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PROBLEMS AND PROSPECTS FOR THE IMPLEMENTATION OF BRUSHLESS MOTORS ON TRACTION ROLLING STOCK

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ПРОБЛЕМИ ТА ПЕРСПЕКТИВИ ВПРОВАДЖЕННЯ БЕЗКОЛЕКТОРНИХ ДВИГУНІВ НА ТЯГОВОМУ РУХОМОМУ СКЛАДІ

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Abstract. *The article discusses topical issues of improving the reliability and efficiency of traction electric motors used in locomotives and other traction rolling stock. The purpose of the study is to conduct a comprehensive analysis of the technical and operational aspects of the use of brushless traction motors in railway rolling stock, identify key problems in their implementation, and justify promising areas for the development and improvement of this type of traction drive to increase the efficiency, reliability, and energy efficiency of railway transport. Brushless electric motors, in particular asynchronous and synchronous motors with permanent magnets, are considered a promising alternative to traditional commutator motors due to their increased reliability, simplified design, and reduced operating costs. The paper systematizes the technical and operational aspects of the application of brushless traction systems and compares their characteristics with those of classic commutator motors, taking into account reliability, efficiency, and service life. It has been established that the key advantages of brushless motors are increased energy efficiency, reduced maintenance, no need for regular inspection of the commutator and brush assembly, and increased service life of the traction drive. At the same time, the main problems limiting the widespread introduction of the technology have been identified, in particular the high initial cost, the complexity of electronic control systems, the need to modernize existing infrastructure, and the need to adapt to*

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the specifics of different types of rolling stock. Despite the existing challenges, brushless motors offer significant operational advantages: increased reliability due to the absence of a commutator and brush assembly, reduced maintenance costs, improved energy efficiency, higher overload capacity, and the ability to control precisely across a wide range of operating modes. Based on the analysis, promising areas for the development of brushless traction systems have been identified, including improvements to electric drive control systems, integration with energy-saving technologies and energy recovery systems, and phased implementation across various categories of rolling stock. The results obtained are of practical importance for substantiating strategies for modernizing the railway traction fleet, improving operational efficiency, and optimizing energy and technical costs. They also serve as a scientific and technical basis for further research into improving the cost-effectiveness, environmental friendliness, and reliability of locomotives in the long term.

Keywords: *brushless motor, locomotive, traction rolling stock, asynchronous electric drive, converter, reliability, control, insulation.*

Анотація. *У статті розглянуто актуальні питання підвищення надійності та ефективності тягових електричних двигунів, що застосовують на локомотивах та іншому тяговому рухомому складі. Метою дослідження є проведення комплексного аналізу технічних та експлуатаційних аспектів застосування безколекторних тягових двигунів на рухомому складі залізничного транспорту, виявлення основних проблем їх впровадження та обґрунтування перспективних напрямів розвитку і удосконалення такого типу тягового привода для підвищення ефективності, надійності та енергоощадності залізничних перевезень. Безколекторні електродвигуни, зокрема асинхронні та синхронні з постійними магнітами, розглядають як перспективну альтернативу традиційним колекторним двигунам завдяки їхній підвищеній надійності, спрощеній конструкції та зниженим експлуатаційним витратам. У роботі систематизовано технічні та експлуатаційні аспекти застосування безколекторних тягових систем, порівняно їхні характеристики з класичними колекторними двигунами з урахуванням надійності, ефективності, тривалості експлуатації. Встановлено, що головними перевагами безколекторних двигунів є підвищена енергетична ефективність, зменшення обсягів технічного обслуговування, відсутність потреби в регулярному контролі колекторно-щіткового вузла та збільшений ресурс роботи тягового привода. Водночас ідентифіковано основні проблеми, що обмежують масове впровадження технології, зокрема високу початкову вартість, складність систем електронного керування, необхідність модернізації існуючої інфраструктури та адаптації до специфіки різних типів рухомого складу. Попри наявні виклики, встановлено значні експлуатаційні переваги безколекторних двигунів: підвищену надійність за рахунок відсутності колекторно-щіткового вузла, зменшення витрат на обслуговування, поліпшені енергетичні показники, вищу перевантажувальну здатність і можливість точного керування в широкому діапазоні режимів. На підставі проведеного аналізу сформульовано перспективні напрями розвитку безколекторних тягових систем, включаючи удосконалення систем керування електроприводами, інтеграцію з енергозберігаючими технологіями та системами рекуперації енергії, а також поетапне впровадження на різні категорії рухомого складу. Отримані результати мають практичне значення для обґрунтування стратегій модернізації тягового парку залізничного транспорту, підвищення ефективності експлуатації та оптимізації енергетичних і технічних витрат, а також слугують науково-технічною основою для подальших досліджень підвищення економічності, екологічності, надійності роботи локомотивів у довгостроковій перспективі.*

Ключові слова: *безколекторний двигун, локомотив, тяговий рухомий склад, асинхронний електропривод, перетворювач, надійність, керування, ізоляція.*

Relevance of the research topic. The introduction of brushless motors in traction rolling stock is a strategic direction in the development of modern transport. Despite technical and economic difficulties, the prospects for their use are extremely broad. Thanks to their high energy efficiency, reliability, and ease of operation, such motors can significantly increase the efficiency of railway and urban transport systems.

Introduction. The modern development of the transport industry requires increasing the energy efficiency, reliability, and environmental friendliness of traction electric drives. Traditionally, DC brushless motors are used in traction rolling stock of railway transport. Despite their many years of operation, these motors have a number of disadvantages: increased maintenance costs, the presence of a commutator brush assembly, significant weight and dimensions, and limited reliability under high loads. Therefore, DC brushless motors are gradually being replaced by brushless electric machines, which demonstrate high efficiency, improved dynamic characteristics, lower operating costs, and increased reliability. Table 1, as an example, shows comparative characteristics for different types of motors at minimum and maximum shaft loads, because, as is known, electrical efficiency is one of the main indicators that are used when choosing a motor.

Table 1

Energy characteristics of motors [1]

Motor type	Efficiency at minimum load (10 %)	Efficiency at maximum load (100 %)
DC brushless motor (DTRN-45/27)	80–85	85–90
Brushless DC motor (Compro REB60)	70–80	>95
Asynchronous motor (4MTKM2П225L6)	>90	>90
Valve jet motor (ABB 3GBL222217-HSC)	90	90–95
Permanent magnet synchronous motor (Remi HVH250)	85	92–95

In combination with modern control systems based on power electronics, brushless electric machines are becoming a promising alternative for upgrading the traction drives of locomotives, electric trains, trams, and other types of electric transport.

However, the introduction of brushless motors in traction rolling stock has a number of problems – technical, economic and production. The article is aimed at analyzing these problems and determining the prospects for further development and application of brushless motors in traction drives.

Analysis of recent research and publications. The review article [2] analyzes the reengineering strategies adopted in Poland and Croatia, focusing on technical, organizational, and policy measures that have contributed to the sustainable renewal of the transport fleet and may be useful in Ukraine on its path to joining the European Union. The challenge of modernizing outdated railway rolling stock equipped with DC traction motors, operating under conditions of limited financial and technical resources, is considered. Using a comparative method based on documentation, case studies and reports (2004–2024), this study shows that reengineering can extend service life by 15–25 years, reduce energy consumption by 20 % and increase reliability by 30–40 %. A limitation of the study is that using data over a twenty-year period creates the risk of uneven quality and relevance of sources. Technological and economic conditions have changed significantly, which may affect the validity of comparisons and conclusions. In addition, the study compares only the experiences of Poland and Croatia. Although these countries are relevant to Ukraine, the sample may not be sufficient to form universal recommendations, as the situation in other EU or Central European countries may differ significantly.

In work [3], the energy efficiency of modern control systems for brushless traction motors was analyzed, taking into account the conditions of their operation. Permanent magnet synchronous motors and asynchronous machines are considered, as well as modern control methods and the structure of converters. A comparison of losses and efficiency indicators in typical operating modes was performed. However, the results do not fully take into account the impact of long-term equipment aging and non-standard operating modes.

The study [4] substantiates the use of an additional diagnostic indicator for assessing the technical condition of stator windings of induction motors in operation. It is shown that in the presence of interturn short circuit, the phase shifts between currents and voltages remain the same in all phases. However, the results were obtained for a limited range of operating modes, which requires further verification of the method under conditions of variable load and different types of motors.

Scientific works [5, 6] are devoted to determining the optimal parameters of an asynchronous traction motor of electric rolling stock, which is necessary for creating a computer simulation model to reproduce electromagnetic processes in the traction electric drive and converters with different control algorithms in traction and regenerative braking modes.

In article [7], a comprehensive analysis of the operating conditions and operating modes of traction electric motors of locomotives was carried out with detailed consideration of the influence of temperature regimes, insulation condition, nature of loads, operational factors, electromagnetic interference, and modern cloud monitoring technologies. The specifics of thermal processes in windings, approaches to insulation control and diagnostics, as well as the possibilities of using remote monitoring systems are outlined. The importance of a comprehensive approach to assessing the technical condition of traction electric motors, which combines traditional control methods with analytical tools of cloud platforms, is emphasized.

The paper [8] provides a justification for the feasibility of implementing an asynchronous traction electric drive on the rolling stock of the metro. The advantages of asynchronous traction electric drives compared to collector systems based on DC motors are disclosed. An analysis of the technical characteristics of modern innovative metro rolling stock equipped with an asynchronous traction electric drive was conducted, the specifics of choosing an asynchronous traction electric drive with a frequency-controlled control system for innovative trains were determined, and the energy saving potential under given operating conditions was outlined. However, the article does not detail the possible technical, logistical, and economic risks of modernization, which makes the conclusions somewhat simplistic.

The scientific study [9] reviews methods for detecting faults in induction motors, assessing their effectiveness and limitations at each stage of diagnosis. A limitation of the study is that it does not cover practical implementation and the impact of real-world operating conditions on the accuracy of the methods.

In [10], a method for direct torque control of an induction motor using fuzzy logic to estimate two stator components is proposed, which improves control quality and dynamics. Simulation confirmed the robustness of the method to changes in stator resistance, however, the speed response slows down during individual oscillations, which limits the application of the proposed approach.

The materials of publications [11–15] are devoted to the study of increasing the energy efficiency of brushless traction motors of locomotives.

Summarizing the analyzed literary sources, it can be noted that modern research focuses on the technical, energy and operational aspects of the use of brushless traction motors, as well as on the issues of their diagnostics, control and modernization of rolling stock. Significant potential for increasing energy efficiency, reliability, and service life of the traction drive has been shown by transitioning from collector machines to asynchronous and synchronous brushless motors with modern control systems. At the same time, a number of unresolved problems related to failures, equipment aging, limited adaptation of modeling results to real operating conditions, and insufficient consideration of technical and economic risks of implementation were identified. This necessitates a comprehensive analysis of the causes of failures, problems with the integration and operation of brushless motors, as well as the systematization of their advantages and development prospects.

Defining the purpose and objectives of the research. The purpose of the article is to conduct a comprehensive analysis of the technical and operational aspects of the use of brushless traction motors in railway rolling stock, identify key problems in their implementation and substantiate promising areas of development and improvement of this type of traction drive to increase the efficiency, reliability and energy efficiency of railway transportation. To achieve the goal, the following tasks were set:

– analyze the main causes of failures of collector and brushless traction electric motors of locomotives;

– to investigate the problems that arise when implementing brushless motors;

– to consider the advantages and identify the prospects for implementing brushless motors in traction rolling stock.

The main part of the research.

The main causes of failure of collector and brushless traction electric motors of locomotives. Difficult economic conditions in the state and in the railway transport sector, as well as the progressive aging of the locomotive fleet, make the problem of the most rational use of available resources urgent. This necessitates the implementation of measures aimed at increasing the efficiency of railway rolling stock operation. It is known that one of the key factors determining the performance of traction rolling stock is the level of its reliability [16].

The problem of ensuring the reliability of technical systems has become significantly more acute in recent decades [17]. This is due to a number of objective factors, including:

– a significant increase in the complexity of modern technical systems, containing hundreds of thousands or even millions of components and assemblies;

– operation of traction electric machines in conditions close to extreme (high accelerations, temperatures and pressures, intense vibration, sharp temperature fluctuations, etc.);

– increased intensity of operating modes of both the system as a whole and its individual elements (operation at high temperatures, rotation frequencies, pressures, current loads, etc.);

– increasing requirements for accuracy and efficiency of equipment operation;

– increasing the responsibility of the functions performed by the system;

– widespread implementation of full or partial automation, which often involves minimizing or eliminating direct human control over the state and operation of the system.

One of the key elements that determine the level of reliability of traction rolling stock are traction electric motors, the failure of which during operation can cause significant material losses. The cost of repairing a traction electric motor is influenced by a complex of interrelated factors, including the degree of physical and electrical wear, the nature and number of detected defects, the cost of spare parts and materials, as well as the complexity of repair operations and the level of personnel costs. Taking into account the above factors, the average cost of repairing one traction electric motor is estimated at about 40 thousand UAH (Table 2), with the dominant share in the cost structure – over 60 % – being material resources and costs for repair and restoration work. This distribution is typical for major and medium repairs of electric traction machines and is consistent with known approaches to the economic assessment of their life cycle.

Table 2

Cost of current repairs of one traction motor [18]

Expense item	Conditional cost, UAH
Winding and insulation	14,000
Bearings	5,000
Staff work	10,000
Electricity	3,000
Equipment depreciation	2,000
Overhead	6,000
Together	40,000

Traction motors are one of the most stressed elements of locomotive equipment, as they are simultaneously exposed to thermal, electrical, mechanical, and climatic factors. Therefore, despite the systematic implementation of design and technological improvements during the production and repair of locomotives, the level of their damage in operating conditions, although it tends to decrease, still remains quite significant [19].

A large proportion of failures of traction electric motors of locomotives is due to the occurrence of unacceptable static or periodically changing dynamic loads, which cause fatigue damage to their elements [20]. More than 65 % of malfunctions related to insufficient reliability of traction motors are recorded on locomotives with a mileage after overhaul that does not exceed 350 thousand km. The most common types of failures are damage to inter-coil connections, failure of main poles, mechanical defects in winding insulation, destruction of connecting bolts, malfunctions of the motor-axial bearing, as well as destruction of brush holder fingers or the rotary traverse. About half of the total number of defects is due to interturn short circuits and insulation breakdowns of the armature windings and poles of electric motors.

The main reason for the high level of damage to traction motors is the influence of mechanical factors. They cause additional phenomena, such as instability of the brush contact, fluctuations in the air gap between the armature and the pole core, changes in the voltage distribution in the collector circuit, as well as specific conditions for arc formation on the collector and other associated effects [21, 22].

Under the influence of vibrations, the intensity of brush sparking increases, which leads to a significant increase in their wear, accelerated destruction of the collector, and an increase in the temperature of the contact node. Increased brush wear with increasing vibration energy is explained by the fact that electric brushes, the longitudinal vertical axis of which is oriented along the direction of action of the external dynamic force, receive a corresponding acceleration. Under certain ratios between the pressing force and inertial forces, this can cause contact breakage and sparking. Under the influence of an electric arc, individual collector plates partially melt (scorch is formed), which increases the roughness of their working surface and, accordingly, increases the abrasive effect on the brushes.

A large proportion of failures are due to breakdowns and interturn short circuits of the armatures [23]. Also recorded are a significant decrease in insulation resistance, disruption of connections between poles and windings, defects in bearing assemblies, loosening of shields and covers, and destruction of the bandage.

Such malfunctions are difficult to prevent during locomotive operation, as they are mostly a consequence of inadequate quality of current and major repairs. To eliminate them, it is often necessary to roll the traction motor out from under the locomotive, which leads to significant operating costs. Traction motor failure statistics mainly reflect the quality of repairs performed. It is important to emphasize the existing discrepancy between the standard service life of locomotives and the traction motors installed on them, as well as possible discrepancies in the current regulations for their repair cycles [24, 25].

The discrepancy between the standards for the maintenance intervals of locomotives and the traction motors installed on them causes a situation where, when the locomotive is put in for maintenance, the traction motors actually require major repairs at the factory [26]. As a result, this creates additional difficulties for depot workers responsible for the operation of locomotives. Despite the presence of technical passports, electric motors can lose their individuality – the regulated intervals and procedure for their repair are not always observed. As a result, there is accelerated aging of the insulation and exceeding of the standard resource of motor-armature bearings [27].

In railway traction rolling stock, asynchronous traction motors are increasingly used both on direct current lines with a voltage of 3 kV and on alternating current sections of 25 kV, 50 Hz [28]. The use of a regulated asynchronous traction drive on rolling stock, capable of operating from two power systems, is one of the most effective areas of development. The increase in the design speed of locomotives is ensured by the introduction of high-power asynchronous motors with a squirrel-cage rotor.

Asynchronous traction motors operate over a wide range of angular speeds and loads, operating from non-sinusoidal pulsed voltage. At low frequencies, such motors exhibit pronounced pulsating torques, which leads to increased mechanical loads on the rotor bars and other structural elements. Switching processes in stand-alone voltage inverters cause overvoltages in the stator windings, which are dangerous for their insulation [29]. Significant current fluctuations in the motor windings increase energy losses, contribute to overheating of the windings of asynchronous traction motors and, as a result, can cause premature failure [30, 31]. Ensuring the required level of reliability of an asynchronous traction drive during operation is determined, first of all, by the parameters of the power circuit and the control system, which form the nature of transient processes and affect its energy performance [32, 33].

Statistical analysis of the operating experience of induction motors shows that the largest part of failures that occur during operation is associated with the stator, rotor and bearing assembly. Fig. 1 shows the results of a study of factors leading to emergency failures of squirrel-cage induction motors.

Most of the emergency failures of induction motors are related to their overheating or overloading. These problems arise due to violations of operating conditions, in particular, inconsistency of motor characteristics with specific operating conditions, frequent switching on and off, insufficient cooling, delays in operation of overload protection, etc. [35, 36]. The consequence of such violations is the destruction of the winding insulation, as well as the gap and interphase insulation, which can ultimately cause an electrical breakdown.

The second most common cause of emergency failures is an interturn short circuit in the stator winding. Such short circuits constitute the most common form of stator failure [37]. When shorted turns occur, the motor can continue to operate normally, but its performance and energy efficiency deteriorate. Due to the increase in current in the damaged phase, the defect gradually progresses, increasing the number of short-circuited turns, which ultimately leads to an emergency failure of the electric motor.

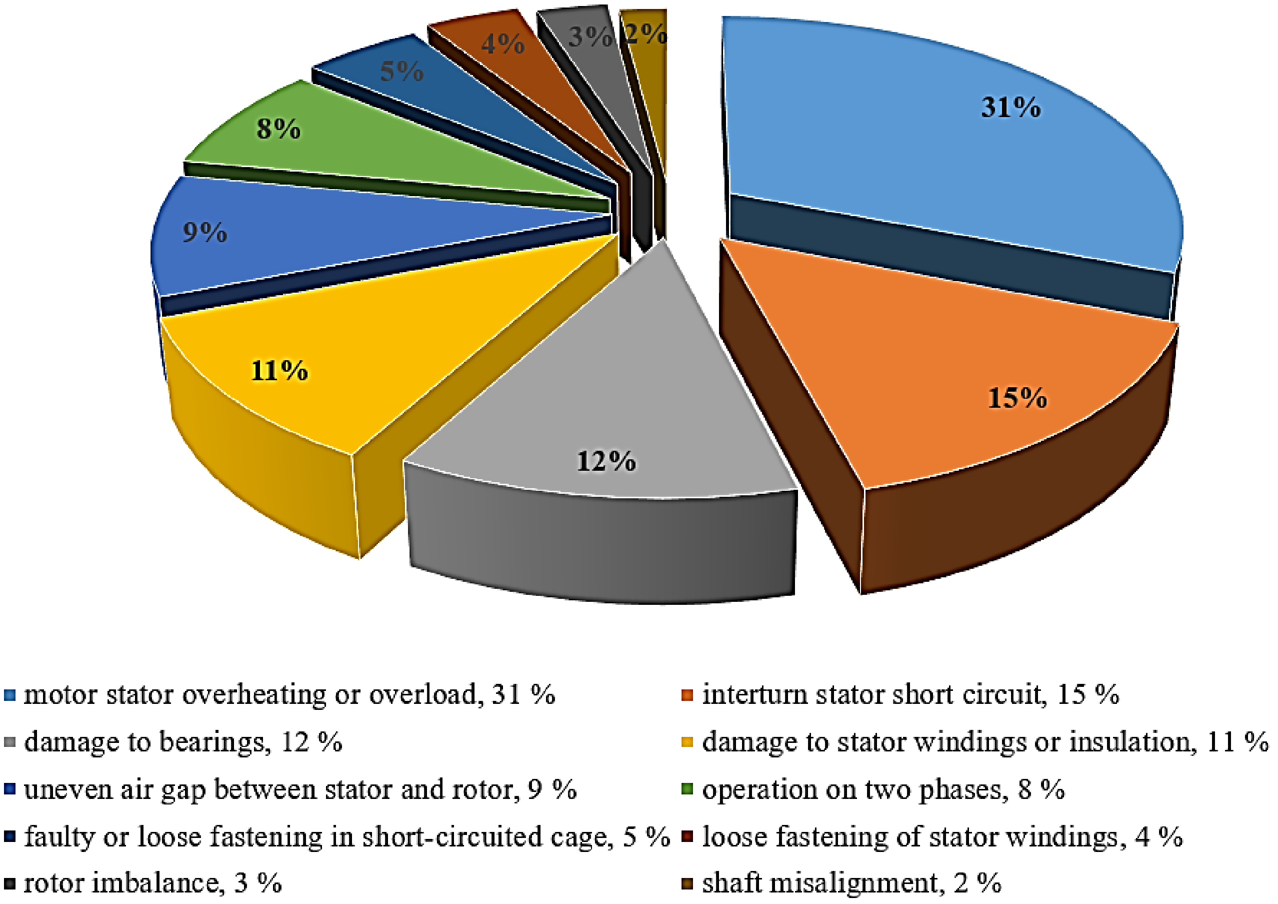

Fig. 1. Results of the study of factors leading to emergency failures
of squirrel-cage induction motors [34]

Insulation damage occurs under the influence of various factors – structural, technological and operational – and at the initial stage of the defect, as a rule, is not critical. However, with the further development of such damage, electric motors may fail. The main types of stator winding insulation damage arise as a result of the implementation of the considered causes of failures and manifest themselves as inter-turn short circuits within the winding phases, winding short circuits to the housing, and breakdown of interphase insulation. Other damage mainly affects the rotor and mechanical components of the motor, causing vibration, which in turn accelerates the breakdown of the winding insulation. Therefore, the highest failure rate of electric induction motors is due to damage to the stator winding, which is a consequence of the degradation of dielectric materials under the influence of various operational factors [38].

Although the proportion of structural and technological damage to the insulation of induction motors has significantly decreased in recent years, the problem of detecting operational defects remains extremely relevant. The type and rate of damage development are determined by both external operational factors and internal characteristics of the motor insulation system. During operation, induction motors are exposed to various external factors [39], which can significantly deteriorate the insulation properties, including high vibrations, significant mechanical loads, elevated temperatures, frequent overloads, etc. Insulation damage develops under the influence of humidity, thermal loads, mechanical damage, electric fields of operating voltage and surges, as well as contamination.

Despite the constant improvement of stator winding insulation, the introduction of new materials, the improvement of technologies for applying varnish coatings to wires, the use of special impregnation and drying methods, as well as high-precision methods of winding laying and machine assembly, the problem of low insulation reliability of electrical machines remains unresolved due to design and technological factors. First of all, this concerns the winding insulation of low and medium-power machines, in the phase of which a large number of turns are used, since the specific strength of inter-turn insulating overlaps is significantly reduced due to various technological operations with thin enameled wire [40, 41].

Interturn short circuits in the stator winding, which occur due to insulation damage, are among the most common and difficult to detect defects (Fig. 2). They lead to deviations of motor parameters from nominal values and can cause a gradual transition from normal operation to an emergency stop. With a small number of short-circuited turns in a damaged phase, an asynchronous motor is able to function for some time, although its operating parameters and characteristics differ from the nominal ones. As the number of short-circuited turns in a phase increases due to the increase in phase current and winding temperature, the motor eventually goes out of operating condition.

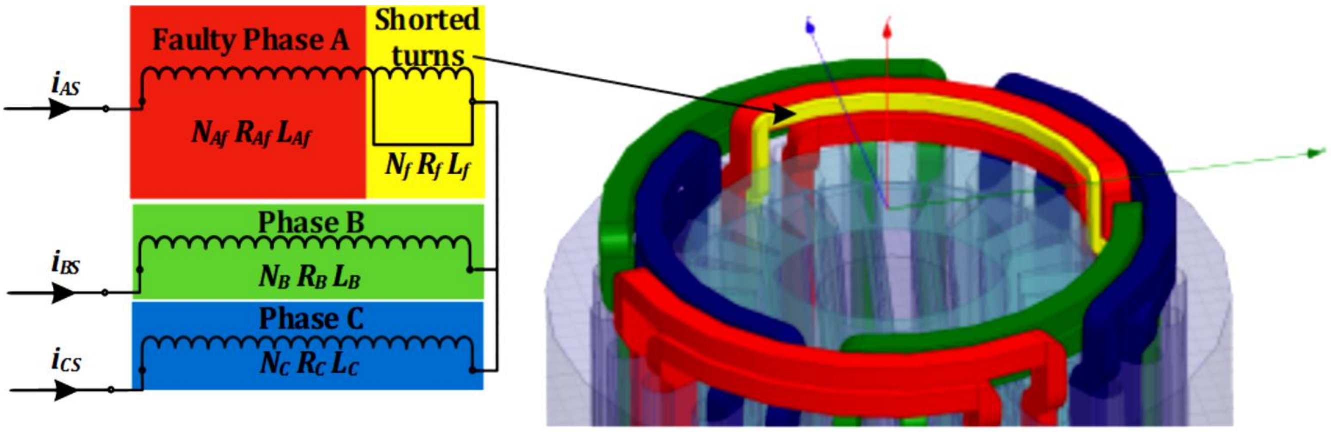

Fig. 2. Stator winding diagram taking into account interturn short circuits [42]

Problems arising from the implementation of brushless motors. Due to their simple structure and easy availability, induction motors have been widely used in variable speed drives [43]. Compared to DC motors, they are more reliable, have lower operating costs, and are easier to maintain [44]. In addition, such motors are characterized by high strength and the ability to withstand significant loads [45, 46]. At the same time, the listed advantages are accompanied by certain disadvantages.

During the development of locomotives with an asynchronous drive, a number of new important scientific and technical tasks arise that did not previously arise when creating rolling stock with commutator traction motors.

The operation modes of an asynchronous traction motor are regulated by changing the frequency and amplitude of the supply voltage. For this purpose, static frequency and phase number converters are used, which form non-sinusoidal voltage curves at the output [47, 48].

The non-sinusoidality of the supply voltage leads to a decrease in the efficiency of the induction motor, the power factor (cosφ), and also causes increased heating and a decrease in the useful power [49–51]. This necessitates the search for methods to increase these indicators. The non-sinusoidal shape of the voltage curve, i.e. the presence of higher harmonics, causes additional losses in the steel magnetic cores and stator and rotor windings. The resulting temperature increase should be taken into account when designing the motor structure, its operation, and the selection of materials, especially insulation.

The increase in torque pulsations, especially at low frequencies, leads to increased mechanical stresses in the chassis components, rotor winding rods, short-circuiting rings of the synchronous motor, and elements of the power mechanical drive [52–54]. The negative impact of these factors can be reduced by appropriate circuit design solutions, but this increases the weight of electrical equipment and requires a larger volume of its placement.

Regardless of the chosen circuit or design solution, there is a close relationship between the static converter, the traction motor, and the power mechanical drive [55]. A major role is played by the correct selection of parameters and design features of these components, as well as determining the optimal range of operating frequencies of the voltage supplied to the induction motor.

When using a brushless drive on traction rolling stock, compared to a collector drive, additional conversion of the total power occurs: on AC electric locomotives – inverting the rectified voltage, and on DC electric locomotives – inverting the contact network voltage. In this regard, the urgent task of increasing the efficiency of the brushless drive arises. It can be implemented not only by increasing the efficiency of individual elements of the power circuit (converters, traction motors, transformers, etc.), but also by implementing energy-saving methods of controlling the locomotive power drive [56, 57].

When developing locomotives with brushless traction motors, it is necessary to apply special measures to ensure their electromagnetic compatibility with the traction power supply system [58, 59]. Ignoring such measures may lead to a negative impact of a locomotive with a brushless drive on communication lines, signaling and auto-blocking systems, as well as on traction substation equipment.

The constant tasks of developers of traction rolling stock with a brushless drive include not only reducing the total mass of the equipment, but also reducing the volume of its placement inside the body. This led to the introduction of new layout principles: instead of two side aisles, a central one is used, on some types of AC electric locomotives the transformer is located under the body, and the power converters are equipped with liquid or evaporative cooling [60]. At the same time, the length of electric locomotives with brushless drives slightly exceeds the similar indicator for locomotives with traditional collector motors. Increasing the rigid base of an electric locomotive, along with increasing nominal and maximum speed, makes it more difficult to navigate curves, increases mechanical loads on the rails and bogie frames, which affects the dynamics of movement. Partial compensation for these effects is achieved by lowering the locomotive's center of gravity by placing the transformer under the body.

Traditional approaches to calculating and designing traction rolling stock do not provide a quick and sufficiently accurate solution to all complex problems. Achieving such results in the early stages of developing new locomotives, as well as optimizing the parameters of all components of the traction drive, is possible only with the help of a mathematical model of the drive. Such a model allows us to reflect the relationships between all elements and systems involved in the transmission of electrical energy from the contact network to the traction motor, the conversion of electrical energy into mechanical energy, and the realization of the developed traction force [61–63].

Thus, summarizing the problems that arise when implementing brushless motors in traction rolling stock, the following can be added to those already considered:

– high production cost – the use of expensive materials, in particular rare-earth magnets, significantly increases the cost of the motor;

– complexity of control systems – the need to use microprocessor systems, rotor position sensors and high-speed converters requires complex control methods and reliable software;

– thermal loads and reliability of electronics – operation in conditions of high currents and temperatures requires effective cooling systems and high quality electronic components;

– repair and diagnostic problems – the high level of integration and electronization makes servicing motors in the field difficult.

Advantages and prospects of introducing brushless motors in traction rolling stock. Modern electric transport (locomotives, electric trains, metro trains, trams) places strict requirements on reliability, energy efficiency, specific power, and maintenance of traction equipment. Brushless motors have significant potential for application in traction drives due to higher power density, energy efficiency, lower maintenance requirements, and better driving dynamics. They offer a range of advantages that make them attractive for use in traction drives. For example, the following advantages can be achieved when using an asynchronous traction drive in electric traction [64–66]:

– the design of the traction motor is significantly simplified compared to the collector analogue, which increases its reliability, since the need for regular inspection of the collector-brush assembly is eliminated;

– the reliability of electrical equipment on the body increases due to the use of contactless power converters;

– the traction characteristics of locomotives are improved due to a stiffer traction characteristic during boxing (the possibility of increasing the traction coefficient by 20–40%);

– with the same dimensions, the motor power and torque increase, since there is no collector, additional pole windings, and compensation winding;

– it becomes possible to fully automate the train driving process;

– due to the implementation of the above-mentioned advantages, the overall productivity of traction rolling stock increases;

– the use of copper in the production of traction motors is reduced (the need for copper for asynchronous machines is reduced by 2–2.5 times).

In addition, the introduction of brushless traction motors in rolling stock has a significant environmental component, as it provides a reduction in energy consumption, an increase in the efficiency and recovery efficiency, which directly leads to a reduction in greenhouse gas emissions and toxic compounds at the energy system level and contributes to the development of rail transport in compliance with environmental requirements [67, 68]. The absence of a brush-collector assembly eliminates the source of fine graphite-copper dust and reduces maintenance, which reduces waste and lubricant consumption. Additional environmental benefits include reduced noise, vibration, and increased equipment life [69]. Thus, brushless drives are a key technology for the development of energy-efficient and environmentally friendly electric transport.

The prospects for further development and implementation of brushless motors in traction rolling stock are as follows [70–73]:

– reduction in the cost of components – permanent magnets and semiconductor elements are expected to become cheaper due to technological development and mass production;

– introduction of digital control systems – the use of artificial intelligence and adaptive control methods will increase the efficiency and reliability of traction wires;

– development of energy-efficient converters – new generations of IGBT and SiC transistors provide lower energy losses and more compact converter designs;

– integration with energy recovery systems – brushless motors are well compatible with regenerative power technologies, which allows braking energy to be returned to the network;

– expanding the scope of application – brushless drives are being actively implemented not only in locomotives, but also in trams, metro, electric buses and freight transport.

The listed advantages and directions for further development clearly indicate the validity of the widespread use of asynchronous traction motors in electric traction systems. Practical experience in the design and operation of rolling stock with such motors fully confirms this statement.

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

– brushless traction motors demonstrate greater reliability compared to collector counterparts, as there is no need for daily inspection of the collector-brush assembly and the likelihood of emergency failures is reduced, which helps reduce rolling stock maintenance costs;

– the main problems of the widespread introduction of brushless motors remain the high cost of production and modernization of the electric traction system, as well as the need to develop new diagnostic and repair methods, which requires significant capital investments and personnel training;

– the use of brushless motors opens up prospects for increasing the energy efficiency of rolling stock, provides more precise traction control and the possibility of integration with modern energy recovery systems, which will help reduce energy consumption and the environmental impact of transport vehicles.

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