ISSN 2413-3833 (Online), ISSN 1681-4886 (Print)

UDC 621.313 DOI: https://doi.org/10.18664/ikszt.v31i1.357736

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Features of the use of brushless motors in traction rolling stock

Abstract. *The review study examines a range of technical, design, and operational features of modern brushless valve and asynchronous traction electric machines, which are widely used in locomotive construction and transport electric drives. The object of research is electromagnetic, thermal, and energy processes occurring in brushless valve and asynchronous traction motors during their operation in traction rolling stock systems. The design features of brushless traction motors are analyzed, which are characterized by high energy efficiency, increased specific power, the absence of a mechanical collector, as well as the ability to provide wide ranges of torque and speed control while minimizing maintenance. The specifics of working processes in valve and asynchronous motors have been identified, which are determined by the principles of electromagnetic conversion, control methods, and the response of an electric machine to variable loads. Compare the features of electromagnetic torque formation, commutation, and thermal modes of these motors in traction systems. Special attention is paid to the issues of regulating the rotation speed of asynchronous traction motors, which is implemented using frequency converters with scalar, vector, and direct control methods. The advantages of vector control, which ensures dynamic stability and maximum utilization of the motor's overload capacity in traction and recuperation modes, have been identified. The structural and technological features of designing asynchronous traction motors for locomotives have been studied, in particular the requirements for the magnetic system, rotor strength, cooling systems, and electrical insulation materials. The trends in the development of modern traction electric machines are summarized, in particular, the introduction of energy-efficient materials, the expansion of the operating frequency range, the improvement of thermal reliability, and the integration of the motor with power electronics into single electromechanical modules.*

Keywords: *brushless traction motor, electric machine, locomotive, traction electric drive, asynchronous motor, valve motor, converter, energy efficiency.*

Relevance of the research topic.

The relevance of researching the features of using brushless (valve and asynchronous) traction motors in rail transport is due to the need to improve the energy efficiency, reliability, and environmental friendliness of rolling stock. Modern transportation requirements are driven by the need to reduce operating costs, increase maintenance intervals, and ensure stable operation under high loads. Brushless motors, thanks to the absence of a commutator-brush assembly, demonstrate improved dynamic performance, longer service life, and lower maintenance costs. Research into their design features, operating modes, and control methods is important for the development of efficient electric traction systems, the modernization of locomotives, and the introduction of innovative technical solutions in rail transport.

Introduction.

The current development of rail transport is characterized by increasing demands for energy efficiency [1–4], reliability [5–7], and environmental friendliness [8–10] of traction electric drives. In the context of the transition to intelligent control systems and the growth in transport volumes, it is becoming increasingly important to optimize traction electric drives, which determine the dynamic, energy, and operational properties of rolling stock [11, 12].

An important trend in recent decades has been the widespread integration of semiconductor converters into traction systems, which has opened up opportunities for the use of various types of electric motors, primarily valve and asynchronous motors [13–15]. These two types of electric machines are currently considered the dominant solutions for locomotives, electric trains, subway trains, trams, and city electric buses, and comparing them is a key step in the technical and economic justification of the choice of power equipment (Table 1).

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Internal switching			External switching	
With mechanical switching (collector)		With electronic switching (valve)	Asynchronous motors	Synchronous motors
Alternating current	Direct current	Alternating current	Direct current	
Universal; Repulsive	DC commutator motor with different excitation windings; Permanent magnet DC commutator motor	Brushless DC motor; Valve jet motor; Synchronous jet motor with salient pole rotor	Asynchronous motor with squirrel cage rotor; Asynchronous motor with phase rotor	Synchronous motor with excitation winding; Synchronous motor with permanent magnets; Synchronous motor with built-in permanent magnets; Synchronous motor with surface-mounted permanent magnets; Hybrid synchronous jet motor; Synchronous jet motor with permanent magnets; Synchronous jet motor with permanent magnets, reactive-hysteresis; Stepper motor
Simple electronics	Straighteners	More complex electronics	Complex electronics	

Valve motors, which operate in conjunction with inverter commutation and modern control systems, combine high dynamic characteristics with the absence of a mechanical commutator, which has traditionally been a factor in increased wear in classic DC motors [17, 18]. Thanks to their ability to precisely control electromagnetic torque, these motors are gaining popularity in areas of rail transport where it is important to achieve a wide range of speed control and limit energy losses at low and medium speeds. In addition, the prospect of using synchronous valve motors with permanent magnets increases interest in this technology, as it provides increased specific power and high efficiency in a compact size [19].

Asynchronous traction motors, on the other hand, are characterized by their simple design and exceptional reliability. The absence of a commutator and a simple squirrel-cage rotor ensure high service life, low maintenance requirements, and resistance to adverse operating conditions such as dust, moisture, shock loads, and temperature fluctuations [20]. Thanks to the development of frequency converters, vector control, and direct torque control algorithms, asynchronous motors have been able to provide traction properties that were previously only available to DC motors [21]. This has made them the primary choice in many countries when modernizing locomotive fleets and designing new high-speed and freight electric locomotives.

The comparison of valve and asynchronous motors in the context of rail transport is complex, as it includes an analysis of energy performance, dynamic properties, recuperation capabilities, power electronics reliability, operational suitability, life cycle costs, and specific applications in various types of traction electric drives. Another important factor is the impact of the motor type on the control system, traction control functions, smooth start-up, acceleration performance, and compliance with international standards for energy efficiency and reduced operating costs [22].

Therefore, research into the characteristics of valve and asynchronous motors in railway traction rolling stock is relevant from both a scientific and practical point of view. It allows determining the optimal technical solutions for specific operating conditions, formulating recommendations on the choice of electric drive type for new and modernized locomotives and electric trains, and contributes to improving the efficiency of railway transport in general.

Analysis of recent research and publications. The paper [23] presents a critical analysis of traction electric motors for distributed traction systems of high-speed rail transport, taking into account their design and electromagnetic characteristics. The main advantages and disadvantages of different types of motors are considered, and the limitations of structural modeling of stator elements and windings are outlined. At the same time, the study is of a review nature and does not fully take into account operating modes and dynamic loads in real operating conditions.

Review work [24] is devoted to a comparative assessment of the main types of traction motors in terms of torque density, efficiency, and economic efficiency. The limitation of the study is its focus only on generalized integral indicators without taking into account the specifics of operating modes and operating conditions.

In [25] an overview of current achievements in the field of brushless synchronous motors is presented, driven by the need to improve control methods and eliminate the shortcomings of traditional PI controllers, which, despite their simplicity, are sensitive to changes in motor parameters. To improve control efficiency, particularly taking into account current, voltage, speed, and torque ripple limitations, modern approaches are used: predictive control, slip mode control, fuzzy logic, and reinforcement learning. At the same time, the work mainly summarizes theoretical results, while the issues of experimental verification and adaptation of methods to real operating conditions remain limited.

In the work [26], an improved model of an asynchronous traction motor was developed, which takes into account the temporal change in magnetic losses in steel. The study was performed using mathematical modeling in MATLAB, the results of which determined the average values and time diagrams of magnetic losses in nominal mode with comparison to the motor's passport data. The limitation of the study is that it considers only the nominal mode without taking into account transient and non-nominal modes of operation.

Article [27] provides a comparative analysis of FOC and DTC control strategies for a permanent magnet synchronous motor in an automotive drive based on modeling in MATLAB/Simulink. Their main advantages and disadvantages in terms of performance are evaluated, which made it possible to determine the appropriate areas of application for each method. At the same time, the results are limited by the conditions of mathematical modeling, accepted assumptions, and the lack of experimental verification on a real object.

The materials [28] provide a comprehensive overview of modern traction motor topologies for railway transport. Key aspects of their electromagnetic design, cooling systems (mainly air-cooled) and insulation systems of classes H and N are considered. A comparison of different topologies is provided, taking into account operational requirements, and their main advantages and disadvantages for different types of rolling stock are identified. The main trends in the development of traction motors are also outlined. However, the review is general in nature and is limited mainly to traditional railway applications without detailed quantitative analysis and experimental verification of the results.

The paper [29] presents the results of designing and manufacturing a basic linear asynchronous motor for traction applications. The main design concepts common to rotating electrical machines are considered; the rotor is made of aluminum sheet on an iron core, and the stator has a two-layer two-pole winding. However, the study is limited to a laboratory sample and does not cover issues of scaling and operational characteristics in real conditions.

Summarizing the above-mentioned literary sources, it can be noted that modern research in the field of brushless traction motors focuses mainly on comparative analysis of types of electric machines, improvement of control methods, and development of approaches to electromagnetic design. At the same time, most of the work is of a review or model nature and is limited to considering individual operating modes, integral efficiency indicators, or idealized operating conditions without comprehensive consideration of dynamic loads and real traction modes. The relationships between the design features of brushless traction motors, the patterns of their operating processes, and the control methods used remain insufficiently systematized. This necessitates further analysis of the designs of valve and asynchronous traction motors, the characteristics of their operating processes, methods of regulating rotation speed, and approaches to the design of asynchronous traction motors for locomotives from the perspective of ensuring high operational and energy performance.

Defining the purpose and objectives of the research.

The purpose of the article is to comprehensively evaluate and systematize the design features, regularities of working processes and control methods, as well as to formulate key principles for the design of modern high-efficiency brushless traction motors, which will increase energy efficiency, improve traction characteristics, and ensure increased operational reliability of traction electric drives for locomotives and motor-car rolling stock. To achieve this goal, the following tasks were set:

– to analyze the design features of modern brushless traction motors;

– to identify the features of the working process of valve and asynchronous traction motors;

– to consider methods of regulating the rotation speed of asynchronous traction motors;

– to investigate the design features of asynchronous traction motors for locomotives.

The main part of the research.

Design features of modern brushless traction motors. Modern electric traction systems for rolling stock are characterized by high requirements for energy efficiency, reliability, weight and size parameters, and operational durability. The production trend of recent decades has been a transition to brushless valve (BLDC/PMSM) and asynchronous traction electric motors integrated with semiconductor converters based on IGBT/SiC modules [30, 31]. The design of motors has undergone significant changes due to the development of materials, cooling technologies, digital control systems, and optimization methods of electromagnetic modeling [32].

Compared to DC motors, both valve electric motors and asynchronous machines have a number of well-known disadvantages: rigid mechanical (speed) characteristics, increased sensitivity to power supply voltage fluctuations, and, in railway operation, even more stringent requirements for the permissible diameters of the running wheels [33]. However, these limitations can be compensated for by using static semiconductor frequency and voltage converters with the necessary feedback channels in automatic control systems [34, 35]. The use of such conversion devices makes it possible to form the speed characteristics of brushless motors in accordance with specified operating requirements. It is possible to ensure the required overload capacity ratio in terms of torque, while voltage fluctuations at the output of modern static converters, which power brushless motors, practically do not occur [36, 37]. The compounding effect is formed due to the system of interrelationships between individual links of the converter. Increased requirements for the accuracy of rotating wheel diameters are largely eliminated by block power supply to the motors of two-axle or three-axle bogies. In addition, asynchronous electric drives are characterized by a «run-in effect» of the wheels when traction motors are powered by a single common converter [38].

This list of considerations should also include the characteristics specific to brushless motors: increased reliability (due to the absence of a commutator); lower weight and dimensions, which allows for the integration of a more powerful motor with a given diameter of the moving wheel; lower complexity of operational maintenance. Finally, due to the significantly lower rotor torque of an asynchronous motor compared to a DC motor, the dynamic impact on the gear transmission and track is reduced [39].

In traction valve motors, the most common design is a permanent magnet synchronous machine (PMSM). The electromagnetic torque is generated by the interaction of the rotor's permanent magnet field with the stator's alternating field, which is created by an inverter using FOC (Field Oriented Control) or DTC (Direct Torque Control) algorithms. This achieves a virtually linear dependence of torque on current over a wide speed range.

The rotor design determines most of the characteristics of a PMSM. Three main types are used [40, 41]:

– SPM-rotor (Surface Permanent Magnet), where magnets are installed on the surface of the rotor. The advantages are maximum flux density; the disadvantage is greater sensitivity to centrifugal loads;

– IPM-rotor (Interior Permanent Magnet), where magnets built into the rotor volume form so-called magnetic barriers. This provides increased mechanical strength, reduces the risk of demagnetization, and allows operation in field weakening modes;

– combined structures, which are a combination of surface and internal magnets to reduce harmonic components of torque.

The topologies of the PMSM rotor for high-speed drives are shown in Fig. 1.

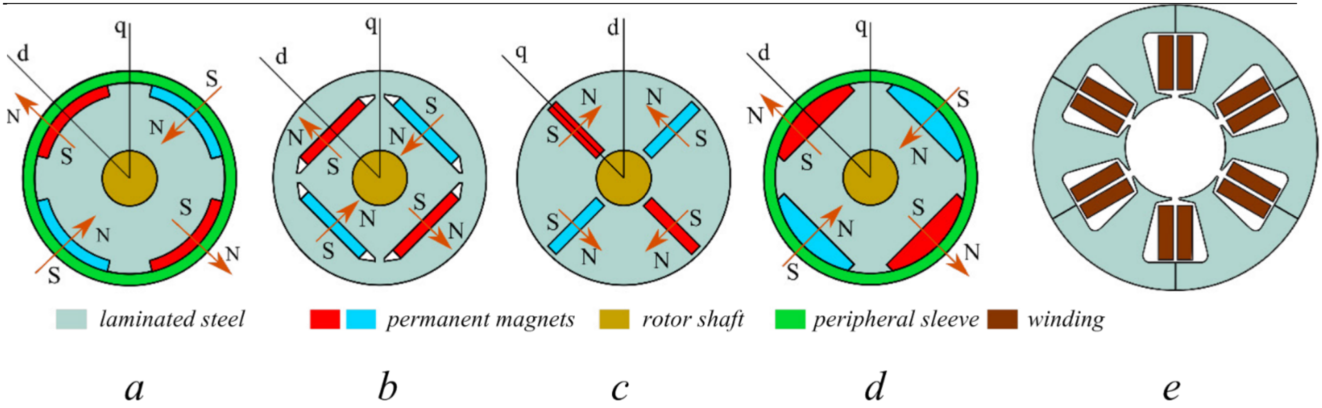

Fig. 1. PMSM rotor topologies with direct and quadrature axes marked [42]:

a – SPM-rotor with peripheral (external) bandage shell;

b – IPM-rotor with tangentially integrated permanent magnets;

c – IPM-rotor with radially integrated permanent magnets;

d – SPM-rotor with permanent magnets of the «bread loaf» type and peripheral band shell; *e* – general stator design

Magnets are made of NdFeB or SmCo, using special anti-corrosion coatings (Ni–Cu–Ni, epoxy composites) and designs that prevent mechanical damage at high speeds [43, 44]. Table 2 shows the electrical conductivity and magnetic permeability values of common materials used in typical structural elements of high-speed permanent magnet motors, including permanent magnets, shells, and spindles.

2

General parameters of electromagnetic materials [45]

Material	Electrical conductivity σ, S/m	Relative permeability μ_r
NdFeB	$6.25 \cdot 10^5$	1.07
Sm_2Co_{17}	$1.11 \cdot 10^6$	1.06
35CrMo	$3.94 \cdot 10^6$	1.0
Carbon fiber	$3.33 \cdot 10^4$	1.0
Stainless steel	$1.10 \cdot 10^6$	1.0

The motor stator is distinguished by the use of high-alloy electrical steel with a thickness of 0.2–0.3 mm to reduce eddy current losses, optimization of slot shapes to minimize torque ripple, the use of concentrated windings in high-pole designs, and improved heat dissipation thanks to longitudinal ventilation and cooling channels [46, 47].

Insulation materials belong to classes H or F, which ensures permissible operating temperatures up to 180 °C [48, 49].

Traction PMSMs typically feature cooling systems such as stator liquid cooling using a closed coolant circuit, oil splash cooling for high-load motors, and direct winding cooling in the latest designs (channels inside copper conductors) [50]. Heat dissipation efficiency is critical because overheating can cause partial demagnetization of the rotor.

PMSM traction motors operate exclusively with converters based on IGBT (traditionally) and SiC MOSFET, which allows increasing the switching frequency and reducing the weight of passive components [51, 52]. Control systems include rotor position sensors (resolvers, optical or magnetoresistive encoders), high-speed digital controllers, torque optimization algorithms, and magnetic harmonic loss minimization algorithms.

Unlike PMSM, an asynchronous motor generates torque through electromagnetic induction in the rotor, which operates in slip mode. The torque generation mechanism determines the need for precise control of the frequency and amplitude of the power supply, which is implemented by IGBT/SiC-based inverters [53, 54].

Asynchronous traction motors with squirrel-cage rotors are practically identical in their internal structure to standard asynchronous electric motors of similar power used in general industrial installations. The rotor winding in such motors is a «birdcage» type design: aluminum, obtained by die casting, is optimal for medium-duty motors; copper with a special profile, which provides better conductivity and reduces slip losses, is used in locomotive traction. The mechanical features of the rotor of an asynchronous motor include increased thickness of the bars in areas of maximum current load, special channels and holes for internal cooling, and rigid fastening of the end rings to ensure strength at high speeds [55].

The stator is made of laminated electrical steel with slots for three-phase winding. The stator of an asynchronous motor is characterized by the use of steels with low hysteresis and eddy current losses, optimization of the shape of the slots to minimize spatial harmonics, the use of class F or H insulation, and the use of impregnation to increase the mechanical resistance of the windings to centrifugal forces and vibrations [56].

The traction motor housing, its mounting elements to the bogie frame, and the motor-axle bearings are similar in design to the corresponding components of DC or rectified current motors with similar power and voltage ratings.

Asynchronous motors have a developed cooling system: forced air cooling – for trams and electric trains; water liquid cooling of the stator – for locomotives and mainline systems; centrifugal rotary cooling, which uses the rotation of the rotor to force air through.

Asynchronous electric motors are characterized by increased sensitivity to voltage drops. Thus, when the voltage drops by 10%, the torque decreases by approximately 19 % [57, 58]. Unlike general-purpose asynchronous machines, traction asynchronous motors have specific design features due to the peculiarities of their operation on locomotives. These features include: power supply from a frequency and phase converter, the need to place significant power in limited dimensions determined by the design of the locomotive's running gear [59].

In traction collector motors of electric locomotives with an axial ventilation system, approximately 30 % of the air flow passes through the air gap, ensuring intensive heat removal from the surfaces of the armature and poles. In traction asynchronous motors, on the contrary, in order to reduce the magnetizing current and increase the power factor cosφ, the air gap between the stator and rotor is minimized as much as possible, subject to design and technological limitations. However, axial independent ventilation does not provide effective cooling of the stator and rotor surfaces facing the air gap. In order to improve heat dissipation and increase the volume of air passing between the stator and rotor, super-pass ventilation channels are used in the design of traction asynchronous motors. About 30 % of the total cooling air flow passes through them.

The height of the slot channel is usually $(1.0...1.5)\cdot b_{ss}$, where b_{ss} denotes the width of the stator slot [60]. In valve motors, the use of super-slot channels in the stator design is impractical, as they increase the inductive resistance of the stator by approximately 40%, which causes a decrease in electromagnetic (rotational) torque. However, for asynchronous machines, such an increase in the inductive resistance of the stator is not critical, since the commutation process in them is forced.

In multipole electric machines, active materials are used more efficiently, which allows the asynchronous motor to operate with lower electrical losses and provides an increase in efficiency [61]. The characteristics of the motor and locomotive as a whole are also influenced by the nominal and maximum frequencies of the current supplying the stator winding.

There are certain design limitations associated with the use of bearings, whose maximum rotational speed is only 3000–4000 rpm. In addition, there are difficulties in implementing a traction gearbox with a high transmission ratio. The number of poles of an asynchronous traction motor also affects the level of losses in the converter [62–64]. To minimize them, it is necessary to take the frequency (speed) ratio coefficient at the level of 2.5.

From a design perspective, the advantages of an asynchronous traction motor compared to a brushless valve motor are the absence of magnets, which contributes to high reliability and thermal stability, greater resistance to overloads, lower production costs, and a simpler heat dissipation system [65].

From the point of view of traction application, both types of electric machines have specific advantages. A comparative characteristic of BLDC/PMSM and asynchronous motors is given in Table 3.

Comparative characteristics of BLDC/PMSM and asynchronous motors [66]

Parameter	BLDC/PMSM motors	Asynchronous motor
Excitation source	Permanent magnets	Induction in the rotor
Energy density	High	Medium
Efficiency coefficient, %	95–97	92–95
Reliability	Average (risk of magnet overheating)	Very high
Cost	High	Low
Recovery mode	High efficiency	Effective, but inferior
Control	Complex with sensors	Somewhat simpler
Maintenance	Minimal	Cheap and affordable

Features of the working process of valve and asynchronous traction motors.

The traction electric drive with a valve motor consists of a synchronous electric motor, a valve converter, a smoothing reactor, and a rotor position sensor. The voltage coming from the secondary winding of the transformer is converted by a thyristor converter into an alternating voltage of controlled frequency and fed to the stator windings of the synchronous motor. The motor speed and the applied voltage frequency are kept in constant correlation. The process of switching the frequency converter valves on and off is carried out strictly in accordance with the actual spatial position of the rotor; the rotor shaft is equipped with a sensor, the signals from which are sent to the thyristor control system. If the thyristor switching moment does not correspond to the actual position of the rotor, a braking moment occurs in the system. When powered by an AC mains supply, valve switching at low frequencies is provided by the mains voltage itself, and at higher frequencies by the electromotive force of the synchronous motor [67].

The specificity of the valve motor's operating process lies in the fact that the stator winding terminals are sequentially disconnected to the linear voltage of the converter. Each phase conducts current for one third of the conversion period. Provided that the winding is correctly designed, the distribution of the magnetizing force along the pole pitch of the electric machine approaches sinusoidal [68]. If the number of slots per pole and phase is equal to one, the magnetizing force of one phase is evenly distributed over a 120° section of the stator. For phase current I_d, the amplitude of the first harmonic of the resulting magnetizing force is determined by the geometric sum of the magnetizing forces of the active phases, between whose vectors there is an angle of 60°.

This phase connection sequence generates a rotating magnetizing force in space. In a two-pole machine ($p = 1$), this magnetizing force shifts by 360° during one current period, i.e., it makes one full revolution. Since the windings are switched six times per period, the rotation of the magnetizing force is realized in the form of six steps of 60°.

The converter control system generates pulses to turn on the thyristors of the next phase every 1/6 of a period, i.e., every 60°, as soon as the magnetic axis of the rotor shifts by the corresponding angle. In this case, the rotor axis lags behind the resulting magnetizing force of the stator by an angle $\theta = 30°$.

The jump-like displacement of the magnetic field vector causes torque pulsations with a frequency six times higher than the rotation frequency [69]. In traction systems, such fluctuations usually do not affect the operation of the electric drive due to the large inertia of the masses set in motion by the traction motors. However, the discrete nature of the resulting field displacement places serious demands on the thyristor control system. The rotation speed sensor signal must also contain information about the angle θ, since the electromagnetic torque depends on it. The control pulse to the thyristor connecting the next phase should be applied at the moment when the torque becomes less than its average value. For motors operating under stationary loads, it is not difficult to ensure the required angular alignment between the rotor and the resulting magnetic field. However, with sudden load changes, which are typical for traction electric drives, the certainty and accuracy of sensor signals are significantly reduced.

When the direction of the torque applied to the shaft changes, the valve motor automatically switches to braking mode with energy recovery without additional switching in the power circuit, i.e., to generator mode, which is permitted by the converter. At the same time, the sign of the angle θ also changes, and the rotor begins to lead the magnetic field of the stator.

When an electric machine is operating in generator mode, the activation of maximum protection leads to increased voltage on the rotor slip rings. This value may exceed the rated excitation voltage by an order of magnitude. For high-power electric motors (1500 kW and above), it is necessary to use a discharge resistor that automatically connects to the rings when the protection is activated [70].

The use of asynchronous motors with squirrel-cage rotors as traction motors is only possible if they are powered by a frequency and voltage converter equipped with appropriate feedback loops in the automatic control system of the traction electric drive [71]. This type of power supply provides the necessary traction characteristics across a wide range of motor speeds. The converter regulates the frequency and voltage level according to the specified operating mode.

The physical mechanism of electromagnetic driving force formation is generally similar to the processes in a valve motor, but differs in that the current flows through three phases simultaneously, with its value in one of the phases being twice that in the other two [72]. The change in phase currents, as in a valve motor, is abrupt in nature, which is caused by the opening and closing of the inverter valves. The distribution of the magnetizing force in the air gap becomes step-like. The graph of instantaneous phase voltage values practically repeats this shape. It should be noted that the main spatial harmonic of the magnetizing force, and therefore the induction it creates in the gap, does not move uniformly at a constant angular velocity, but makes jump-like movements at 60° intervals.

Methods for regulating the rotational speed of asynchronous traction motors. Regulating the speed of asynchronous traction motors is a key element of electric drive control in transport systems, particularly in trams, trolleybuses, electric trains, and locomotives. The rotational speed of an asynchronous motor rotor is determined by the synchronous rotational speed of the magnetic field and the slip value [73]. Therefore, effective speed control requires targeted influence on the electromagnetic state of an electric machine by changing the frequency and amplitude of the supply voltage, as well as by optimizing energy conversion processes.

The frequency of traction electric motors varies within a very wide range – from fractions of a hertz at the initial moment of start-up, when the train begins to move from a standstill, to approximately 200 Hz when the motor reaches its maximum rotational speed, which corresponds to the maximum operating speed of the rolling stock. At low frequencies, the active resistance of the stator winding becomes comparable to its inductive resistance.

During locomotive operation, three main control zones are usually distinguished: train start-up and acceleration mode; steady power mode; high speed mode accompanied by magnetic field weakening.

During start-up, the traction electric motor must generate a torque that is 1.5 to 2 times higher than its nominal value. This result is achieved by correctly selecting the ratio between the supply voltage and frequency [74, 75]. To implement automated control of the electric drive, it is necessary to use feedback systems for rotation speed and current [76].

During acceleration, as speed increases, the power of the traction motors also increases. The maximum speed at the end of the start-up mode is determined by the endurance power of the power source. For electric locomotives, this available power is significantly greater than for diesel locomotives. With the same coupling weight of locomotives, the power of an electric locomotive that can be used to generate traction is 1.4 to 1.5 times greater than that of a diesel locomotive. This is because a diesel locomotive has more massive mechanical equipment, as it is equipped with a primary energy source – a diesel motor – and must carry the fuel supply necessary for its operation.

At low frequencies, similar to valve motors, electromagnetic torque pulsations occur in asynchronous traction electric machines. As the supply voltage frequency increases, the amplitude of these pulsations decreases. Increasing the frequency at a constant voltage causes the motor's magnetic field to weaken and the traction force to decrease.

For high-speed electric locomotives, it is possible to provide power close to the nominal value even at maximum speed. This is an important advantage of asynchronous traction motors compared to DC machines, whose power at high speeds is limited by commutation conditions in a weakened magnetic field. Only motors with compensation windings can provide approximately 80 % of continuous power at maximum speed. Asynchronous motors do not have such limitations and are usually capable of developing continuous power at maximum speed if the converter is designed for the corresponding increased voltage level.

The most common and technically advanced method is to regulate the supply voltage frequency using semiconductor converters – frequency inverters [77]. The control law is based on maintaining a constant *U*/*f* ratio, which ensures approximately constant magnetic induction in the air gap and prevents core saturation. Frequency control is highly efficient because it allows the synchronous rotation speed to be changed smoothly and operates over a wide speed range with minimal losses.

For traction electric drives requiring high dynamic characteristics, vector control of the rotor (Fig. 2) or stator flux linkage is used.

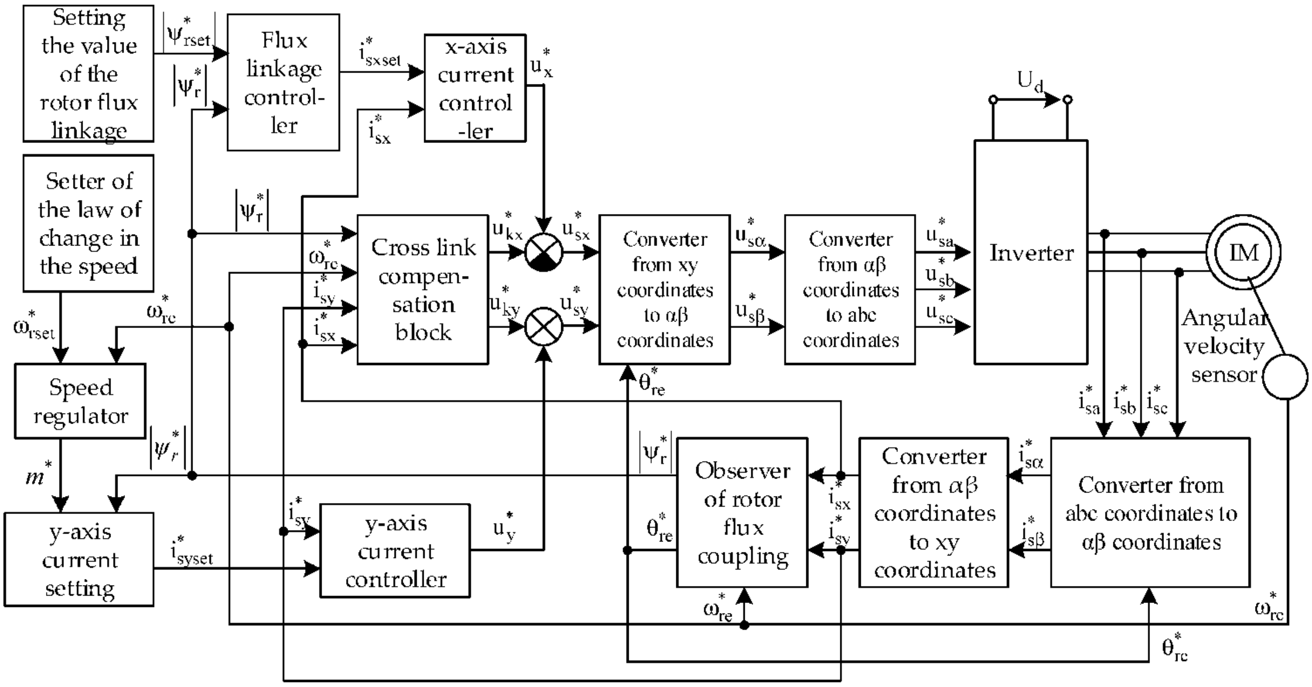

Fig. 2. Structural block diagram of the vector control system for an asynchronous electric motor [78]

This method provides independent control of the current and torque components, making the asynchronous motor equivalent to a DC motor in terms of dynamics [79, 80]. The advantages are accurate torque control, high speed, and the ability to operate at low speeds and high overloads, which is important for traction applications.

Direct torque control provides extremely fast traction motor regulation, as the algorithm directly generates torque and flux linkage based on data from current and voltage sensors. Direct torque control requires high switching frequencies and complex digital control systems, but provides minimal time delay and good resistance to parametric deviations.

Classic methods, such as changing the resistance in the rotor circuit of phase rotor motors, are rarely used in modern traction systems due to high losses, bulky equipment, and low energy efficiency. However, historically, this method was used to gradually reduce speed and improve starting characteristics.

In traction asynchronous motors, cyclic load changes, starting and recuperative modes, as well as requirements for high starting torque at low speeds are significant [81]. Fig. 3 shows the speed and torque characteristics of an asynchronous motor, which consists of three zones: the braking zone, the movement zone, and the generation zone.

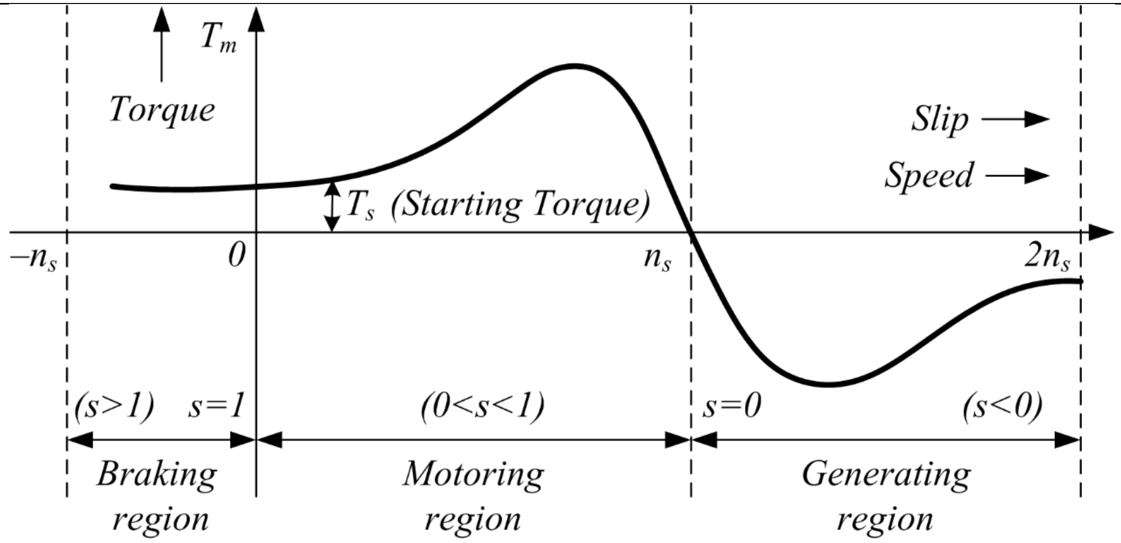

Fig. 3. Speed and torque characteristics of an asynchronous motor [82, 83]

The use of frequency and vector control makes it possible to achieve high torque across a wide frequency range, ensure smooth vehicle operation, reduce energy losses, and expand the capabilities of regenerative braking.

Features of designing asynchronous traction motors for locomotives. The design of asynchronous traction motors for locomotives is associated with the need to ensure high dynamic and energy performance in difficult operating conditions. Requirements for such electric machines include high overload capacity, reliability under prolonged mechanical and thermal loads, as well as resistance to fluctuations in traction network parameters and environmental conditions.

When designing asynchronous traction motors, the output parameters are selected in the same way as those used for DC traction motors. AC traction systems equipped with their own conversion units allow the selection of a motor voltage level that makes its design optimally light and compact, as well as improving its operating characteristics.

One of the key features of the design is the optimization of the motor's electromagnetic system, taking into account the wide range of operating frequencies and voltages provided by the traction drive converters. Since the torque of an asynchronous motor depends on slip and magnetic flux, the design of the stator and rotor magnetic circuit must minimize losses, prevent saturation, and maintain stable characteristics under variable supply frequency conditions [84].

Special attention is paid to the rotor design. For traction machines, cage rotors made of copper or highly conductive aluminum alloys are usually used, which increases efficiency and reduces slip losses in high-load modes [85]. Eliminating the oblique arrangement of the slots reduces additional losses during operation under load. These losses must be taken into account, considering the non-sinusoidal nature of the supply voltage. To ensure high-quality casting, the minimum width of the rotor slot at its narrowest point should be 3–5 mm. For motors with a power rating of over 1000 kW, it is possible to use a rotor with a short-circuited copper winding and trapezoidal profile bars. The geometry of the rotor bars and ring elements is designed to ensure the necessary mechanical strength under the action of centrifugal forces at high speeds, as well as sufficient thermal stability during start-up and recuperative modes. After determining the rotor speed at the maximum speed of the locomotive, the required range of supply voltage regulation is set.

The stator design must combine high electromagnetic efficiency with the ability to dissipate heat intensively. When selecting the number of pole pairs in the stator winding, the conditions for reliable operation of semiconductor converters at limit frequencies must be taken into account. Several typical configurations are usually considered to assess their impact on motor performance. A larger number of poles is typically characteristic of high-power motors. Reducing the number of poles causes a decrease in the output voltage frequency, which, in turn, allows for a reduction in the weight of the converter. At the same time, this design solution leads to an increase in the length of the stator winding end pieces, which causes an increase in the overall length of the electric machine. In addition, the height of the stator back increases due to the increase in magnetic flux, which causes an increase in the outer diameter of the stator. The outer diameter of the traction motor frame is limited by the dimensions of the rolling stock and the size of the center. The maximum permissible length of the stator package is mainly determined by the number of poles and the diameter of the stator's inner cavity.

Traction motors use a reinforced insulation system, the front parts of the windings are fixed with mechanically stable elements, and the ventilation system – forced or combined – is designed taking into account the dustiness and humidity of the environment. When insulating the stator windings, insulation materials belonging to thermal classes F and H should be used [86, 87].

Engineering requirements also include optimizing weight and size parameters and ensuring ease of maintenance. The motor must have a compact design that allows it to be integrated into the locomotive's bogie area and guarantees access to components for repair [88]. The desire to reduce the size and weight of the motor leads to a tendency to increase the supply voltage frequency. In addition, it is important to ensure the motor's resistance to vibration loads and shock impacts characteristic of railway transport.

Strict requirements for mass and dimensional characteristics, effective cooling, and the use of high-quality steels and high-class insulating materials allow for increased electromagnetic loads [89]. To achieve the required starting torque and high overload capacity, the stator slots must be open [90]. The most optimal design solution for stator windings, which should be strived for, is a two-layer winding with two conductors per slot. This completely eliminates the possibility of coil short circuits and ensures maximum reliability of the stator winding [91]. However, due to the limitations imposed by calculations, it is not always possible to implement such a design.

Modern control systems for asynchronous traction motors based on vector control influence design features, as they allow flexible changes to the operating parameters of the electric machine, optimizing the magnetic flux and currents depending on the operating mode [92]. This requires accurate calculation of the parameters of the equivalent motor circuit and coordination of the characteristics with the capabilities of the power converter.

The designed electric motor must be tested for stability against overturning in various operating modes. Thus, in the starting mode, it is necessary to ensure a stability reserve at maximum torque sufficient to prevent overturning. The calculation of traction asynchronous electric motors is generally similar to the calculation of conventional asynchronous machines. To obtain the required operating characteristics, this calculation is performed for different values of voltage and supply frequency.

The integration of asynchronous traction motors for locomotives with power electronics into single electromechanical modules is one of the key trends in the development of modern traction electric drives for rail transport. This approach involves the constructive and functional integration of an electric machine with semiconductor frequency converters, control systems, and auxiliary units into a compact module with a single cooling system and electromechanical interfaces. This makes it possible to significantly reduce the length of power connections, reduce parasitic inductance and energy losses, and improve the electromagnetic compatibility of the traction electric drive.

The use of modular architecture helps to increase the specific power and reliability of the traction motor by optimizing the thermal conditions of both the windings of the electric machine and the power semiconductor elements. The joint design of the motor and converter allows for the coordination of winding parameters, power supply frequency range, and control algorithms, which reduces electromagnetic torque ripple, improves dynamic characteristics, and reduces acoustic noise. In addition, integration facilitates the implementation of modern vector and predictive control methods aimed at improving energy efficiency and adapting to changing operating conditions (Table 4).

4

Advantages and disadvantages of different traction drive control methods [93, 94]

Control method	Advantages	Disadvantages
Scalar	– simple design; – affordability	– ineffective dynamic response; – low torque control; – inaccurate control

Vector	FOC	
	– effective dynamic characteristics; – ability to achieve full torque at zero speed; – fixed switching frequency	– need for feedback; – cost; – compared to DTC and MPC, it reacts more slowly; – requires an external modulator, which is more complex
	DTC	
	– extremely fast dynamic response; – non-sensory; – lightweight construction; – low processing time	– high torque and current ripple compared to FOC; – oscillating switching frequency; – very difficult to regulate at low speeds; – greater sensitivity to motor characteristics
Predictive	– cost-effective and improved energy savings; – improved transient response; – prediction of future control actions and time savings during the calculation process	– requires determination of the appropriate system model; – installation costs may be high
Touchless	– better noise immunity; – less complex hardware and higher durability; – low maintenance requirements	– high installation cost

Another important advantage is the simplification of installation, maintenance, and standardization of traction electric drives for different types of locomotives. Uniform electromechanical modules create the conditions for a transition to plug-and-play concepts in locomotive construction, which reduces rolling stock downtime and overall operating costs. At the same time, the implementation of this approach requires solving complex problems of thermomechanical compatibility, vibration resistance, and electrical insulation, which determines the relevance of further scientific research in this field.

Thus, the design of asynchronous traction motors for locomotives is a complex process that combines electromagnetic, mechanical, thermal, and operational aspects. Competent integration of these factors ensures high efficiency of the traction electric drive, reliability in difficult operating conditions, and reduced operating costs.

Conclusions.

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

– modern brushless traction motors demonstrate significant progress in design due to the absence of a commutator-brush assembly, which reduces losses and ensures high reliability in heavy-duty locomotive operation. The use of permanent magnets increases specific power and efficiency, while optimized stators and cooling systems allow operation with high currents and torques. Designs are focused on reducing weight, improving heat dissipation, and integrating with converters, making brushless motors promising for modern transportation;

– the operating processes of valve and asynchronous traction motors have fundamental differences that determine their performance characteristics. In valve machines, torque is generated by electronic commutation and precise control of phase currents, which ensures high efficiency and stable traction. In asynchronous motors, the processes are determined by the slip and interaction of the rotor with the rotating magnetic field, which allows them to operate efficiently over a wide range of loads. Both types have advantages, but differ in dynamics and sensitivity to mode changes;

– the speed control of asynchronous traction motors is based on the use of frequency converters that change the ratio of voltage and supply frequency. Scalar control is easy to implement but has limited dynamics. Vector methods allow precise control of flux linkage and torque, maintaining efficiency in traction and braking modes. This allows asynchronous motors to operate under conditions of sudden load changes and provides optimal energy performance for locomotives;

– the design of asynchronous traction motors for locomotives requires consideration of increased mechanical and thermal loads, which necessitates optimization of the magnetic circuit, rotor, and ventilation system. Designers are focusing on increasing the strength of the cage rotor, using special alloys, and improving insulation materials. It is also important to ensure effective integration of the motor with the converter and adaptation to different traction modes. Modern approaches are aimed at improving reliability, efficiency, and durability in the harsh conditions of locomotive operation.

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Нерубацький В. П. Особливості застосування безколекторних двигунів на тяговому рухомому складі.

Анотація. *В оглядовому дослідженні розглянуто комплекс технічних, конструктивних та експлуатаційних особливостей сучасних тягових електричних машин безколекторного вентильного та асинхронного типів, що широко застосовують у локомотивобудуванні і транспортних електроприводах. Об'єктом дослідження є електромагнітні, теплові та енергетичні процеси, що протікають у безколекторних вентильних і асинхронних тягових двигунах під час їхньої роботи в* *системах тягового рухомого складу. Проаналізовано конструктивні особливості безколекторних тягових двигунів, для яких характерні висока енергоефективність, підвищена питома потужність, відсутність механічного колектора, а також можливість забезпечення широких діапазонів регулювання моменту і швидкості за мінімізації обслуговування. Виявлено специфіку робочих процесів у вентильних і асинхронних двигунах, що визначена принципами електромагнітного перетворення, методами керування та реакцією електричної машини на змінні навантаження. Порівняно особливості формування електромагнітного моменту, комутації і теплових режимів цих двигунів у тягових системах. Окрему увагу приділено питанням регулювання частоти обертання асинхронних тягових двигунів, що реалізовано за допомогою перетворювачів частоти зі скалярними, векторними та прямими методами керування. Визначено переваги векторного керування, яке забезпечує динамічну стабільність і максимальне використання перевантажувальної здатності двигуна в режимах тяги і рекуперації. Досліджено конструктивні і технологічні особливості проєктування асинхронних тягових двигунів локомотивів, зокрема вимоги щодо магнітної системи, міцності ротора, систем охолодження та електроізоляційних матеріалів. Узагальнено тенденції розвитку сучасних тягових електричних машин, зокрема впровадження енергоефективних матеріалів, розширення діапазону робочих частот, підвищення теплової надійності та інтеграції двигуна з силовою електронікою в єдині електромеханічні модулі.*

Ключові слова: *безколекторний тяговий двигун, електрична машина, локомотив, тяговий електропривод, асинхронний двигун, вентильний двигун, перетворювач, енергоефективність.*

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Стаття надійшла 08.02.26
Стаття прийнята до друку після рецензування 14.03.26
Стаття опублікована (оприлюднена) 27.04.26