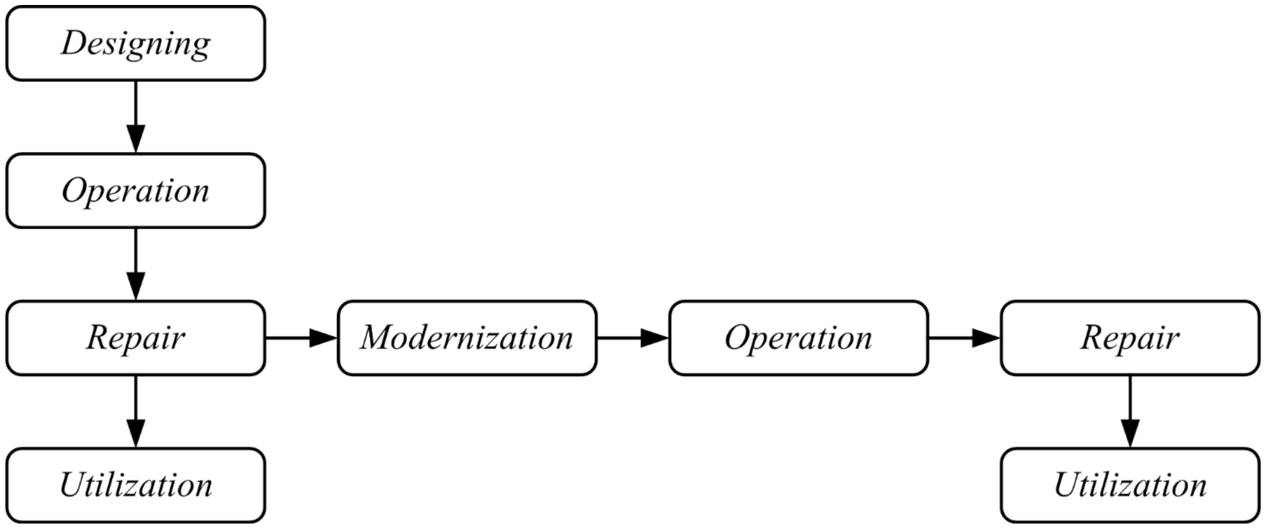

Fig. 1. Locomotive life cycle structure [1]

At the design stage, resources and reliability indicators are established through the selection of technical and technological solutions. The main stage of the life cycle is operation, during which external and internal factors cause a gradual deterioration in technical condition and resource depletion. To ensure the necessary level of reliability during operation, technical diagnostic tools are used both during operation and during maintenance. The final stage of the life cycle is repair, during which the technical condition of the locomotive is restored or improved.

One of the most important elements of locomotive power equipment is traction electric motors, which convert electrical energy into mechanical energy and generate the traction force necessary for train movement. The energy performance of locomotives, their operational readiness, and maintenance costs depend largely on the reliability, efficiency, and durability of traction motors.

During operation, traction motors work in difficult and variable conditions characterized by significant load fluctuations, frequent start-stop modes, external environmental influences, vibrations, and mechanical shocks [2]. Such conditions lead to increased thermal loads, increased electrical and mechanical losses, aging of insulation, and wear of structural elements. Prolonged overloads and uneven operating modes, which are characteristic of modern traction rolling stock operating conditions, have a particularly negative impact on the service life of traction motors [3, 4].

An important aspect of improving the efficiency of traction motors is reducing energy consumption. Electricity accounts for a significant portion of railway transport operating costs, so even a slight increase in the efficiency of traction electric machines can provide significant economic benefits. In this regard, it is important to apply modern methods of optimizing the operating modes of traction motors aimed at reducing losses in copper, steel, and mechanical components.

In addition to energy aspects, it is important to ensure a high level of reliability and fault-free operation of traction motors. The operational reliability of traction electric machines is a key parameter determining the efficiency and continuity of modern locomotive rolling stock [5]. Failures of traction electric machines lead to locomotive downtime, disruption of traffic schedules, and additional repair costs [6, 7]. Traditional approaches to maintenance based on scheduled intervals do not always allow for timely detection of defects and optimal use of motor resources.

The development of digital technologies, microprocessor control systems, and sensor devices creates the conditions for the implementation of technical diagnostics and real-time monitoring systems for traction motors [8, 9]. Such systems allow implementing the concept of operation based on actual technical condition, which contributes to increased reliability, reduced maintenance costs, and extended service life of traction electric machines [10].

Due to the diversity of existing methods and means of improving the efficiency of traction motors, there is a need for their systematization and critical analysis. The review study allows us to summarize existing scientific and practical achievements, identify the most promising areas of development, and form a basis for further applied research and implementation.

Analysis of recent research and publications. Article [11] analyzes control systems for traction asynchronous motors of electric locomotives in various operating modes. The study was aimed at improving operational efficiency by optimizing algorithms for controlling the current and electromagnetic torque of motors. Mathematical modeling of the traction electric drive was applied, taking into account changes in load and driving modes. The possibility of reducing energy losses by improving the control system is shown. The disadvantage of the work is the lack of analysis of the impact of aging, insulation defects, and real long-term operating conditions.

In [12], the effectiveness of adaptive methods for filtering higher harmonics of stator currents in a vector control system for traction drives was investigated with the aim of improving the energy efficiency of electric rolling stock. It is proposed to introduce an adaptive filtering block into the basic vector control system using the first harmonic component of the current as the desired signal, and an algorithm for its determination at variable supply frequency has been developed. The simulation results show that the Wiener filter provides the highest efficiency and convergence speed among the adaptive algorithms considered, which allows reducing losses from higher harmonics in the traction drive. The limitation of the study is that the results obtained are based mainly on modeling and do not fully take into account the influence of real operational factors and experimental verification on real electric rolling stock.

Article [13] discusses a method for improving the energy efficiency of a multi-motor traction electric drive in a locomotive.

The study aims to optimize operating modes by disconnecting some of the traction motors at reduced loads. A mathematical model is proposed that allows estimating the reduction in energy losses in such modes. The potential energy savings during operation are shown. The disadvantage of the work is the lack of assessment of the impact of frequent motor switching on their service life and reliability.

Review scientific papers [14–17] are devoted to the study of operating conditions, operating modes, and areas for improvement of locomotive traction motors, with an emphasis on the use of brushless electric machines. The works consider the peculiarities of traction motor loads under different locomotive operating modes, which determine the requirements for their reliability and durability. Considerable attention is paid to analyzing the efficiency of modern control systems for brushless traction motors and their impact on the energy performance of traction rolling stock. The specifics of integrating brushless motors into locomotive traction drives are highlighted, taking into account design and operational factors. The main problems of introducing such motors are outlined separately, as well as promising areas for their further development and application in rail transport.

Scientific articles [18–21] are aimed at improving energy efficiency and improving locomotive traction motor control systems based on the use of pulse converters and modern control algorithms. The works consider the issues of reducing energy losses and improving electromagnetic modes by optimizing pulse width modulation, which makes it possible to reduce current ripple and associated losses in traction motors. Considerable attention is paid to the influence of power converter parameters and their discrete nature on dynamic processes in automatic control systems, in particular armature current. The proposed mathematical and impulse models allow for a more accurate description of transient processes and assessment of harmonic distortion, power factor, and control system response time. The results obtained are of practical value for the design of traction electric drives, as they contribute to improving the efficiency, reliability, and service life of locomotive traction motors. The limitation of the research is that the models do not take into account temperature and mechanical factors that may affect the actual operation of the converters.

In [22] a new method for predicting the condition of a high-speed train traction motor based on statistical characteristics and an improved Support Vector Regression (SVR) model is considered. The system analyzes the characteristics of the motor's temperature signals to predict failures. The prediction method proposed in this article works well, demonstrates good adaptability to different operating conditions, and is suitable for applications related to high-speed trains.

Study [23] proposes a method for clustering loads on the track to assess the fatigue life of welded traction motor structures. The method allows compressing measured data, reducing computational complexity, and taking into account the influence of stationary and non-stationary loads, which provides a basis for the design and improvement of railway structures. A limitation of the study is that the method has only been tested on a limited set of weld lines, which may not fully reflect the diversity of real operating conditions.

Article [24] discusses the technological aspects of traction motor repair. The study aims to improve the efficiency of further motor operation by reducing repair defects. The causes of defects after repair are analyzed. Measures to improve the quality of repair processes are proposed. A drawback is the lack of a direct analysis of the impact of repairs on the energy efficiency of motors.

Scientific work [25] is aimed at reviewing modern methods of improving the energy efficiency of rail transport and systematizing approaches to reducing the energy consumption of traction systems. Technical and organizational measures are considered. The work allows us to identify general development trends. A limitation is the lack of detail on methods specifically for the operation of locomotive traction motors.

Publications [26–31] are devoted to a comprehensive consideration of the problem of improving the energy efficiency of traction electric motors of locomotives and rolling stock with asynchronous electric drives. The works emphasize the need to initiate applied research aimed at improving the energy efficiency of traction motors, taking into account the actual operating modes of traction converters. Considerable attention is paid to the use of modern digital technologies for monitoring the technical condition of brushless traction motors, which creates the conditions for reducing energy losses and increasing reliability. Separate publications summarize modern technological solutions aimed at optimizing the design and operating modes of brushless machines. Ways to improve the energy efficiency of asynchronous electric drives with frequency converters are also considered. In general, the theses form a holistic vision of ways to improve the energy efficiency of locomotives based on a combination of technical, algorithmic, and digital approaches.

Summarizing the results of the analysis of the above-mentioned literary sources, it can be stated that modern research is focused mainly on improving the efficiency of locomotive traction motors by improving control systems, optimizing operating modes, and reducing energy losses. Considerable attention is paid to mathematical modeling, vector control algorithms, adaptive filtering, and the use of power converters, which allows for increased energy efficiency and dynamic performance of traction electric drives. At the same time, most studies do not sufficiently take into account real long-term operational factors, aging processes, temperature and mechanical influences, as well as the relationship between energy efficiency and the reliability and service life of motors. Individual studies demonstrate the promise of applying technical diagnostics, condition forecasting, and digital monitoring methods, but they often have a limited experimental basis. These limitations and the fragmentary nature of existing approaches necessitate a comprehensive analysis and generalization of methods and means of improving the efficiency of locomotive traction motors and identifying promising areas for their further development.

Defining the purpose and objectives of the research. The purpose of the article is to review, systematize, and analyze modern methods and means of improving the efficiency of locomotive traction motors, taking into account their operating conditions, energy efficiency, reliability, and technical diagnostic capabilities, which will make it possible to identify the most promising scientific approaches, form a generalized concept for improving operational efficiency, and outline directions for further research in the field of traction electric drives. To achieve this goal, the following tasks were set:

– analyze and summarize scientific approaches to describing the operational processes in locomotive traction motors that determine their energy efficiency, reliability, and service life;

– review and systematize modern methods for improving the efficiency of traction motors, which are applied at the stage of controlling operating modes and organizing technical operation;

– to study existing technical diagnostic and monitoring tools for traction motors in terms of their informativeness, ability to detect defects early, and support for operational decision-making;

– to identify promising areas for further development of methods and tools to improve the operational efficiency of locomotive traction motors.

The main part of the research

Scientific approaches to describing operational processes in locomotive traction motors. Locomotive traction motors operate under conditions of significant load variation, external climatic factors, fluctuations in power supply parameters, and intense mechanical and thermal loads [32, 33]. Taken together, this determines the complex nature of operational processes, which directly affect the energy efficiency, reliability, and service life of traction electric motors. The scientific description of such processes requires the application of a set of complementary approaches, each of which reflects a separate aspect of the functioning of an electric machine in real operating conditions.

The electromagnetic approach is fundamental in the study of traction motors and is based on the analysis of electromechanical energy conversion processes. This approach uses mathematical models based on electrical circuit equations, Maxwell's equations, and electrical machine theory, which allow describing the formation of electromagnetic torque, the distribution of magnetic fluxes and currents in windings [34, 35]. Particular attention is paid to the analysis of energy losses, in particular copper losses in the armature and excitation windings, losses in the magnetic circuit steel, as well as additional losses caused by the presence of higher harmonics of current and voltage [36]. Under real operating conditions for locomotives, these harmonics arise as a result of the operation of power converters, uneven loads, and transient modes, which negatively affect the efficiency of traction motors. The electromagnetic approach allows establishing dependencies between locomotive operating modes, power supply system parameters, and motor energy performance [37, 38]. Based on such models, energy efficiency in traction and braking modes is assessed, and the conditions for the occurrence of overloads and local saturations of the magnetic circuit, which can lead to increased thermal and mechanical loads, are analyzed.

The thermal approach is aimed at studying the processes of heat generation and heat transfer in traction motors, which are a direct consequence of electrical and mechanical losses [39, 40]. Temperature is one of the key factors determining the reliability and durability of an electric machine, as overheating leads to accelerated aging of insulation, reduced material strength, and increased likelihood of failure. Within the thermal approach, thermal equivalent circuits, thermal resistance and heat capacity models, as well as numerical methods for analyzing temperature fields are used. Such models allow for the uneven distribution of temperatures in various structural elements of the traction motor, in particular in the windings, slot insulation, core, bearings, and cooling system [41, 42]. Of particular importance is the analysis of non-stationary thermal processes that occur during frequent starts, braking, and changes in traction modes. If an electric machine is operated in continuous mode with variable load P_j (Fig. 2), a non-stationary thermal process occurs in it, caused by the fact that at separate time intervals t_j different levels of power losses and, accordingly, different intensities of heat generation occur. Under such conditions, the temperature state of the machine is determined by the thermal inertia of its structural elements and the ratio between electrical, magnetic, and mechanical losses, which vary over time and must be taken into account during thermal calculations and the assessment of permissible operating modes.

It is under these conditions that local overheating zones can form, which are not detected by traditional control methods but significantly affect the motors service life [44]. The thermal approach allows us to justify acceptable load modes and develop recommendations for improving the efficiency of cooling systems.

The mechanical-dynamic approach focuses on analyzing the force and vibration processes that occur in traction motors during the transmission of torque to wheel sets. Within this approach, dynamic loads on the shaft, bearing assemblies, fasteners, and gear transmissions are studied, as well as the conditions for the occurrence of resonance phenomena. Particular attention is paid to the analysis of vibrations caused by uneven electromagnetic torque, rotor eccentricity, bearing wear, and balancing defects [45–47]. Vibration processes not only worsen the mechanical condition of the motor, but also contribute to the accelerated destruction of insulation and contact connections [48]. The mechanical-dynamic approach allows establishing a connection between locomotive operating modes and the intensity of mechanical element wear [49]. Based on such studies, limit state criteria are formed, which are used to predict service life and prevent emergency failures.

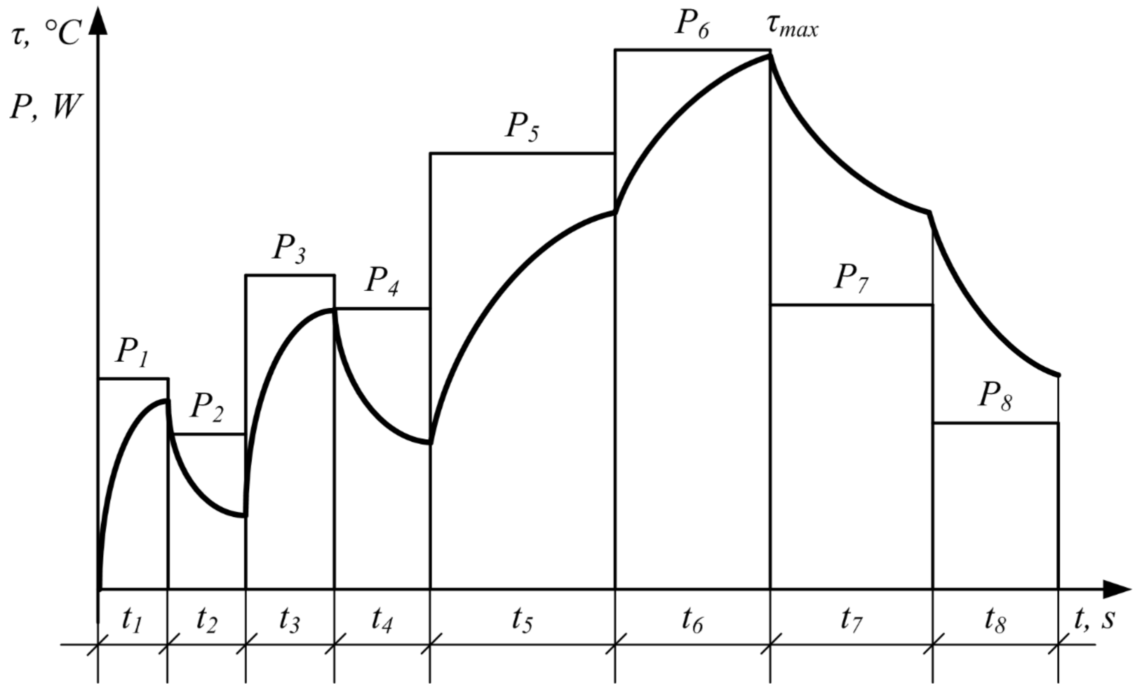

Fig. 2. Nature of motor temperature change with load variation [43]

The insulation degradation approach aims to describe the processes of aging and destruction of electrical insulation of traction motors during long-term operation [50]. Insulation is subject to the combined influence of thermal, electrical, mechanical, and climatic factors, the effects of which are cumulative. Within this approach, physicochemical and kinetic models of insulation material degradation are used to quantitatively describe the decrease in electrical strength, elasticity, and adhesive properties over time [51, 52]. Considerable attention is paid to the impact of repeated thermal cycles, overvoltages, and partial discharges, which are typical for traction motor operation [53, 54]. The insulation degradation approach is the basis for assessing residual life and justifying maintenance and repair schedules.

The probabilistic-statistical approach allows for the random nature of operational loads and traction motor failures to be taken into account. It is based on the analysis of operational statistics, diagnostic measurement results, and defect data. This approach uses methods from reliability theory, statistical analysis, and stochastic modeling to determine the probability of failure-free operation, failure rate, and mean time between failures [55, 56]. The results are used to optimize maintenance and repair strategies.

The current stage of research development is characterized by a transition to integrated multiphysics models (integrated multiphysics approach), which combine electromagnetic, thermal, mechanical, and degradation processes [57–59]. This approach allows for a comprehensive assessment of the operational condition of traction motors and the identification of critical modes that determine the limits of energy efficiency, reliability, and service life.

Table 1 presents a comparison of scientific approaches to describing operational processes in locomotive traction motors.

Table 1

Comparison of scientific approaches to describing operational processes in locomotive traction motors

Approach	Scientific essence	Operational processes described	Typical models and methods	Advantages of the approach	Main restrictions	Practical application in traction motors
1	2	3	4	5	6	7
Electromagnetic	The motor is considered as an electro-magnetic energy conversion system with a description of fields, currents, and torque	Electromagnetic losses, traction torque, current overloads, traction and recuperation modes	Equations of electric machines in dq co-ordinates, equivalent circuits, FEM analysis of magnetic fields	Fundamental basis of electrical machine theory, high accuracy for electromagnetic modes	Does not take into account the aging of insulation and mechanical wear	Analysis of traction characteris-tics, optimization of electromagnetic design and control modes
Thermal	An motor is described as a thermal energy system with sources of loss and heat transfer processes	Heating of windings, thermal aging, local overheating, load restrictions	Thermal equivalent circuits, heat conduction equations, CFD cooling simulation	Allows you to evaluate temperature conditions and insulation life	Requires accurate data on losses and heat exchange	Calculation of permissible traction loads, design of cooling systems
Mechanical-dynamic	The motor is considered as an element of a mechanical system, taking into account the dynamics of rotation and vibrations	Impact loads, vibrations, resonance phenomena, bearing wear	Rotor motion equations, torsional vibration models, vibration signal analysis	Enables assessment of mechanical reliability and dynamic limitations	Does not describe electromagnetic processes without reference to other models	Analysis of motor operation under traction shocks, diagnosis of bearing defects
Insulation degradation	The main focus is on the aging of the insulation	Thermal aging, partial discharges, enamel	Aging models, partial discharge	Directly related to the traction	Requires experimental basis and	Forecasting the service life of windings,

Continuation of the tables 1

1	2	3	4	5	6	7
	system under the influence of temperature, electrical, and mechanical factors	degradation, insulation breakdown	analysis, insulation testing	motor resource	diagnostic data	monitoring insulation in locomotive operation
Probabilistic-statistical	Operational processes are described as random variables with failure risk assessment	Failure rate, damage statistics, component reliability	Reliability theory, Weibull distributions, statistical analysis methods	Provides a quantitative assessment of reliability and failure prediction	Depends on the volume of operating statistics	Maintenance planning, life cycle assessment of traction machines
Integrated multiphysics	The motor is modeled as an interconnected electromagnetic-thermal-mechanical system, taking into account degradation.	Complex operational phenomena: heating + vibrations + aging + electromagnetic overloads	Coupled FEM (EM + thermal + stress), digital twins, multi-domain models	The most complete reflection of real operating conditions	High complexity and need for large computing resources	Modern systems for predicting the condition of traction motors, optimizing design and operating modes

Thus, scientific approaches to describing operational processes in locomotive traction motors are based on a comprehensive analysis of electromagnetic, thermal, mechanical, insulation, and probabilistic processes. Each of the approaches considered reflects a separate component of the functioning of traction electric motors, but only their integrated application allows for an adequate assessment of real operating conditions. Electromagnetic and thermal processes directly determine the level of energy efficiency, while mechanical and insulation processes determine reliability and durability indicators. Probabilistic and statistical methods ensure that the random nature of loads and failures is taken into account. The use of multiphysics models provides a scientific basis for developing effective diagnostic methods, optimizing operating modes, and implementing condition-based maintenance, which is key to increasing the service life and operational efficiency of locomotive traction motors.

Modern methods for improving the efficiency of traction motors. The efficiency of traction motors in modern transport systems is influenced by a combination of interrelated factors, among which the methods of controlling their operating modes and the principles of technical operation play a leading role [60]. In practical terms, these components cannot be considered in isolation, since control parameters directly determine wear intensity, thermal loads, and motor reliability, while the maintenance system, in turn, affects permissible operating modes and the stability of electromechanical characteristics. That is why it is advisable to consider modern methods of improving the efficiency of traction motors as a single scientific and technical direction.

During operation, traction motors implement a wide range of electromechanical modes, including start-up, acceleration, steady motion, transient processes during load changes, and various types of electrical braking. Each of these modes is characterized by specific values of currents, voltages, electromagnetic moments, and temperatures, which determine the level of energy losses and the rate of degradation of structural elements. From a scientific and practical point of view, improving operational efficiency involves establishing operating modes that minimize total energy losses while limiting thermal and mechanical stresses [61, 62].

Start-up and transition modes are particularly important, as these are the moments when maximum electrical and thermal loads occur. Reasonable limitation of starting currents, control of the rate of increase of electromagnetic torque, and optimization of the dynamic characteristics of the electric drive make it possible to reduce local overheating of windings and mechanical shocks in transmission elements [63]. In steady-state operating modes, efficiency is increased by maintaining motor operation in ranges close to the nominal or optimal operating mode in terms of efficiency, which is confirmed by both theoretical models of electric machines and the results of operational observations [64, 65].

The introduction of vector control systems (Fig. 3), which provide separate regulation of the current components responsible for creating magnetic flux and electromagnetic torque, has made a significant contribution to improving efficiency.

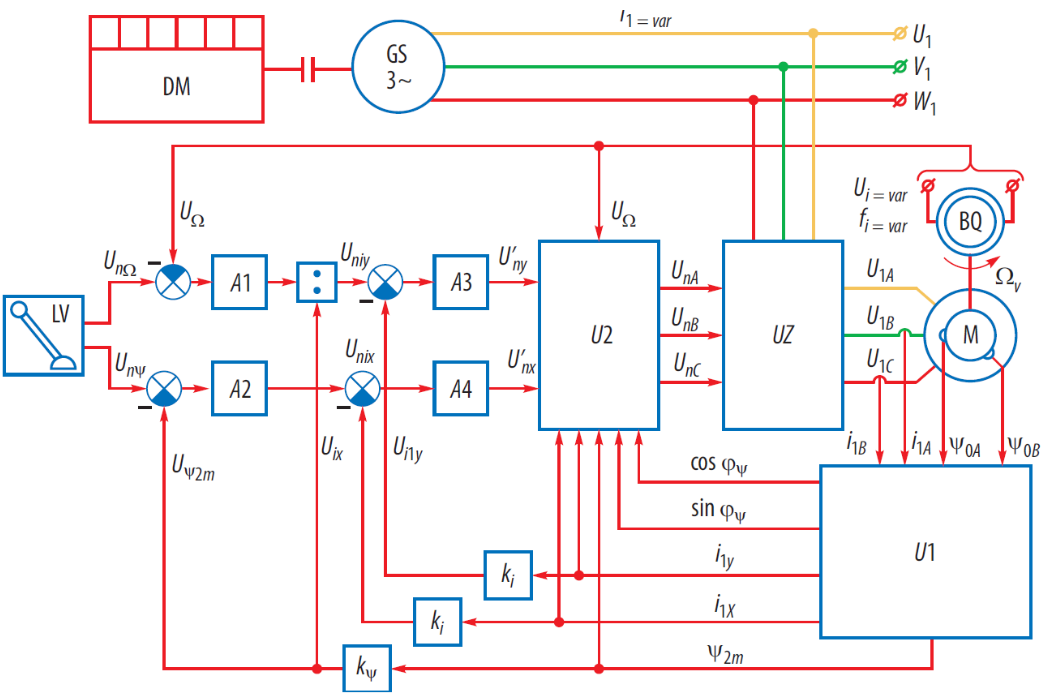

Fig. 3. The structural scheme of ATM vector control [66]:
GS – traction generator; *UZ* – frequency converter; *M* – asynchronous traction motor;
U1, *U2* – coordinate changing units; *A3*, *A4* – regulators of current vector components;
A1 – speed regulator; *A2* – rotor magnetic field regulator;
BQ – sensor of rotor speed and position (encoder)

This approach allows for more precise adaptation of the traction motor's operation to changing traffic and load conditions, reducing the additional losses characteristic of traditional control methods [67, 68]. The further development of these systems is associated with the use of parametrically adaptive algorithms that take into account changes in the electrical and magnetic parameters of the motor due to heating, saturation of the magnetic circuit, and prolonged operation. Real-time adaptation of control parameters ensures stability of electromechanical characteristics and reduction of energy losses throughout the entire service life of the motor [69, 70].

An important area is the energy optimization of electric braking modes, primarily regenerative braking. Switching the traction motor to generator mode allows part of the kinetic energy of the rolling stock to be returned to the energy system or storage devices [71, 72]. The efficiency of recuperation is determined by the coordination of the control algorithms of the motor, power converters, and contact network parameters [73]. Scientifically based control of regenerative braking not only reduces overall energy consumption, but also reduces thermal loads on windings and mechanical braking systems, which has a positive effect on motor life.

The implementation of complex control algorithms is impossible without advanced monitoring systems that provide continuous control of currents, voltages, temperatures, speeds, and vibrations. The data obtained in real time is used for operational correction of operating modes in order to prevent overloads and parameters from exceeding acceptable limits [74]. This approach is in line with the modern concept of condition-based management, where permissible operating modes are determined not only by the specifications, but also by the actual condition of the motor.

A logical extension of operating mode control is the rational organization of the technical operation of traction motors. Practice shows that traditional planned preventive maintenance systems do not always ensure optimal resource utilization, as they do not take into account individual operating conditions and uneven wear [75]. In this regard, it is scientifically and practically justified to switch to condition-based maintenance, which is based on the results of diagnostic measurements and analysis of operational data.

Electrical, thermal, and vibration diagnostics methods allow detecting the initial stages of defects in windings, bearing assemblies, insulation, and other critical elements. Timely intervention in the early stages of damage development significantly reduces the likelihood of sudden failures and emergency stops, which is confirmed by the results of operating modern electric rolling stock [76, 77]. Thus, diagnostics based on actual condition is directly related to the possibility of implementing more intensive but safe motor operating modes.

One of the determining factors for the durability of traction motors is their thermal regime. Exceeding permissible temperatures leads to accelerated aging of insulating materials and deterioration of electromechanical characteristics. Therefore, modern technical operation involves not only temperature control, but also active optimization of cooling systems, cleaning of ventilation ducts, and the use of thermal models to predict temperature processes in different operating modes [78, 79]. This allows the thermal state of the motor to be maintained within acceptable limits even under increased loads.

A comprehensive approach to the operation of traction motors also involves managing their service life and reliability based on an analysis of failure statistics, operating conditions, and diagnostic results [80]. The accumulation and processing of operational information using technical condition management information systems creates the conditions for predicting residual life and optimizing maintenance and repair schedules. This results in a rational balance between reliability, energy efficiency, and economic costs.

Organizational and personnel factors play an important role in the implementation of the methods discussed. The complexity of modern control and diagnostic systems requires a high level of staff training, standardization of technical operation procedures, and unification of technical documentation [81]. Operational practice shows that a combination of technical and organizational measures is a prerequisite for fully utilizing the potential of modern methods for improving the efficiency of traction motors.

Thus, modern methods for improving the efficiency of traction motors are based on a comprehensive combination of optimized control systems for operating modes and technical operation. The use of vector and adaptive control, regenerative braking, and real-time monitoring systems reduces energy losses and stabilizes thermal loads. The transition to maintenance based on actual condition and the use of modern diagnostic methods allow for more rational use of motor resources, increasing their reliability, energy efficiency, and economic feasibility of operation.

Technical diagnostics and monitoring tools for traction motors. Traction electric motors are among the most critical components of traction rolling stock, as they provide traction force, determine the energy efficiency of the transport process, and directly affect the level of reliability and safety of operation. Traction motors operate under complex and variable loads, frequent starts and stops, power supply fluctuations, external climatic factors, and gradual aging of insulation and structural materials. Under such conditions, even minor deviations in parameters can lead to the development of hidden defects that do not manifest themselves in the form of failures for a long time, but cause degradation of the technical condition and reduction of the motor's service life.

In this regard, the traditional maintenance system based on strictly regulated maintenance intervals is increasingly giving way to modern approaches focused on assessing the actual technical condition of equipment. These approaches are based on the use of technical diagnostics and monitoring tools that provide objective information about the condition of traction motors in real time or during specialized tests [82, 83]. The informative value of these tools is determined by their ability to record parameters that are sensitive to the development of defects, as well as their ability to interpret measured signals for the purpose of early damage detection and operational decision support.

The most common methods used in practice are electrical technical diagnostics based on the analysis of the electrical parameters of traction motors. These parameters include currents and voltages in power supply circuits, active and insulation resistance of windings, the shape and spectral composition of electrical signals, as well as the characteristics of starting and transient processes. The advantage of electrical methods is that they can be implemented without interfering with the motor design, making them suitable for continuous or periodic monitoring under operating conditions [84]. Analysis of deviations in current and voltage characteristics allows detecting phase asymmetry, interturn short circuits, malfunctions in the power supply and control systems, as well as the initial stages of insulation degradation. Frequency analysis of currents is particularly informative, as it can be used to identify characteristic harmonics arising from electromagnetic and mechanical defects before they cause emergency operating modes [85].

Along with electrical methods, thermal methods based on monitoring the temperature regimes of traction motors play an important role in the technical diagnostics system. Temperature is an integral indicator that reflects the combined effect of electrical losses, mechanical friction, and cooling system efficiency. Recording the temperature of individual components using built-in sensors, thermistors, or thermal imaging devices allows for the detection of overloads, ventilation problems, local insulation defects, and increased losses in the magnetic circuit [86, 87]. At the same time, thermal methods have certain limitations, since in the early stages of defect development, temperature deviations may be insignificant and not exceed the established permissible limits. Therefore, their effectiveness increases significantly when combined with other diagnostic methods.

High sensitivity to mechanical disturbances is provided by vibration-acoustic methods based on the analysis of oscillatory processes in traction motors. Sources of vibration can include bearing defects, rotor imbalance, shaft misalignment, loosened fasteners, and electromagnetic forces that change due to magnetic field asymmetry. Spectral analysis of vibration and acoustic signals allows not only to detect the presence of a defect, but also to identify its type and assess its stage of development [88]. This creates the conditions for predicting the remaining service life of components and planning repair measures. At the same time, the use of vibration methods requires complex equipment, high noise immunity of measurement channels, and advanced signal processing algorithms.

These approaches are supplemented by magnetic and electromagnetic diagnostic methods, which involve the analysis of magnetic fluxes, scattering fields, and changes in the electromagnetic characteristics of traction motors [89]. These methods are particularly informative for detecting defects in windings, cores, and air gaps, which do not always manifest themselves in electrical or thermal parameters at early stages. Their advantage is the possibility of non-contact control, but the practical implementation of such methods is complicated by the need to use highly sensitive sensors and complex data processing systems.

The current stage of development of technical diagnostics for traction motors is characterized by a transition from the isolated application of individual methods to the introduction of integrated monitoring systems. Such systems combine electrical, thermal, vibration, and magnetic information using digital signal processing methods, statistical analysis, and elements of artificial intelligence. The combination of diverse diagnostic features significantly improves the informative value of monitoring, reduces the likelihood of false alarms, and ensures early detection of defects [90]. An important function of such systems is to generate recommendations for operating personnel regarding optimal operating modes, maintenance schedules, and the advisability of repair measures, which effectively transforms diagnostic tools into elements of an operational decision support system.

Thus, the effectiveness of technical diagnostics of traction motors is determined by the level of informativeness of the methods used and their ability to detect defects at early stages of development. Electrical methods provide high availability and suitability for continuous monitoring, but need to be supplemented with other types of control. Thermal methods are comprehensive and effective for assessing overall technical condition, although they are less sensitive to initial damage. Vibration and acoustic methods are highly sensitive to mechanical defects and allow for resource forecasting. Magnetic methods open up additional opportunities for non-contact diagnosis of electromagnetic disturbances. The most promising direction is the use of integrated monitoring systems that combine diverse diagnostic features and enable informed operational decisions.

Promising areas for further development of methods and means to improve the efficiency of locomotive traction motors. The efficiency of modern rail transport is largely determined by the technical level and operational characteristics of the traction electric drive of locomotives, in which traction electric motors play a key role. The efficiency of traction electric motors is a multifactorial indicator that is influenced by design features, material characteristics, load modes, control systems, cooling conditions, technical condition, and maintenance organization.

Traditional approaches to improving the efficiency of traction motors were mainly based on improving individual design elements or improving the quality of maintenance. However, the current level of scientific and technological development necessitates a transition to a systematic approach that simultaneously takes into account the electromagnetic, thermal, mechanical, and information processes occurring in the traction electric drive [91].

From the perspective of electrical machine theory, the efficiency of a traction electric motor is primarily determined by its coefficient of performance, which depends on the ratio of useful mechanical power to total losses. The main components of losses include losses in the stator and rotor windings, magnetic losses in steel elements, mechanical losses due to friction and ventilation, as well as additional losses caused by higher harmonics of currents and voltages, magnetic field unevenness, and load fluctuations. In traction modes, these losses are strongly dependent on the speed of the locomotive, the weight of the train, and the track profile, which complicates the task of ensuring optimal motor operating modes [92].

The modern locomotive fleet operates using various types of traction electric motors, including asynchronous motors with squirrel-cage rotors, synchronous motors with permanent magnets, and DC commutator motors, which are still widely used on certain types of rolling stock. Each of these types has its own advantages and limitations in terms of energy efficiency, controllability, and operational reliability. In particular, asynchronous motors are characterized by high reliability and simplicity of design [93], but they are inferior to synchronous machines in terms of efficiency in partial load modes. Synchronous motors with permanent magnets provide high efficiency and specific power, but require the use of expensive materials and complex control systems.

One of the promising areas for improving the efficiency of traction motors is the introduction of new structural and functional materials, in particular nanocomposites and nanostructured ceramics based on zirconium dioxide (ZrO_2), which improve the physical and mechanical characteristics, wear resistance, and reliability of electric machines by optimizing their functional parameters and improving metrological quality control [94–98].

The use of electrical steels with improved magnetic characteristics reduces hysteresis and eddy current losses, which is particularly important when working with high-frequency harmonics typical of power supplies from semiconductor converters [99]. The development of technologies for the production of insulating materials with increased thermal stability and thermal conductivity contributes to the improvement of thermal conditions and an increase in the service life of windings. The thermosetting polymer insulation layer, which in copper or aluminum winding (magnetic) wires is usually called enamel or coating, is the main element of the insulation system of rotating electrical machines (rotor and stator windings). Thermosetting materials belong to the class of organic resins and determine the key performance characteristics of magnetic wires, in particular their chemical resistance, solderability, and permissible operating temperature range. Standardized types of insulation coatings for magnetic wires and their corresponding thermal classes are listed in Table 2. The thermal class of the insulation system (e.g., «F» or «H») is determined based on tests conducted in accordance with international standards.

Further improvement of the design of traction electric motors is closely related to the optimization of the geometry of magnetic systems, the shape of slots, the configuration of windings, and cooling systems. The use of numerical modeling methods for electromagnetic and thermal processes makes it possible to minimize losses, reduce local overheating, and improve the uniformity of the magnetic field distribution at the design stage [103]. The use of multiphysical models that take into account the interrelationship between electrical, thermal, and mechanical processes in the motor during actual operation is particularly promising.

Table 2

Thermal classes and insulating materials of round copper magnet wires [100–102]

Magnet wire thermal class	Standard	Insulating material	
		Underlying coating	Superimposed coating
105	MW15-C	polyvinyl acetal-phenolic	
130	MW28-C	polyurethane	polyamide
155	MW79-C	polyurethane	
155	MW80-C	polyurethane	polyamide
155	MW41-C	glass fibre covered	
180	MW76-C	polyester (amide) (imide)	polyamide
180	MW77-C	polyester (imide)	
180	MW78-C	polyester (imide)	polyamide
180	MW82-C	polyurethane	
180	MW83-C	polyurethane	polyamide
180	MW50-C	glass fibre covered	
200	MW74-C	polyamide (amide) (imide)	
200	MW35-C	polyester (amide) (imide)	polyamideimide
200	MW44-C	glass fibre covered	
220	MW61-C	aromatic polyamide	
220	MW37-C	polyester (amide) (imide)	polyamideimide
220	MW81-C	polyamideimide	
240	MW16-C	aromatic polyimide	

Modern traction electric drive control systems play an important role in improving operational efficiency. The transition from classic control algorithms to adaptive and intelligent control systems makes it possible to optimize the operation of traction motors in real time, taking into account changing traffic conditions. The use of vector control, direct torque control, and artificial intelligence-based algorithms reduces energy losses, improves dynamic characteristics, and reduces mechanical loads on drive components [104].

Significant potential for improving efficiency is associated with the development of power electronics. The use of semiconductor devices based on silicon carbide and gallium nitride makes it possible to reduce switching losses, increase the conversion frequency, and reduce the weight and size of traction converters [105–108]. This, in turn, creates conditions for more accurate formation of voltage and currents supplying traction motors and reduction of additional losses in them.

A separate area of development is the introduction of systems for monitoring the technical condition and predictive diagnostics of traction motors (Fig. 4).

Modern sensor and information technologies enable continuous monitoring of temperature, vibration, and electrical parameters, which opens up opportunities for early detection of defects and a transition from scheduled to condition-based maintenance [110]. This not only increases the reliability of motors, but also reduces unproductive energy costs associated with operating in suboptimal modes.

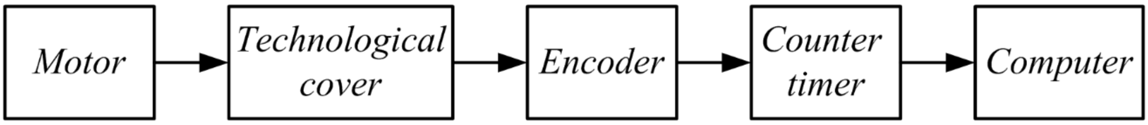

Fig. 4. Structural diagram of the diagnostic and measuring device [109]

A significant factor in improving the efficiency of traction motors is the use of regenerative braking and the integration of energy storage devices [111, 112]. The accumulation and reuse of electrical energy generated by traction motors during braking modes reduces overall energy consumption and reduces the load on the power system [113]. In combination with intelligent control systems, this creates the conditions for the formation of a new generation of energy-efficient and adaptive traction systems.

Thus, promising areas for the development of methods and means to improve the efficiency of locomotive traction motors are complex in nature and are based on the integration of advances in materials science, electrical machine theory, power electronics, automated control, and digital technologies. Implementing this approach not only improves energy efficiency, but also ensures increased reliability, service life, and competitiveness of the modern locomotive fleet.

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

– operational processes in locomotive traction motors are systematic and interrelated, and they can only be adequately described by combining different levels of analysis. Each scientific approach forms its own information field regarding the behavior of the motor in operation, but the isolated use of individual models significantly limits the completeness of the assessment of its condition. Establishing cause-and-effect relationships between operating modes, internal processes, and component degradation creates the basis for transitioning from scheduled to predictive maintenance management and makes it possible to justify the integration of models into digital monitoring and decision support systems. This, in turn, opens up prospects for improving the adaptability of traction electric drives to changing operating conditions and reducing energy and resource losses in the life cycle of locomotives;

– the modern methods of improving the efficiency of traction motors discussed above show that the greatest practical effect is achieved through a comprehensive combination of rational control of operating modes and scientifically based organization of technical operation. Optimization of electromechanical modes, use of vector and adaptive control systems, and effective implementation of regenerative braking significantly reduce energy losses and thermal loads. Integration of real-time monitoring systems creates a basis for control focused on the actual technical condition of motors. The transition to maintenance based on technical condition and the use of modern diagnostic methods ensure more complete utilization of traction motors and reduce the likelihood of emergency failures. A combination of technical, operational, and organizational measures forms a unified approach to improving the reliability, energy efficiency, and economic feasibility of traction electric motors in modern transport systems;

– technical diagnostics and monitoring tools for traction motors are a key factor in improving the reliability and safety of rolling stock. Their informative value and ability to detect defects at an early stage determine the effectiveness of the transition to condition-based maintenance. A comprehensive approach to diagnostics reduces operating costs, minimizes breakdowns, and optimizes traction motor resource management. Further development in this area is linked to the introduction of intelligent data analysis systems and digital monitoring technologies;

– improving the efficiency of locomotive traction motors is an important component of the development of modern rail transport. The main areas of focus are the use of highly efficient materials, design improvements, the integration of intelligent control systems, and the development of diagnostic tools. Modern electronic converters and energy storage devices have a significant impact. A comprehensive scientific and technical approach makes it possible to reduce energy losses, increase reliability, extend the service life of motors, and reduce operating costs. This approach creates the conditions for the sustainable and efficient operation of the rail transport of the future.

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і ZrO_2–SiC для підвищення надійності тягових електродвигунів. Тези ІІІ міжнародної науково-практичної конференції *«Енергетичні установки та альтернативні джерела енергії ‘2026»* (Харків, ХНАДУ, 11–12 березня 2026 р.). Харків: ФОП Бровін О.В.

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