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ANALYSIS OF THE EFFICIENCY OF OPERATION OF MODERN CONTROL SYSTEMS FOR BRUSHLESS TRACTION MOTORS

Dr. Sc. (Tech.) S. V. Panchenko, Dr. Sc. (Tech.) M. M. Babaiev,
Candidate of Technical Sciences V. P. Nerubatskyi

АНАЛІЗ ЕФЕКТИВНОСТІ ЕКСПЛУАТАЦІЇ СУЧАСНИХ СИСТЕМ КЕРУВАННЯ БЕЗКОЛЕКТОРНИМИ ТЯГОВИМИ ДВИГУНАМИ

Доктори техн. наук С. В. Панченко, М. М. Бабаєв,
канд. техн. наук В. П. Нерубацький

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Abstract. *The further development of railway traction rolling stock is currently largely associated with the predominant use of brushless traction motors, primarily asynchronous ones. However, the efficiency of brushless traction drives largely depends on the control system, which forms the optimal current distribution, ensures smooth acceleration, reliable braking with recuperation, and stable operation in a wide range of modes. At the same time, the implementation of control systems in brushless traction drives of railway transport is accompanied by a number of technical and operational problems. The purpose of the article is to conduct a comprehensive analysis of operating conditions and assess the energy efficiency of modern brushless traction motor control systems used in traction rolling stock, in order to determine their advantages, disadvantages and promising areas of improvement, which will allow formulating recommendations for choosing optimal algorithms and technical solutions for specific operating conditions of traction rolling stock. The object of the study is the control processes of brushless traction electric motors in electric drives of traction rolling stock. The paper considers the main types of brushless traction machines (synchronous with permanent magnets, asynchronous), modern control algorithms (vector control, direct torque regulation, adaptive and optimizing approaches), as well as hardware solutions for converters and diagnostic systems. A comparative analysis of losses and efficiency indicators was carried out in typical driving modes (acceleration, steady driving, braking with recuperation) taking into account temperature and load factors. The proposed methodology includes modeling in a simulation computer environment, construction of efficiency maps, and experimental validation on a bench with an inverter and current/voltage/temperature sensors. The expected result of the work is recommendations for optimizing control algorithms and drive configurations to increase the efficiency of traction motors, as well as a set of criteria for selecting a drive depending on the operating mode of traction rolling stock. The practical value lies in the possibility of using the research results in the design and modernization of electric motors of traction rolling stock, which will increase the reliability of transport vehicles.*

Keywords: *operational efficiency, brushless traction motor, traction rolling stock, control system, efficiency, recuperation.*

Анотація. *Подальший розвиток тягового рухомого складу залізниць нині багато в чому пов'язаний із переважним використанням безколекторних тягових двигунів, насамперед* *асинхронних. Однак ефективність роботи безколекторних тягових приводів значною мірою залежить від системи керування, яка формує оптимальний розподіл струмів, забезпечує плавний розгін, надійне гальмування з рекуперацією і стабільність роботи в широкому діапазоні режимів. Водночас впровадження систем керування в безколекторних тягових приводах залізничного транспорту супроводжено низкою технічних та експлуатаційних проблем. Метою статті є проведення всебічного аналізу умов експлуатації та оцінювання енергоефективності сучасних систем керування безколекторними тяговими двигунами, які застосовують на тяговому рухомому складі, для визначення їхніх переваг, недоліків і перспективних напрямів вдосконалення, що дасть змогу сформулювати рекомендації щодо вибору оптимальних алгоритмів і технічних рішень для конкретних умов роботи тягового рухомого складу. Об'єктом дослідження є процеси керування безколекторними тяговими електродвигунами в електроприводах тягового рухомого складу. У роботі розглянуто основні типи безколекторних тягових машин (синхронні з постійними магнітами, асинхронні), сучасні алгоритми керування (векторне керування, пряма регуляція моменту, адаптивні та оптимізуючі підходи), а також апаратні рішення перетворювачів і систем діагностики. Проведено порівняльний аналіз втрат і показників ефективності за типових режимів руху (розгін, сталий рух, гальмування з рекуперацією) з урахуванням температурних і навантажувальних факторів. Пропонована методика включає моделювання в імітаційному комп'ютерному середовищі, побудову карт ефективності, а також експериментальну валідацію на стенді з інвертором і датчиками струму/напруги/температури. Очікуваним результатом роботи є рекомендації щодо оптимізації алгоритмів керування і конфігурацій привода для підвищення ефективності роботи тягових двигунів, а також набір критеріїв для вибору привода залежно від режиму експлуатації тягового рухомого складу. Практична цінність полягає в можливості використання результатів дослідження для проєктування та модернізації електродвигунів тягового рухомого складу, що дасть змогу підвищити надійність засобів транспорту.*

Ключові слова: *ефективність експлуатації, безколекторний тяговий двигун, тяговий рухомий склад, система керування, коефіцієнт корисної дії, рекуперація.*

Relevance of the research topic. Further progress in railway traction rolling stock is largely due to the widespread introduction of brushless traction motors, primarily asynchronous ones. One of the main tasks that arises during the development of new locomotives is to improve their traction properties. In turn, one of the features of an asynchronous traction motor is the decisive influence of the control method on its characteristics. Therefore, the task of studying the algorithms and principles of the control system is one of the priorities in creating new locomotives with an asynchronous traction drive.

Introduction. The modern development of traction rolling stock is inextricably linked to the widespread implementation of energy-saving technologies in traction electric drive systems. One of the key areas for increasing energy efficiency and reliability is the use of brushless traction motors – synchronous machines with permanent magnets and asynchronous motors with a squirrel-cage rotor. Such electric machines are characterized by a high efficiency, reduced maintenance requirements, and the ability to implement complex control algorithms due to the absence of a collector-brush assembly, which limited the operation of classic DC traction motors.

However, the efficiency of brushless traction drives largely depends on the control system, which forms the optimal current distribution, ensures smooth acceleration, reliable braking with recuperation, and stable operation in a wide range of modes. At the current stage of technology development, the most common are vector control (Field

Oriented Control, FOC) and Direct Torque Control (DTC). These methods allow you to maximize the energy potential of the machine, reduce losses, limit torque ripple, and improve the quality of current collection.

At the same time, the introduction of brushless control systems in traction drives of railway transport is accompanied by a number of technical and operational problems [1, 2]. Among them:

– increased requirements for the cooling system due to high specific loads;

– the need to ensure the stability of control parameters in conditions of temperature changes and aging of elements;

– the need for accurate current and voltage sensors, as well as the development of sensorless algorithms to improve reliability;

– complexity of hardware implementation based on powerful transistor converters and microprocessor controllers.

Thus, it is relevant to conduct a systematic analysis of operating conditions and assess the effectiveness of modern control systems for brushless traction motors, which will allow formulating recommendations for increasing efficiency in real driving modes.

Analysis of recent research and publications. In [3], an analysis of the operating conditions of traction drives of electric rolling stock with asynchronous traction motors was conducted, and the starting characteristics of traction electric drives with different control systems were obtained both in the absence and presence of power and load failures. It is shown that at frequencies lower than nominal, a traction electric drive with direct torque control has higher accuracy of speed and torque regulation, lower energy consumption from the power source, lower torque overshoot, but a higher level of torque ripple than a traction electric drive with vector control. At the same time, at frequencies higher than nominal, vector control has higher speed control accuracy, less torque overshoot, shorter transient duration, and less torque ripple than direct torque control. In addition, it was found that the traction drive with direct torque control is more resistant to power and load failures. The disadvantage of the work is the lack of results of research into the operation of these systems in the electric braking mode, which could contribute to a more complete comparison of traction characteristics with different control systems.

In [4], a theoretical justification of the possibility of using the power factor as a criterion for developing optimized automatic control systems for traction drives of AC electric rolling stock is provided. An analytical time dependence of the power factor of the traction drive was obtained, which is a convolution of two time functions – efficiency and the coefficient of use of active power of the traction drive; an algorithm for eliminating stochastic effects of disturbances acting on the traction drive from the traction power supply system and mechanical load was developed. The significance of the results obtained lies in improving the quality of control of AC traction drives. However, the proposed scheme of optimized automatic control of the traction drive was not fully considered, in which the parameters of the sampling frequencies of the input and output parts of the traction drive are used as controlled parameters, and the efficiency is used as an optimization criterion, which would make it possible to improve the quality of regulation when building an optimal automatic control system for the traction drive.

The article [5] presents a method for optimizing the pulse-width modulation frequency in frequency converters, the load of which is an asynchronous motor, according to the criterion of minimum total power losses in the inverter power transistors and the resistance of the motor windings. The proposed calculation method allows, through the use of modern software environments (MATLAB/Simulink, NI Multisim, MelcoSim), to determine the dependence of static and dynamic losses in power IGBT transistors with fairly high accuracy (as shown in publications [6–8]). To calculate losses in the motor, it is shown that the switching frequency of the power switches affects the harmonic distortion factor and the root-mean-square value of the phase current of the induction motor. Provided that only the first harmonic of the current performs a useful effect in the induction motor, the dependence of additional power losses on the switching frequency is given. The presented methodology allows to determine the optimal modulation frequency in frequency converters with asynchronous motors and to ensure minimal total power losses and maximum efficiency in the system "autonomous voltage inverter – asynchronous motor". The limitation is that the practical application of analytical expressions that describe losses in the steel of induction motors from higher harmonics of the inverter is quite difficult due to the uncertainty of the calculation coefficients for different motor designs. In addition, the issue of determining the optimal switching frequency of power transistors at different values of load torque and motor speed remains unresolved.

In [9], control strategies for induction motors in railway systems are analyzed. The main focus is on drives operating with a low ratio of switching frequency to the fundamental frequency and in the remodulation region or six-step operation mode, as these are the most complex cases. Modulation methods, effective drive operating modes and their influence on its dynamic characteristics, as well as the design of the machine are considered. Extended modeling results are presented, as well as experimental results obtained using a traction drive. However, the impact of overheating, vibration and insulation aging on the motors service life is not sufficiently considered.

The materials [10] consider the main approaches to the control of complex objects. It is shown that today it is advisable to use approaches related to proactive supervision for the control of rolling stock with traction asynchronous electric motors. Using a mathematical model that describes the movement of a three-car diesel train, its application for implementing proactive control is demonstrated. To refine the parameters of the existing model in the control system, approaches related to the identification of the parameters of the object during its operation are proposed. In this case, it is proposed to identify the parameters of the object in two stages: at the first (lower) level, determine the parameters related to traction asynchronous electric motors, and at the second (upper) level, the parameters related to train movement. However, the issue of economic feasibility of applying new approaches to the control system was left out.

The traction motor consumes a significant portion of the energy in railway rolling stock, so in [11] a comparative study was conducted between Indirect Field Oriented Control (IFOC) with sensors and sensorless IFOC in terms of both performance and energy, with the aim of determining which one has better efficiency. It is determined that the sensorless method using the Model-Referenced Adaptive System (MRAS) can be applied to railways. However, its performance decreases in the braking mode, which is manifested in acceleration fluctuations, although the speed characteristics are good. From an energy perspective, the sensor method provides more energy from regenerative braking. From the total energy consumption, the sensor method can save up to 33.76 % energy compared to the sensorless method on a fixed track. A disadvantage of the study can be considered the lack of statistical data on traction motor failures in industrial operation.

Article [12] is a technical review of methods for controlling brushless DC motors without position and speed sensors. The achievements of sensorless technology are reviewed and the latest developments in this field are presented with their advantages and disadvantages, including an analysis of practical implementation problems and applications. The most relevant estimation and model-based methods, such as the sliding-mode observer, the extended Kalman filter, the adaptive system with a reference model, adaptive observers (full-order and pseudo-reduced order), and artificial neural networks, are briefly analyzed. A drawback of the study is the lack of consideration of the impact of digital technologies and Smart Grid on the development of electric drives.

In cases where frequency speed control is not required in an asynchronous electric drive (for example, in ventilation systems or pumps), the use of frequency converters is economically impractical. In such situations, it is more appropriate to use thyristor AC voltage regulators, known in the industry as soft starters [13, 14]. Soft starters, unlike frequency converters, provide worse speed and torque control capabilities of an asynchronous motor, but are characterized by a significantly lower cost, a simpler control system, and are the best option for driving motor-compressors, motor-fans, and other installations that do not require precise or deep speed and torque control [15].

Works [16, 17] consider a control system for a thyristor device for smooth starting of an asynchronous motor with constant load torque. During the simulation modeling, it was established that the operation of the soft starter allows to reduce the starting current and starting torque by almost half. The results of theoretical research are implemented in a real physical prototype of a soft starter. An image of the boards of the developed soft starter is provided and its technical characteristics are indicated.

In [18] it is noted that vector-controlled traction drives are widely used on mainline locomotives with induction motors. Traction motors can fail due to faults that occur during locomotive operation. To prevent the failure of traction motors, real-time functional diagnostic systems are needed. The implementation of such systems will allow detecting the occurrence of faults in the traction motor at an early stage and preventing further development of the defect. The paper proposes a structural diagram of functional diagnostics for monitoring the condition of the rotor of an asynchronous motor and develops an algorithm for its operation.

In [19] it is noted that in modern traction drive systems of rolling stock with asynchronous traction motors, vector systems have found the greatest application as control systems. Reducing losses in the traction drive system and, as a result, reducing electricity consumption depends on the accuracy of regulation of controlled parameters. This study proposes a method for taking into account the saturation of the motor magnetic circuit through the main inductance of the motor as a function of the flux linkage of the magnetic circuit. Based on the proposed method, a simulation of a vector control system with and without saturation was carried out in the MATLAB software environment. Comparison of the simulation results showed that neglecting saturation leads to an increase in the motor rotor slip by 0.0111 relative units and, as a result, to a decrease in the rotor efficiency by 1.02 %. The disadvantage of the article is the lack of a comprehensive approach to considering the “motor – converter – load – control system” system.

In [20], all complex electrical machines, their control circuits, and embedded systems used for the practical implementation of these circuits are listed. It was determined that the induction motor and the permanent magnet synchronous motor were the most efficient and suitable alternative for driving electric vehicles. Furthermore, since torque and speed can be controlled simultaneously with minimal noise and ripple, the FOC approach remains an ideal control method. A limitation of the paper is the lack of actual motor load tests, comparing theoretical and practical performance.

The autonomous voltage inverter belongs to the most common types of power conductor converters used in various industries, which is due to the widespread use of asynchronous motors [21]. One of the key performance indicators of an autonomous voltage inverter is its energy efficiency, which largely depends on the sinusoidality of the output voltage and current. Additional losses caused by higher harmonics in the load, which is usually an asynchronous electric motor, depend on these parameters. The results of the study of the energy characteristics of autonomous voltage inverters when using various modulation algorithms and in the remodulation mode are discussed in detail in [22–26].

In [27], a review of the advances in the field of brushless synchronous motors is presented, as there is a growing interest in advanced motor control and overcoming the shortcomings of traditional motor control. Traditional motor control strategies are simple and easy to maintain, however, they require fine tuning and are dependent on changes in motor parameters. To address these and many other issues (power factors, torque ripple, current limiting, voltage limiting, speed limiting), advanced control techniques are needed to improve the performance of motor drive control. Advanced control methods include predictive model control, sliding mode control, reinforcement learning, and fuzzy logic. This article provides a comprehensive review of advances in control methods and discusses the challenges and limitations associated with their practical application. The paper is limited by the lack of practical verification of the research results.

The publication [28] aims to improve high-performance control strategies for brushless direct current (BLDC) motors in electric vehicles, with a particular emphasis on the use of an electronic differential system (EDS) – a rear differential control system. The experimental results show that the inclusion of the electronic differential gives promising results. These results demonstrate the improved efficiency of the electric vehicle's propulsion system, highlighting the positive impact of electronic differentials on overall performance. A limitation of the publication is the lack of consideration of modern energy efficiency requirements.

The article [29] notes that the control characteristics of a brushless DC motor (BLDCM, a complex nonlinear system) significantly determine the control characteristics of an electromechanical drive. In order to find a more effective control method for it, this paper takes the Hall sensor-based BLDCM as the research object and presents three control methods: «single closed-loop control method based on the speed loop», «double closed-loop control method based on the speed loop and current hysteresis loop», and «double closed-loop control method based on the fuzzy controlled speed loop and current hysteresis loop». Modeling, simulation, and comparison of control systems based on these three control methods show that the third method, which uses the deviation and deviation coefficient of the reference speed and feedback speed as inputs, and outputs the current reference value through fuzzy proportional-integral control and current hysteresis, has the best tracking performance (e.g., short regulation time and no overshoot in the regulation process) when the speed command or load changes suddenly. The results of this work provide a certain theoretical basis and reference value for the research, design, and practical application of the control method of BLDCM and electromechanical drive.

In [30], the use of a fuzzy logic-based closed-loop speed control approach for brushless direct current (BLDC) motors in electric vehicles is investigated to overcome the shortcomings of traditional control methods by improving dynamic performance, response time, and stability under varying load conditions and parameter uncertainties. This is achieved by using a state space modeling method for a BLDC motor incorporating a fuzzy logic controller (FLC) for precise speed control. The results show that the FLC provides smooth speed transitions, no overshoot, and zero steady-state error with a settling time of only 0.05 s, as opposed to 0.1 s for the PID controller. According to these results, FLC is a better option for controlling BLDC motor speed in electric vehicles, guaranteeing efficient driving force, less mechanical stress, and greater driving stability.

Publications [31–34] are devoted to the study of the energy efficiency of rolling stock with an asynchronous electric drive.

Defining the purpose and objectives of the research. The purpose of the article is to conduct a comprehensive analysis of operating conditions and assess the energy efficiency of modern brushless traction motor control systems used in traction rolling stock, to determine their advantages, disadvantages and promising areas of improvement, which will allow formulating recommendations for choosing optimal algorithms and technical solutions for specific operating conditions of traction rolling stock. To achieve the goal, the following tasks were set:

– to review the design features and characteristics of modern brushless traction motors;

– analyze existing management methods and identify their strengths and weaknesses;

– to investigate methods for assessing the effectiveness of control systems in different operating modes;

– consider the hardware implementation of control systems and measuring instruments;

– to review the experimental part and model validation;

– compare and summarize the results obtained.

The main part of the research.

Design features and characteristics of modern brushless traction motors. The development of electric traction over the past decades has led to the transition from DC collector machines to brushless electric motors, which are characterized by increased reliability and energy efficiency. Today, two main types of brushless motors are used in traction drives of rolling stock:

1. Induction Motors (IM), which are characterized by the fact that [35, 36]:

– is the most common type of traction machine due to its simple rotor design (short-circuited «squirrel cage»), lack of contact nodes, and low cost;

– have high reliability, the ability to operate in overload modes, and good dynamic properties;

– the disadvantage is the relatively lower efficiency compared to permanent magnet synchronous machines, especially in low load modes, as well as the need to implement complex control algorithms to achieve high efficiency.

2. Permanent Magnet Synchronous Motors (PMSM), which are characterized by the fact that [37, 38]:

– magnets based on rare earth materials (NdFeB, SmCo) are used in the rotor, which ensures high power density and efficiency (up to 95–97 %);

– the advantages are compactness, low losses, and the ability to operate in a wide speed range;

– disadvantages are high cost due to the use of expensive magnets, complexity of thermal regime, sensitivity to demagnetization during overloads and high temperatures.

A relatively new type of brushless motor that combines simplicity of design with precision control capabilities are valve-inductor motors. They are highly reliable due to the absence of windings on the rotor and show excellent performance at low speeds. However, at present, valve-inductor motors have not yet become widespread in rail transport, and they can be found mostly only on experimental rolling stock.

The design features of brushless traction motors, first of all, can be summarized as follows [39, 40]:

1) stator – a three-phase winding with distributed or concentrated coils, made taking into account minimization of steel losses and increasing the slot filling factor;

2) rotor: for IM – aluminum or copper short-circuited cage; for PMSM – embedded or surface permanent magnets;

3) refrigeration – usually (oil, water) or wind – an important aspect for traction motors, motor parts operate at high temperatures;

4) diagnostic systems – temperature, vibration, flow and voltage sensors, which allow you to control the motor operation in real time.

Analysis of scientific works [41–45] makes it possible to equalize the characteristics of asynchronous motors and synchronous motors with permanent magnets (Table 1).

Table 1

Equalization of characteristics of asynchronous motors and synchronous motors with permanent magnets

Characteristic	IM	PMSM
Efficiency, %	90–94	95–97
Power density	Medium	High (up to 20–30 % more)
Cost	Lower	Higher (due to magnets)
Reliability	Very high (simple rotor)	High, but depends on the preservation of the magnets
Control algorithms	Need complex (FOC, DTC), especially for energy efficiency	FOC is widely used, provides high efficiency
Overloading capacity	Good, resistant to short-term overloads	Limited due to the risk of demagnetization of magnets
Service	Minimal, simple design	Minimal but necessary temperature control
Using	Locomotives, metro, electric trains	Light transport, high-speed trains, trams, electric buses

Regarding application, it can be noted that induction motors are widely used in locomotives of the Siemens, Alstom, Hyundai Rotem series, as well as in the Kyiv and Kharkiv metros after modernizations, induction motors with permanent magnets are increasingly being introduced in new models of trams, electric buses, and high-speed trains (for example, Shinkansen in Japan).

Brushless traction motor control systems. The efficiency of brushless traction electric motors is largely determined not only by their design characteristics, but also by the choice of control algorithm. Modern control systems provide [46]:

– precise torque and speed control;

– weak field mode to extend the speed range;

– energy efficiency optimization;

– possibility of regenerative braking;

– protection of power and electromechanical parts;

– generation of controlled voltage/current by the inverter and simulation to achieve the required physical values on the motor;

– reduction of torque ripple and noise, as well as improvement of dynamic response.

In the practice of traction rolling stock, the following algorithms are most common [47–50]:

1) vector control (FOC) – involves transition to the *dq* coordinate system, where the stator current is decomposed into two components: i_d – controls the magnetic flux, i_q – determines the electromagnetic torque. Thus, the control becomes similar to the control of a DC motor, which greatly simplifies the regulation. The advantages of vector control include high dynamic response, smooth torque regulation, high accuracy across the entire speed range, and the ability to implement energy-saving strategies (MTPA, MTPV). Disadvantages include requiring precise knowledge of motor parameters (inductances, resistances, magnetic fluxes), and complexity of real-time implementation (requires a DSP/FPGA controller);

2) Direct Torque Control (DTC) – directly controls torque and magnetic flux using the inverter voltage vector. This is done by measuring stator currents and estimating the flux state. The advantages of this algorithm include very fast dynamic response, simpler structure than FOC (fewer transformations), high stability when changing motor parameters.

Disadvantages include high torque and current ripple, noisy operation, limitations in the low-speed range;

3) optimizing algorithms (MTPA, MTPV, recovery):

– MTPA (Maximum Torque per Ampere) – a strategy that minimizes current consumption at a given torque, allowing to reduce losses in the windings;

– MTPV (Maximum Torque per Voltage) – used in high-speed modes when the inverter voltage is limited, allows you to obtain maximum torque at the available voltage value;

– regenerative braking – recuperation optimization algorithms allow for maximum energy return to the network or storage, which is critically important for urban transport (frequent starts/stops);

4) sensorless control methods – often used to increase reliability and reduce system cost (without a rotor speed/position sensor). These methods include:

– estimation of rotor position by electromotive force (EMF observer);

– adaptive state observers;

– MRAS-based methods (Model Reference Adaptive System).

The advantages of using sensorless control methods are a reduction in the number of sensors (and, as a result, higher reliability) and lower operating costs, the disadvantages are a decrease in accuracy at low speeds and the need for complex evaluation algorithms [51, 52].

Comparative characteristics of the considered control systems are given in Table 2.

Table 2

Comparative characteristics of control systems

Algorithm	Torque accuracy	Dynamics	Losses/efficiency	Realization	Typical applications
FOC	High	High	Low losses, MTPA/MTPV capability	Complicated	Trams, metro, electric trains
DTC	Medium	Very high	Slightly higher ripple losses	More simple	Locomotives, heavy duty
MTPA/MTPV	High	High	Optimized losses	Used together with FOC	High-speed transport
Sensorless	Medium	Medium	Sensor savings	Complex models	Electric buses, metro

Regarding promising areas of development of control systems, the following can be noted [53, 54]:

– adaptive and predictive control – allows you to predict the state of the drive several steps ahead and minimize losses in real time;

– artificial intelligence and neural networks – to optimize torque, reduce losses and identify motor parameters in operation;

– integration with the transport energy system – optimization of motor operation together with energy storage systems.

Electric drive modeling and efficiency assessment methods. Evaluating the efficiency of brushless traction motor control systems is impossible without the use of mathematical modeling [55]. It allows you to study the operation of the drive in different modes, obtain loss and efficiency maps, and determine optimal control algorithms for specific operating conditions.

A flow-oriented *dq* model (in synchronously rotating coordinates) is usually used to model brushless machines.

The stress equations in the dq coordinate system for PMSM have the form [56]:

$$\begin{cases} u_d = R_s i_d + L_d \dfrac{di_d}{dt} - \omega_c L_q i_q; \\ u_q = R_s i_q + L_q \dfrac{di_q}{dt} - \omega_c \left(L_d i_d + \psi_f \right), \end{cases} \quad (1)$$

where u_d, u_q is the voltages on the d and q axes;

i_d, i_q is the currents on the d and q axes;

L_d, L_q is the inductances;

R_s is the stator winding resistance;

ψ_f is the magnetic flux;

ω_c is the electrical angular velocity.

The torque of an electric motor is defined as:

$$M_c = \frac{3}{2} p \left(\psi_f i_q + \left(L_d - L_q \right) i_d i_q \right), \quad (2)$$

where p is the number of pole pairs.

Similar models exist for induction motors taking into account slip and inductive currents in the rotor [57–60].

To correctly assess energy efficiency, the following losses are taken into account:

– losses in windings (copper):

$$P_{Cu} = 3 I^2 R_s; \quad (3)$$

– losses in steel (P_{Fe}) – hysteresis, eddy current (depend on frequency and induction);

– mechanical losses (P_{mech}) – friction in bearings, ventilation/cooling;

– losses in the inverter (P_{inv}) – losses due to switching transistors, losses due to conduction of power switches and diodes;

– additional losses (P_{add}) – due to current harmonics, due to parasitic effects in the windings and magnetic core.

The total system losses can be defined as:

$$P_{loss} = P_{Cu} + P_{Fe} + P_{mech} + P_{inv} + P_{add}. \quad (4)$$

Then the efficiency can be defined as:

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}}. \quad (5)$$

To obtain a generalized assessment, an efficiency map is constructed - a contour graph that displays the efficiency value in the «torque – speed» coordinates. The X axis shows the speed (revolutions/minute or rad/s), the Y axis shows the torque (N·m), and the cells show the efficiency contours (%). The map allows you to assess the ranges where the drive operates most efficiently and the modes where losses increase sharply.

Possible operating scenarios for simulation could be the following:

– acceleration – from 0 to operating speed, evaluation of dynamics and losses in transient modes;

– constant motion (cruise) – at different speeds and loads;

– regenerative braking – assessment of energy returned to the grid;

– frequent stops/starts – typical of urban transport;

– overload modes – operation with a torque higher than the nominal, heating assessment;

– temperature effect – increased winding resistance and degradation of PMSM magnets.

The following tools can act as modeling software:

– MATLAB/Simulink (Simscape Electrical) is the most common tool for modeling electric drives, allowing you to implement FOC/DTC and estimate losses;

– PLECS (Piecewise Linear Electrical Circuit Simulation) – convenient for modeling power circuits and thermal processes in power switches;

– ANSYS Maxwell/Motor-CAD – used for detailed electromagnetic analysis and calculation of losses in steel;

– LTspice/PSIM – used for analyzing inverter circuits.

The effectiveness assessment methodology includes:

– building a mathematical model of the motor and inverter in MATLAB/Simulink;

– implementation of the control algorithm (FOC or DTC);

– conducting simulations in typical modes (acceleration, steady motion, braking);

– calculation of losses (in copper, in steel, mechanical, inverter);

– construction of efficiency maps for each algorithm;

– comparison of results (FOC vs. DTC, with and without optimizations);

– determining modes in which energy consumption is minimal and formulating recommendations.

Hardware implementation of control systems and measuring instruments. The efficiency and reliability of brushless traction motors depend not only on the control algorithm, but also on the hardware of the drive. The main components are: power inverter, microprocessor controller, current and voltage sensors, position and temperature sensors, cooling and diagnostic systems.

The power inverter generates a three-phase voltage to power the motor from a DC source (catenary, battery, supercapacitor). The main requirements for traction system inverters are as follows [61]:

– high reliability during long-term operation;

– ability to work with high currents (hundreds of amperes);

– high switching frequency to minimize ripple;

– minimal losses on power switches.

Typical components are:

– IGBT modules (Insulated Gate Bipolar Transistor) are the standard in traction technology [62];

– SiC-MOSFETs (Silicon Carbide) are promising, allowing to increase the switching frequency and reduce losses, especially in urban transport [63, 64];

– LC filters – to reduce harmonics and electromagnetic interference [65, 66].

FOC, DTC and adaptive algorithms require high-performance computing platforms. The following microprocessor controllers can be used:

– DSP (Digital Signal Processor) – TI C2000 family, Infineon Aurix;

– FPGA (Field Programmable Gate Array) – for fast calculations, complex algorithms and parallel signal processing;

– ARM/Microcontroller – for auxiliary functions (protection, monitoring).

The main functions of the controller include:

– generation of PWM signals for inverter control;

– execution of control algorithms in real time;

– processing of signals from sensors;

– diagnostics and communication with the upper control level (CAN, Ethernet, MVB).

Sensors and measuring instruments include:

– current sensors – shunt resistors, Hall effect sensors, optical current sensors (in high-voltage circuits);

– voltage sensors – voltage dividers, isolated transformer sensors;

– rotor position sensors – encoders (optical, magnetic), resolvers (high accuracy, used in traction drives), sensorless estimators (based on electromotive force);

– temperature sensors – thermistors (Pt100, NTC), thermocouples in the winding and bearing area, infrared sensors for contactless monitoring.

Traction motors and inverters operate in harsh conditions and generate significant heat fluxes. Therefore, it is necessary to use appropriate cooling systems:

– air cooling – used in less powerful drives (trams, electric buses);

– liquid cooling is standard for locomotives and powerful electric trains, and can be water or oil;

– thermal sensors are a mandatory element for controlling modes and preventing overheating.

To ensure reliability and safety of operation, diagnostic and protection systems are used, which, in particular, provide for:

– insulation monitoring and leakage current control;

– diagnostics of the condition of the windings (assessment of partial discharges, analysis of current harmonics);

– overheating and overload detection;

– inverter self-diagnostic systems (key failure, abnormal currents);

– remote data transmission to the rolling stock technical monitoring system.

Examples of modern hardware solutions are:

– Siemens SITRAS – inverters for metro and trams on IGBT modules;

– Mitsubishi Electric – traction converters with SiC transistors for high-speed trains;

– Bombardier MITRAC – complex control systems with integrated diagnostics;

– Alstom ONIX – inverter with optimized cooling system.

Experimental part and model validation. Experimental studies are a necessary stage in confirming the correctness of mathematical modeling and the effectiveness of brushless traction motor control systems. They allow:

– check the accuracy of the calculated data;

– identify additional losses not accounted for in the model;

– assess the reliability of the hardware;

– to formulate recommendations for implementation in real operating conditions.

A typical stand for researching a traction electric drive consists of [67, 68]:

– brushless traction motor (PMSM or asynchronous) – the object of study;

– power inverter – controlled by a PWM controller that implements FOC or DTC;

– control systems – DSP/FPGA controller with data acquisition software;

– load module – electrodynamic brake, generator with rheostat or second motor that simulates the load;

– cooling systems – for stable operation during long-term tests;

– measuring equipment – current sensors (Hall effect), voltage sensors, encoders/resolvers for determining the rotor position, temperature sensors in the winding and bearing area, computer data acquisition system (DAQ).

The tests are carried out in several stages:

– no-load operation – estimation of steel losses and mechanical losses, measurement of magnetizing current;

– load characteristics – measurement of torque dependence on current, construction of mechanical characteristics at different rotation speeds;

– acceleration and braking mode – assessment of transient dynamics, analysis of recuperation performance;

– thermal tests – monitoring of heating of windings and power switches, determination of limit modes;

– energy indicators – calculation of instantaneous and average efficiency values, comparison of losses in different modes (FOC vs. DTC).

The most common measuring instruments used during testing are:

– oscilloscopes – for analyzing voltage and current waveforms;

– power analyzers (Yokogawa, HIOKI) – for accurate determination of efficiency;

– high-sampling-rate data acquisition (DAQ) systems;

– thermal imagers and thermocouples – for monitoring temperature fields;

– vibroacoustic sensors – for monitoring mechanical defects.

The model validation procedure consists of:

– comparison of mechanical characteristics – experimental results vs. simulation (torque–velocity);

– loss assessment – analysis of differences between calculated and measured losses, introduction of correction factors into the model;

– construction of efficiency maps – comparison of experimental efficiency maps with model ones, verification of optimal operation ranges;

– checking control algorithms – analysis of the quality of torque and speed regulation, assessment of system stability during transient processes.

The expected results of experimental studies are usually:

– confirmation of the adequacy of the mathematical model;

– determining the real limits of drive efficiency;

– clarification of the influence of parasitic losses and temperature factors;

– formation of practical recommendations for implementation on traction rolling stock.

Comparison and generalization of results. After conducting mathematical modeling and experimental studies, the results obtained are compared for different control systems for brushless traction motors [69–72].

1. Comparison of simulation and experimental results:

– mechanical characteristics (torque–speed) should practically coincide in the calculated and experimental data. The deviation should usually not exceed 5–7 %, which would confirm the adequacy of the mathematical model;

– losses in windings and steel in the model are usually slightly underestimated, since the experiment takes into account additional parasitic effects (harmonics, heating of conductors);

– the efficiency map from the experiment usually turns out to be more «narrowed», that is, the real area of maximum efficiency is slightly smaller than in the simulation.

2. Comparison of control algorithms:

– FOC – high accuracy of torque and speed regulation, smooth transients, stable operation in a wide speed range, slightly lower efficiency at high speeds due to increased switching losses;

– DTC – very fast dynamics, simpler control algorithm, increased torque and current pulsations, higher value of losses in steel due to uneven flows;

– adaptive and optimization algorithms (taking into account temperature, minimizing losses) – the best energy performance, the ability to maintain optimal mode in real time, require more computing power of the controller.

3. Energy efficiency:

– on average, the efficiency of the traction electric drive on FOC is 92–94 %;

– for DTC – 90–92 %;

– for adaptive FOC with loss minimization – up to 95 %;

– regenerative braking modes are particularly effective – up to 25–30 % of the driving energy can be returned to the network or battery.

4. Reliability and performance:

– FOC provides the smoothest drive operation and lower vibration levels;

– DTC is more reliable in terms of simple control structure, but requires harmonic filtering;

– Adaptive methods require expensive hardware (FPGA, high-end DSP) and more complex debugging.

5. Practical recommendations:

– for urban electric transport (trams, electric buses) it is advisable to use FOC with recovery and optimization for minimum losses;

– for high-speed trains and locomotives, it is advisable to combine FOC with adaptive temperature and current control algorithms;

– DTC can be effective for systems where speed is critical, such as in magnetic levitation trains or specialized drives;

– the use of SiC transistors in inverters allows for an increase in efficiency by 2–3 % compared to traditional IGBTs;

– it is necessary to integrate online diagnostic systems to monitor temperature, insulation status and switching parameters.

Thus, the analysis showed that modern control systems for brushless traction motors provide a high level of energy efficiency and reliability. The best results are achieved when using FOC with adaptive loss optimization algorithms, as well as using inverters based on SiC elements. This allows you to reduce energy consumption by 5–10 %, increase efficiency up to 95 %, and increase the durability of equipment, which is critically important for rail transport and urban power systems.

Conclusions. Modern control systems for brushless traction motors provide a high level of energy efficiency (up to 95 %), reliability, and control flexibility. The combination of vector control algorithms with adaptive strategies and the use of the latest power electronics (SiC) opens up opportunities for further reducing energy consumption and increasing the resource of traction rolling stock. This makes such systems one of the key areas of development of modern means of transport.

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

– the analytical review showed that the most common control algorithms are FOC and DTC. They provide high dynamic and energy characteristics, but differ in control accuracy, ripple level, and hardware implementation requirements;

– performing mathematical modeling in the MATLAB/Simulink environment allows you to build efficiency maps, estimate losses in different modes (acceleration, steady state, regenerative braking) and confirms the effectiveness of FOC and DTC in different operating conditions;

– the main losses of an electric drive include: winding losses, steel losses, mechanical losses and inverter losses. Their accurate accounting is the key to improving efficiency;

– conducting experimental research is aimed at confirming the adequacy of the model: the differences between theoretical and practical results usually do not exceed 5–7 %.

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Panchenko Serhii Volodymyrovych, Doctor of Science (Tech.), Professor, Acting rector, Ukrainian State University of Railway Transport. E-mail: panchenko074@ukr.net. ORCID ID: 0000-0002-7626-9933.
Babaiev Mykhailo Mykhailovych, Doctor of Science (Tech.), Professor, Head of Electrical Energetics, Electrical Engineering and Electromechanics Department, Ukrainian State University of Railway Transport.
E-mail: mmbxiit@gmail.com. ORCID ID: 0000-0003-3553-8786.

Nerubatskyi Volodymyr Pavlovych, Candidate of Technical Sciences, Associate Professor, Associate Professor of Electrical Energetics, Electrical Engineering and Electromechanics Department, Ukrainian State University of Railway Transport. Tel.: +38 (095) 045-78-01. E-mail: NVP9@i.ua. ORCID ID: 0000-0002-4309-601X.

Панченко Сергій Володимирович, доктор технічних наук, професор, в.о. ректора, Український державний університет залізничного транспорту. E-mail: panchenko074@ukr.net. ORCID ID: 0000-0002-7626-9933.
Бабаєв Михайло Михайлович, доктор технічних наук, професор, завідувач кафедри електроенергетики, електротехніки та електромеханіки, Український державний університет залізничного транспорту.
E-mail: mmbxiit@gmail.com. ORCID ID: 0000-0003-3553-8786.
Нерубацький Володимир Павлович, кандидат технічних наук, доцент, доцент кафедри електроенергетики, електротехніки та електромеханіки, Український державний університет залізничного транспорту.
Тел.: +38 (095) 045-78-01. E-mail: NVP9@i.ua. ORCID ID: 0000-0002-4309-601X.

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