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Research into methods and means of controlling brushless traction motors of locomotives based on modern power converters

Abstract. *The object of the study is the electromechanical and energy conversion processes occurring in brushless traction electric drives of locomotives during the implementation of traction and regenerative braking modes. The paper examines approaches aimed at improving the energy efficiency and operational reliability of traction systems through the justified selection of power converter topologies and modern methods of controlling the electromagnetic torque of traction motors.*

The structural and energy characteristics of induction motors and permanent magnet synchronous motors are generalized as the main control objects within brushless locomotive electric drive systems. It is established that the operation of traction systems under railway conditions is characterized by a wide speed range, significant load variations, and the requirement to ensure bidirectional energy exchange with the traction power supply system.

The main operating modes of the traction electric drive, particularly the traction mode and the electric braking mode, are systematized, and the structural requirements for their implementation are determined. Typical configurations of power conversion systems used in DC and AC electric locomotives are summarized, including solutions based on a DC link, voltage source inverters, multilevel converters, intermediate energy conversion stages, and hybrid configurations incorporating energy storage systems.

It is shown that the efficiency of regenerative bracing and the stability of energy processes are largely determined by the capability for bidirectional energy conversion, the parameters of the DC link, and the coordination of the electric drive with the characteristics of the catenary traction power supply system. It is established that the application of modern vector control methods and direct torque regulation, and reduced energy losses in power converters.

The prospects of the considered approaches are associated with the integration of next-generation semiconductor power conversion systems, the application of energy storage devices, and adaptive control algorithms capable of operating under variable operating conditions. The results of this review study can be useful in the design and modernization of locomotive traction electric drive control systems, the optimization of regenerative braking modes, and ensuring reliable locomotive operation over a wide range of load conditions.

Keywords: *brushless traction motors, traction drive, locomotive, power converters, voltage source inverter, regenerative braking, control methods, multilevel inverters.*

Relevance of the research topic.

The relevance of research into methods for controlling brushless traction motors of locomotives is due to modern trends in the development of electric rolling stock, focused on increasing energy efficiency and reducing operating costs. Asynchronous motors and permanent magnet synchronous machines are increasingly being implemented in traction electric drives due to their high reliability, absence of a commutator-brush assembly, and improved dynamic characteristics. At the same time, their efficiency significantly depends on the use of modern power electronic converters, in particular voltage source inverters, active four-quadrant (4QS) converters, controlled rectifiers, as well as multilevel inverter structures, which provide improved output voltage quality and reduced harmonic distortion. The further development of semiconductor technologies, in particular the use of SiC devices and modular converter structures, opens new prospects for improving the efficiency and functional capabilities of traction drives.

The implementation of energy-saving modes, such as regenerative braking, becomes especially important, the effectiveness of which largely depends on the possibility of bidirectional energy exchange with the contact network and the integration of energy storage systems into the intermediate DC link. This allows for an increased utilization of regenerative energy and ensures the stability of energy processes in traction systems. In this context, the study of control methods and means for brushless motors based on modern power electronic converters represents an important direction for improving locomotive traction drives.

Introduction. The development of locomotive traction drives at the present stage is inseparably linked with the implementation of next-generation electric machines and high-efficiency power electronic devices. The transition from traditional commutator systems to brushless traction motors is driven by the desire to increase operational reliability, reduce maintenance requirements, and ensure stable energy characteristics across a wide range of operating modes. In this context, asynchronous motors and permanent magnet synchronous machines are considered as the fundamental components of modern traction drives, meeting the demands of intensive railway operation.

Brushless traction motors are characterized by high specific power, the ability to operate under significant overloads, and the capability to achieve efficient electromechanical energy conversion under variable load conditions [1, 2]. Asynchronous motors remain a widely adopted solution due to their structural simplicity and resilience to external influences, whereas permanent magnet synchronous motors provide higher energy efficiency and improved power-to-size ratios. At the same time, the realization of the potential of such machines in traction applications is determined not only by their design but also by the capabilities of control systems and electrical energy conversion [3, 4].

One of the key components of a modern traction drive is the power converter, which provides voltage and frequency shaping according to the operating modes of the motor. Voltage source inverters serve as the basis for supplying asynchronous and synchronous machines with variable-frequency alternating current, enabling flexible control of electromagnetic torque and speed. The presence of an intermediate DC link allows for the stabilization of energy processes, smoothing of ripples, and the creation of conditions for efficient interaction between the contact network and the traction motors [5, 6].

A voltage source inverter is typically implemented based on transistor power modules (IGBTs or SiC MOSFETs) and provides pulse-width modulation of the output voltage, which is a necessary condition for the implementation of modern control methods for traction machines [7, 8]. The use of a voltage source inverter makes it possible to form the required electromagnetic operating modes of the motor, maintain optimal stator current values, and ensure high dynamic performance during locomotive acceleration and braking.

Depending on the type of locomotive power supply system, different topologies of input power conversion devices are used [9, 10]. For AC rolling stock, controlled thyristor rectifiers have historically been employed, providing regulation of the voltage in the intermediate DC link; however, they are associated with limitations in terms of regeneration capability and power quality. Modern solutions are increasingly based on active four-quadrant converters, which enable bidirectional energy exchange with the grid, improve the power factor, and reduce harmonic distortion. Thus, the choice of power topology significantly affects the energy efficiency of the traction drive and the capability to implement regenerative braking.

An equally important aspect is the application of modern control methods that ensure precise torque control and optimization of energy processes. Field-oriented control (FOC) and direct torque control (DTC) methods have become widely adopted in traction systems due to their high dynamic response and ability to maintain optimal operating modes of the motor under rapidly varying load conditions [11, 12]. The effectiveness of such methods is determined both by the characteristics of the electrical machine and by the capabilities of the power converters supplying the traction motor.

Thus, a modern locomotive traction drive represents a complex electromechanical system in which the brushless traction motor, the voltage source inverter, and the input power conversion unit operate in close interaction. Achieving high energy efficiency, reliability, and the implementation of regenerative braking is determined both by the choice of power topology and by the application of effective torque and speed control methods.

Analysis of recent research and publications. In the review paper [13], more than 240 publications (2019–2025) on advanced control of asynchronous motors are analyzed. Control methods – strategies, algorithms, and sensorless approaches (Fig. 1) – are summarized, with descriptions of their operating principles, advantages, limitations, and application areas. The comparison (Table 1) demonstrates the high efficiency of artificial intelligence–based direct torque control strategies, although their industrial implementation is limited by algorithmic complexity and hardware requirements. Prospects for hybrid approaches aimed at developing high-efficiency and reliable electric drive systems are also considered.

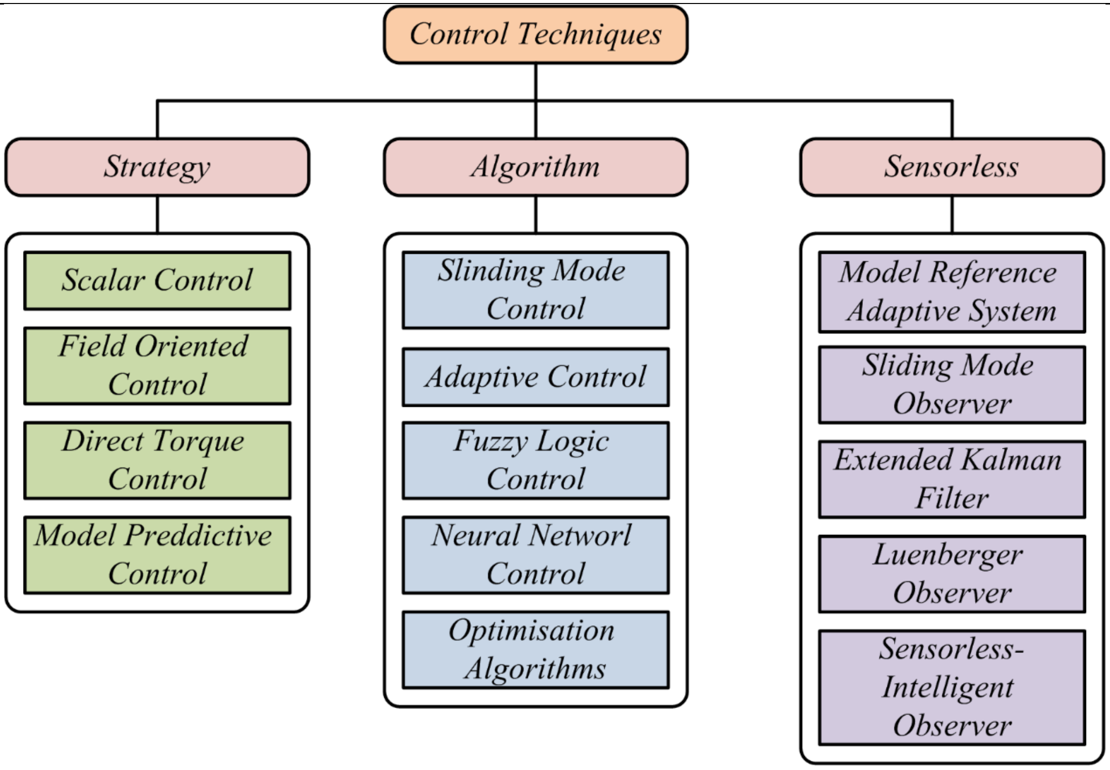


Fig. 1. Induction motor control techniques [13

b
l

Comparative evaluation of induction motor control techniques [13]

Control technique	Advantages	Disadvantages
Scalar control	– simple and cost-effective structure	– limited precision; – sensitive to parameter variations; – no direct torque control; – poor performance at low speeds
FOC	– high precision; – excellent dynamic performance; – decoupled flux-torque control	– complex transformations; – sensitive to parameter variations
CDTC	– simple structure; – fast torque response; – robust against parameter variations	– significant torque and flux ripples; – variable switching frequency
DTC-SVM	– reduced torque ripple;	– complex implementation;

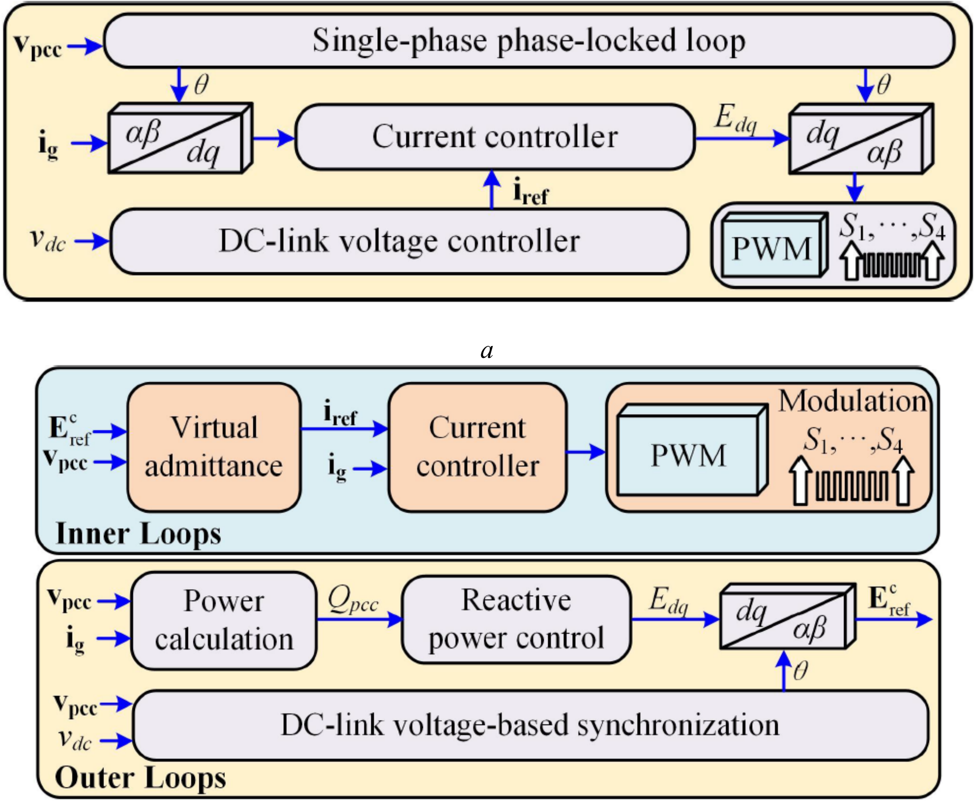
	– fixed switching frequency; – low harmonic distortion	– higher calculation charge
MPC-DTC	– significant ripple reduction; – improved dynamic response; – fast adaptation to disturbances	– high computational demand (real-time prediction); – sensitive to motor model inaccuracies
DTC-SMC	– reduced torque and flux ripples; – robust to parameter variations and disturbances; – fast convergence in transients	– chattering phenomenon; – sensitive to gain tuning
DTC-FL	– adaptive to load variations; – reduced torque and flux ripples; – enhanced robustness	– complex design and implementation; – requires high-performance processors
DTC-ANN	– ripple reduction; – high accuracy; – improved robustness; – machine learning capability	– requires large training datasets; – high algorithmic complexity; – demanding computational resources
FCS-MPC	– very high dynamic performance; – excellent control accuracy (torque, current); – low ripple; – fast response	– high computational burden; – sensitive to parameter variations; – requires fast DSP units

In [14], a combined adaptive control system for an asynchronous motor is proposed, based on passivity principles and aimed at improving drive robustness in the presence of parametric uncertainties and external disturbances. The algorithm is synthesized using an energy-based approach with Lyapunov functions and adaptive parameter update laws, which ensure a reduction in control error during transient conditions. Experimental studies have confirmed improved dynamic performance and stability compared to conventional control methods. A limitation of the study is its focus on laboratory conditions and the lack of analysis of system operation within a high-power locomotive traction drive under real grid influences.

In [15], the improvement of the control algorithm for a 4QS converter of the DS3 electric locomotive with an asynchronous traction drive is investigated, aimed at increasing the converter efficiency and reducing current harmonic distortion. Simulation results have shown that the modified algorithm reduces the discharge of the DC-link capacitor into the transformer secondary winding, thereby improving the energy performance of the drive. A limitation of the study is that the results are obtained for a single locomotive type and a specific load condition, and therefore require validation under a wider range of operating conditions.

In the article [16], a feedforward control method for a four-quadrant converter using a load current observer is considered, which allows improving the dynamic performance of the system under abrupt load changes. The integration of load current observation into the control algorithm is proposed, reducing the need for additional sensors. A comparison with conventional PI control is carried out: simulation and experimental results showed a reduction in voltage ripple and an accelerated system response. Such an approach is promising for high-power traction drives with stringent requirements for dynamic stability and power quality. A limitation of the study is that the proposed method is evaluated mainly on a model with a power of ~1.2 MW and requires further verification on real traction platforms with different grid and load parameters to confirm the universality and robustness of the approach.

In the scientific paper [17], a new grid-forming (GFM) control strategy for a four-quadrant converter in railway traction systems is proposed, adapted to the specific operating conditions of the contact network with a low short-circuit ratio (Fig. 2). Compared with standard schemes, the proposed approach significantly reduces input inrush currents (up to 10 %) and accelerates the synchronization process of the 4QS with the grid. Such control is promising for modern traction drives with stringent requirements for stability and dynamic performance.



a

b

Fig. 2. Traction 4QSs with various control strategies [17]:
a – the conventional GFL control strategy; *b* – the GFM control strategy

In the article [18], model predictive control of the torque of an asynchronous motor supplied through a voltage converter is investigated, with an emphasis on the impact of the algorithm on acoustic noise levels. It was found that predictive control (Fig. 3) allows the current harmonic spectrum to extend beyond the switching frequencies, contributing to a reduction in acoustic noise intensity compared to conventional methods. Experimental measurements confirmed the ability of the adapted control to reduce noise levels according to electric motor acoustics standards. A limitation of the study is that the test setup had low power, and the results may not fully reflect the behavior of high-power locomotive traction drives under complex operating conditions.

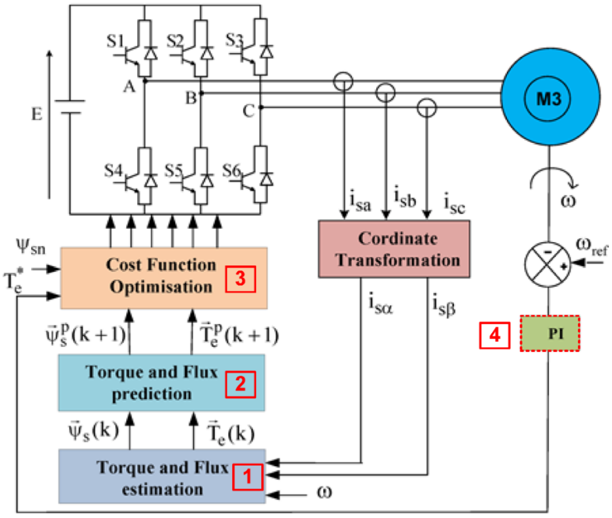


Fig. 3. The predictive torque control block diagram for an IM drive by a three-phase inverter [18]:

1 – estimation stage; *2* – prediction stage; *3* – optimization stage

The research materials [19–23] are devoted to the improvement of scalar control methods for asynchronous motors. These works examine the development of V/f control strategies, slip compensation, robust adaptation, and predictive algorithms for regulating speed and electromagnetic torque, aimed at increasing the accuracy of electromechanical energy conversion. The studies demonstrate the potential for enhancing the energy efficiency and stability of control systems for asynchronous drives under variable load conditions. At the same time, most results were obtained primarily through mathematical modeling or bench experiments, which indicates the need for further verification of the proposed approaches under real operating conditions of asynchronous drives.

In the scientific works [24–27], modern approaches to improving the energy efficiency of voltage source inverters, which are key components of control systems for brushless traction motors of locomotives, are comprehensively considered. The studies analyze the impact of various modulation algorithms on power losses and the quality of output electrical parameters. Particular attention is given to the use of impedance and quasi-impedance branches in the input circuit, which expand the functional capabilities of inverters and ensure improved energy conversion performance. These works form the scientific basis for further improvement of power converters in traction drives. A limitation of the cited publications is their focus primarily on individual operating modes of the inverters, without proper consideration of the real operating conditions of locomotive traction drives and the specifics of their operation within control systems for brushless motors.

The research materials [28–30] are devoted to the application of multilevel power converters in control systems for brushless traction drives. These works substantiate the feasibility of using multilevel inverters to improve output voltage quality, reduce current harmonic distortion, and decrease electromagnetic and acoustic ripples in traction machines. It is shown that increasing the number of conversion levels contributes to reducing the load on power semiconductor switches, improving energy efficiency, and enhancing the electromagnetic compatibility of the drive. Particular attention is given to combining multilevel topologies with robust and nonlinear control algorithms, which ensure stable operation of brushless motors across a wide range of speeds and loads. The summarized results indicate the prospects of integrating multilevel converters into the structure of modern locomotive traction drives.

The research publications [31–35] are devoted to a comprehensive analysis of control systems and energy-efficient topologies of four-quadrant converters for electric rolling stock. The works provide a detailed consideration of control algorithms for compensating 4QS converters, as well as energy-efficient solutions for three-level active rectifiers, taking into account the optimization of the power factor. Significant attention is paid to the application of modern modulation methods, which ensure stable and efficient operation of four-quadrant converters under various operating conditions. Some publications summarize technological approaches to the integration of control systems for active rectifiers in traction electric rolling stock, including the maintenance of a constant switching frequency of power switches. Overall, the materials create a systematic understanding of ways to improve the energy efficiency and reliability of locomotive drives through a comprehensive combination of technical, algorithmic, and digital solutions in the control of four-quadrant converters.

Summarizing the results of the analysis of the cited literature, it can be stated that modern research is focused on improving the energy efficiency, reliability, and dynamic performance of brushless traction motors of locomotives through the enhancement of control methods and the optimization of power converter structures and topologies. These results provide a scientific basis for the systematization of motor design features, control schemes, and traction drives as a whole, allowing for a substantiated determination of promising directions for increasing the efficiency of traction systems under various operating conditions.

Defining the purpose and objectives of the research. The aim of the work is a comprehensive review study of the methods and means of controlling brushless traction motors of locomotives (asynchronous and permanent magnet synchronous) through the analysis of their energy characteristics, modern power converter topologies, and torque and speed control algorithms. This approach allows for a substantiated consideration of ways to improve energy efficiency, reliability, and the implementation of traction and regenerative braking modes under railway operating conditions. To achieve the stated aim, the following tasks were formulated:

– to summarize the design and energy characteristics of brushless traction motors (asynchronous and permanent magnet synchronous) as control objects under railway traction conditions;

– to systematize the main operating modes and control structures of brushless traction drives of locomotives in traction and regenerative braking modes;

– to analyze the main topologies of power converters (voltage source inverters, thyristor rectifiers, 4QS converters) and determine their influence on the implementation of traction and regenerative braking modes;

– to consider modern methods of vector and direct torque control (FOC, DTC) in traction drive systems and evaluate their effectiveness depending on the type of motor and converter;

– to identify promising directions for improving the energy efficiency and reliability of control systems for locomotive traction drives.

The main part of the research.

Design and energy characteristics of brushless traction motors as control objects under railway traction conditions. Brushless traction motors, which include asynchronous machines and permanent magnet synchronous motors, are considered in modern locomotives as the main components of the electromechanical system responsible for propulsion and energy regeneration. They operate under complex railway conditions: with high starting and nominal loads, frequent changes in speed and direction, and during interaction with the contact network and the locomotive braking systems. Therefore, their study as control objects requires a comprehensive analysis of design and energy characteristics that determine the dynamics, energy efficiency, and reliability of the traction drive.

Asynchronous motors are characterized by structural simplicity and robustness [36, 37], resistance to overloads [38, 39], and low maintenance requirements [40, 41]. They are widely used in locomotives due to their reliability and ability to operate under harsh conditions. The squirrel-cage rotor provides mechanical reliability, minimizing the risk of failure under shock loads and vibration. However, as a control object, the asynchronous motor has specific features [42, 43]:

– rotor slip – the motor torque depends on the stator frequency and current, which complicates precise torque control;

– parameter variation with heating – inductance and winding resistance change, requiring adaptive control algorithms;

– limited energy efficiency at low speeds – due to low rotational frequency and losses in the phase windings.

Therefore, the use of asynchronous motors in locomotives requires the application of voltage source inverters with pulse-width modulation and modern control methods (FOC or DTC), which allow compensating for dynamic parameter variations and maintaining optimal traction modes [44, 45].

Permanent magnet synchronous motors provide high specific power and better size-to-weight ratios compared to asynchronous motors [46, 47]. The absence of rotor currents reduces losses and increases system efficiency, which is especially important for locomotives under intensive operation. Permanent magnet synchronous motors enable high dynamic response and precise torque control, ensuring optimal traction and regenerative braking modes. However, these motors have specific limitations [48, 49]:

– requirement for accurate rotor position determination – FOC or DTC methods require sensors or position estimators;

– risk of permanent magnet demagnetization – under overloads and high temperatures, magnetic properties may change, necessitating operational mode control;

– complexity of operation in the field-weakening region – at high speeds, special stator current control is required to provide the full torque range.

In railway applications, brushless motors operate in two main energy modes: the traction mode, in which the motor consumes electrical energy from the contact network to produce traction torque, and the regenerative braking mode, in which the motor operates as a generator, returning energy to the network or storage devices. This defines the key requirements for power converters: bidirectional energy exchange, current and voltage stabilization, and smooth torque control [50, 51]. Only a coordinated combination of the motor, converter, and control algorithms allows achieving high efficiency and reliability of the locomotive.

Table 2 presents a comparative characterization of the asynchronous motor and the permanent magnet synchronous motor.

Comparative characteristics of the asynchronous motor and the permanent magnet synchronous motor

Parameter	Asynchronous motor	Permanent magnet synchronous motor
Rotor design	Squirrel-cage rotor, without magnets	Rotor with high-flux permanent

		magnets
Maximum specific power (kW/kg)	0.7–1.0	1.2–1.5
Efficiency at rated operation (%)	88–92	94–97
Operating frequency/speed range	Wide, but with reduced torque at high speeds	Wide, with stable torque across the entire range
Increased starting losses	High due to rotor induction currents	Lower due to the absence of rotor currents
Need for position sensors	Not required, position control via vector method	Required for precise FOC/DTC
Torque control dynamics	Limited by slip inertia, slower response to command changes	High, fast response to command changes due to direct current control
Energy efficiency in regenerative braking mode	Medium, depends on slip and rotor resistance	High, nearly the entire torque can be fed back to the network
Reliability under harsh conditions	Very high, withstands overheating and mechanical loads	High, but requires monitoring of magnets and temperature
Effect of temperature on performance	Significant, resistance increase reduces torque	Lower, but magnets are sensitive to overheating
Maintenance requirements	Minimal, no brushes or commutators	Minimal, but the magnetic system requires periodic inspection

Thus, asynchronous and permanent magnet synchronous motors have distinct design and energy characteristics, which determine specific requirements for power converters and control methods. Their analysis is necessary for the development of optimal traction drive systems capable of providing high dynamic performance, efficiency, and operational reliability of locomotives under various operating modes.

Main operating modes and control structures of brushless traction drives of locomotives in traction and regenerative braking modes.

The operation of modern brushless traction drives of locomotives is determined by the specifics of railway service, which is characterized by significant load variations, a wide range of operating speeds, the need to perform intensive transient processes, and increased requirements for energy efficiency. Unlike stationary industrial installations, the traction drive operates under conditions of frequent mode changes, which necessitates flexible control means and the ability of the system to provide bidirectional energy exchange with the traction network [52, 53].

The main operating modes of the traction drive are traction, coasting, dynamic braking, and regenerative braking. For brushless electric machines, the traction mode involves the need to control the electromagnetic torque under variable supply frequency and voltage, which is achieved through the use of power semiconductor converters [54, 55]. Effective implementation of regenerative braking in brushless traction drives of locomotives requires modern power converters capable of providing bidirectional energy exchange between the traction motors and the network. Key conditions include stabilization of the voltage in the intermediate DC link, coordination of the traction network parameters with the drive operating modes, and ensuring the stability of the control system. In cases where the traction network has limited capacity to accept regenerated energy, a combination of regenerative and rheostatic braking is used, which leads to a reduction in the energy efficiency of the traction drive system.

The structural organization of a brushless traction drive is determined by the type of locomotive power supply system (DC or AC) and the need to generate a controllable variable voltage to supply asynchronous and synchronous motors [56, 57].

For DC locomotives, a typical structure involves energy from the contact network passing through input filtering elements to the intermediate DC link, after which a voltage source inverter generates a three-phase AC system of the required frequency for the traction motor [58, 59]. Modern systems may include multilevel inverters, which reduce harmonic distortion and increase voltage quality, as well as DC-DC intermediate stages for voltage stabilization and integration of energy storage devices. This configuration allows the implementation of both traction and braking modes, provided that appropriate means for energy exchange are available.

For AC locomotives, the structural scheme includes a transformer stage to match the contact network voltage, followed by conversion of AC to DC to form the intermediate DC link. In traditional systems, controlled thyristor rectifiers were used for this purpose, providing voltage regulation but with limited and less efficient energy regeneration capabilities back to the network [60, 61]. Modern solutions involve the use of active four-quadrant converters [62–65], multilevel voltage source inverters [66–69], and may also include intermediate DC-DC stages [70–72] and energy storage devices (supercapacitors or lithium-ion batteries) [73–76], enabling efficient implementation of traction and regenerative braking modes, stabilization of the intermediate link voltage, and improved overall energy efficiency of the locomotive. As an example, Fig. 4 shows the power structure of an AC locomotive traction drive based on an active four-quadrant rectifier and a voltage source inverter. The diagram includes the following notations: *TV* – transformer; L_1 – choke acting as a buffer reactor to increase the output voltage; C_1 – capacitor representing an energy storage capacitive filter for smoothing the output voltage (intermediate DC link); C_2L_2 – rejector filter used to filter 100 Hz harmonics in the output voltage; S_1–S_4 – power switches representing the fully controlled bridges of the 4QS rectifier; S_5–S_{10} – power switches forming the voltage source inverter; *M* – asynchronous motor.

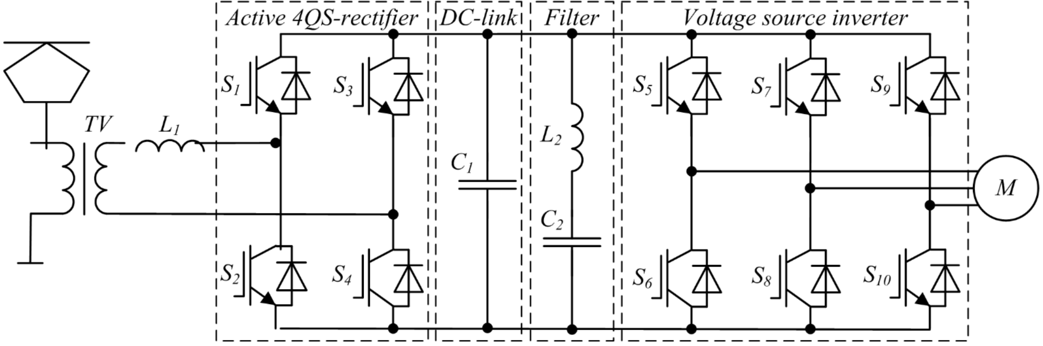


Fig. 4. Power structural scheme of an AC locomotive traction drive based on an active four-quadrant rectifier and a voltage source inverter [77–80]

A summary of the main structural configurations of brushless traction drives is presented in Table 3, showing both basic and modern enhanced architectures with multilevel inverters, intermediate DC-DC stages, and combined schemes with energy storage devices. This allows a clear illustration of the correspondence between the type of contact network, the configuration of power converters, and the capabilities for implementing traction and regenerative braking modes for both asynchronous and permanent magnet synchronous motors.

Typical structural schemes of brushless traction drives of locomotives with modern options

Type of traction network	Main structural elements	Type of traction motor	Regeneration implementation	Features (modern elements)
Direct current	Contact network → DC intermediate link → voltage source inverter → traction motor	Asynchronous or permanent magnet synchronous	Possible if the network can absorb energy	Use of multilevel inverter possible to reduce harmonics and increase voltage
Direct current	Contact network → DC-DC intermediate	Asynchronous or permanent magnet	Possible with connection of energy	The use of an intermediate DC-DC stage allows

	stage → voltage source inverter → traction motor	synchronous	storage devices	adaptation of voltage for regenerative braking and stabilization of the supply voltage
Alternating current	Contact network → transformer → thyristor rectifier → intermediate link → voltage source inverter → traction motor	Asynchronous	Limited (often rheostatic braking)	Traditional scheme; in modernized systems, addition of a DC-DC stage for link stabilization is possible
Alternating current	Contact network → transformer → 4QS converter → intermediate link → voltage source inverter → traction motor	Asynchronous or permanent magnet synchronous	Full regeneration to the network	Possible use of multilevel inverters and energy storage devices (supercapacitors, lithium-ion batteries) to improve efficiency
Alternating current	Contact network → transformer → DC-DC intermediate stage → voltage source inverter → traction motor	Asynchronous or permanent magnet synchronous	Full regeneration + energy storage	Combined scheme with a DC-DC stage and energy storage devices ensures maximum energy efficiency and control flexibility

The operating modes of brushless traction drives of locomotives are determined by the combination of railway operational requirements and the structural capabilities of power conversion systems [81, 82]. The implementation of traction and regenerative braking modes directly depends on the type of contact network, the method of forming the DC intermediate link, and the applied energy conversion schemes [83, 84].

The introduction of multilevel inverters (Fig. 5) allows reducing harmonic distortions and provides more precise control of voltage and frequency at the motors, while the use of intermediate DC-DC cascades ensures voltage stabilization, adaptation to variations in the contact network voltage, and integration of energy storage systems.

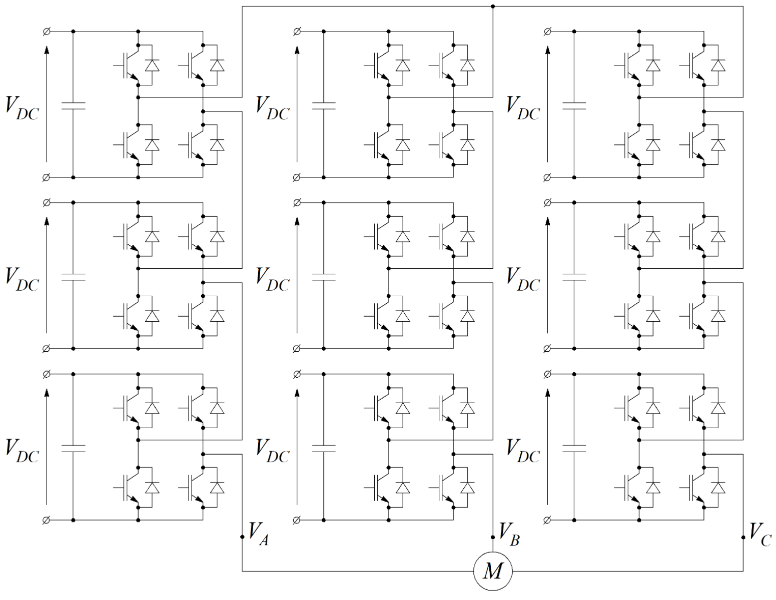


Fig. 5. Cascaded Multilevel Inverter Scheme [85]

Combined schemes with energy storage devices (supercapacitors or lithium-ion batteries) enable full regenerative braking and improve the overall energy efficiency of electric locomotives, while providing backup power during voltage fluctuations in the contact network [86, 87].

All of this necessitates a detailed analysis of the main topologies of power converters, which ensure the efficient operation of modern traction drives and allow precise implementation of traction and regenerative braking modes for both asynchronous and permanent magnet synchronous motors.

Main topologies of power converters and their impact on the implementation of traction and regenerative braking modes. Modern brushless traction drives rely on the use of various power converters, which determine the capabilities for implementing traction and regenerative braking modes [88, 89]. Classical DC electric locomotives usually employ a voltage source inverter, which generates a controlled voltage for asynchronous or permanent magnet synchronous motors. In AC systems, the role of a controlled source is performed by a transformer in combination with a thyristor rectifier, an active 4QS converter, or modern cascaded multilevel voltage source inverters, which allow the generation of a high-quality sinusoidal voltage with a low level of harmonics.

To increase flexibility and efficiency, some modern systems use DC-DC intermediate stages, which match the voltage levels between the power supply and the inverter, as well as combined schemes with integrated energy storage devices, enabling regenerative braking with energy storage for reuse [90, 91].

All these topologies determine the specific features of drive operation, torque control characteristics, and the capabilities of bidirectional energy flow. Table 4 presents the main converter topologies, motor compatibility, mode implementation, and key features of each configuration.

Main power converter topologies for electric locomotives

Type of traction network	Converter scheme	Type of traction motor	Mode implementation	Features
DC	Voltage source inverter	Asynchronous or permanent magnet synchronous	Traction and regenerative braking	Direct torque control, stable operation, enabling bidirectional energy flow
AC	Thyristor rectifier + voltage source inverter	Asynchronous or permanent magnet synchronous	Traction	Voltage control, reliable operation of classical schemes
AC	Active four-quadrant converter + voltage source inverter	Asynchronous or permanent magnet synchronous	Traction and regenerative braking	Operation in four quadrants, bidirectional energy flow, flexible torque control
AC/DC	Cascaded multilevel voltage source inverter + voltage source inverter	Asynchronous or permanent magnet synchronous	Traction and regenerative braking	High-quality voltage, low harmonic level, ability to provide high voltage to the motor
AC/DC	DC-DC intermediate stage + voltage source inverter	Asynchronous or permanent magnet synchronous	Traction and regenerative braking	Voltage matching, system flexibility, optimization of motor operating modes
AC/DC	Combined scheme with integrated energy storage + voltage source inverter	Asynchronous or permanent magnet synchronous	Traction and regenerative braking	Implementation of regenerative braking with energy storage, increased energy efficiency, provision of backup power

The choice of power converter topology determines the efficiency and dynamic characteristics of the electric drive. The voltage source inverter is a fundamental element in all considered configurations, providing controlled voltage and bidirectional energy flow. Thyristor rectifiers and four-quadrant converters determine the capabilities for controlling the electromagnetic torque and implementing regenerative braking in conventional traction drive schemes [92, 93], with four-quadrant converters providing a wider range and higher quality of control compared to thyristor rectifiers. Cascaded multilevel inverters and DC-DC intermediate stages improve the voltage spectral characteristics and enhance the controllability of the power system, while combined configurations with energy storage enable regenerative operation, optimize energy consumption, and can increase the locomotive's operational autonomy [94, 95].

Thus, the structural configuration of the power converter directly determines the capabilities for implementing traction and regenerative modes and is a key factor in the design of modern electric locomotives.

Modern vector control and direct torque control methods in traction drive systems, as well as the assessment of their effectiveness depending on the type of motor and converter. Contemporary brushless traction drives of locomotives, based on asynchronous motors and permanent-magnet synchronous machines, operate under complex conditions characterized by a wide range of speeds, significant load fluctuations, the need to implement traction and regenerative braking modes, as well as increased requirements for energy efficiency and dynamic stability [96–98].

Under such conditions, the key task of the control system is to ensure precise and fast regulation of the traction motor's electromagnetic torque, taking into account the limitations imposed by power semiconductor converters, the parameters of the contact network, and the operating modes of the DC link [99].

The use of voltage source inverters, active rectifiers, and multilevel energy conversion structures has created the prerequisites for implementing highly efficient torque control methods, among which the most common are vector control and direct torque control.

Vector control is one of the fundamental methods for designing AC traction drive systems. Its principle lies in transforming the three-phase current system into a two-component coordinate system aligned with the machine's magnetic flux vector [100]. This allows independent regulation of the components responsible for flux and torque generation, similar to the control of DC motors.

For asynchronous motors, the application of FOC ensures stable formation of the traction torque over a wide range of speeds, the possibility of operation in field-weakening at high speeds, and improvement of energy performance under variable loads [101]. For permanent magnet synchronous motors, vector control is practically the main method, as it allows achieving high torque accuracy and minimal losses in the stator windings [102]. At the same time, the implementation of FOC requires the presence of a rotor position estimation or measurement system, which is especially critical for traction modes with high torques and during regeneration [103, 104].

Direct torque control is an alternative approach in which torque and flux are regulated directly by selecting the optimal switching states of the inverter. The main advantage of DTC is its high dynamic response and the absence of the need for complex coordinate transformations in classical implementations [105]. For traction electric drives, the DTC method is characterized by features such as rapid response to load changes during acceleration and braking, increased robustness to variations in motor parameters, and the ability to operate effectively in regenerative braking mode [106, 107]. A drawback of traditional DTC is the increased level of torque ripples and the strict requirements for inverter voltage quality. Therefore, in modern systems, DTC is often combined with multilevel inverters or pulse-width modulation algorithms to reduce harmonic distortions [108].

The effectiveness of FOC and DTC methods in traction electric drives is largely determined by the structure of the power converter. The voltage source inverter is a fundamental element for generating controlled three-phase voltage for traction motors [109, 110]. Its characteristics, including switching frequency and the ability to operate in four quadrants, significantly influence the quality of torque control, torque ripple levels, and the stability of regenerative braking modes. Active four-quadrant converters used in traction systems provide controlled bidirectional energy exchange between the overhead contact line and the intermediate DC link, as well as high power quality, reduced harmonic distortions, and effective regulation of operating modes [111, 112]. Multilevel inverters contribute to improved output voltage quality, reduced torque ripples, and lower electromagnetic interference, which is especially important for high-power locomotive drives [113–115].

Table 5 presents a comparative assessment of FOC and DTC methods in traction electric drives, while Table 6 demonstrates that the choice of torque control method in locomotive traction drives is determined not only by the type of motor but also by the structure of the power converter and the capability to implement bidirectional energy exchange. Vector control is the fundamental solution for most electric locomotives, especially when using permanent magnet synchronous motors, whereas direct torque control is appropriate for high-dynamic modes when modern inverter structures are employed [116, 117].

Comparative assessment of FOC and DTC in traction electric drives

Parameter	FOC	DTC
Torque control accuracy	High	High, but with ripples
Dynamic response	High	Very high
Need for rotor position sensor	Often required	May be less critical
Torque ripples	Low	Increased
Regeneration capability	Effective	Effective, but filtering is more complex
Inverter requirements	Standard voltage source inverters	Preferably multilevel structures

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Selection of the control method depending on the type of locomotive and the power converter

Type of locomotive and power supply system	Power converter structure	Type of traction motor	Recommended torque control method	Rationale for selection
DC locomotive (3 kV)	Contact network → intermediate DC link → voltage source inverter	Asynchronous	FOC	Provides precise torque control over a wide speed range and stable operation in traction and regenerative braking modes
DC locomotive with an active regenerative energy system	Intermediate DC link + active converter or energy storage → voltage source inverter	Asynchronous or permanent magnet synchronous	FOC or DTC (with pulse-width modulation)	The presence of an active energy channel increases the efficiency of regeneration, and DTC can be used for high-dynamic operating modes
AC locomotive (25 kV, 50 Hz) – traditional structure	Transformer → thyristor rectifier → intermediate DC link → voltage source inverter	Asynchronous	FOC (primarily)	The thyristor rectifier limits regenerative capabilities, so torque stability and minimization of current ripples are required
AC locomotive with an active rectifier	Transformer → 4QS converter → intermediate DC link	Asynchronous	FOC or DTC	The active rectifier provides bidirectional energy flow, enabling

	→ voltage source inverter			efficient implementation of both traction and regenerative braking
AC locomotive with permanent magnet synchronous motors (high-efficiency drive)	Transformer → active rectifier → intermediate DC link → voltage source inverter	Permanent magnet synchronous	FOC (primary method)	For permanent magnet synchronous motors, precise control of currents and rotor position is critical; therefore, vector control is the most justified approach
Next-generation high-power locomotives	Intermediate DC link → multilevel inverter	Asynchronous or permanent magnet synchronous	FOC or DTC with optimized modulation	Multilevel inverters reduce harmonics and torque ripple, improving efficiency in both traction and braking modes
Electric locomotives with hybrid solutions	Intermediate DC link + DC-DC stage → voltage source inverter	Asynchronous or permanent magnet synchronous	FOC (primarily)	Voltage stabilization and energy storage capability make vector control optimal for smooth traction and regenerative braking modes

Thus, vector control and direct torque control are the most widely used modern methods for regulating torque in brushless traction drives of locomotives. Their application depends on the type of motor, dynamic performance requirements, regenerative operation conditions, and the structure of the power converter. FOC provides high torque accuracy and efficiency in steady-state operation, whereas DTC is characterized by enhanced dynamic response and robustness in transient processes, which is critical for traction and braking modes in railway transport.

Prospective directions for improving the energy efficiency and reliability of locomotive traction drive control systems. Improving the energy efficiency and operational reliability of traction drives is one of the key directions in the development of modern railway transport. Increasing demands for energy savings, reducing operational costs, and ensuring stable performance under intensive traction and braking conditions necessitate the enhancement of both the power components of the traction drive and the control algorithms for brushless traction motors [118, 119].

Prospective directions for the development of locomotive traction drive control systems are based on the integration of advanced power converters, the application of modern semiconductor technologies, the improvement of energy exchange with the overhead contact line, and the implementation of intelligent diagnostic methods and adaptive control [120].

One of the most promising directions is the implementation of power modules based on silicon carbide (SiC) [121]. Compared to conventional silicon IGBT devices, SiC components provide lower switching losses, the ability to operate at higher switching frequencies, and reduced size and weight of power converters [122–124]. For locomotive traction drives, this enables an increase in the overall efficiency of the energy conversion system, a reduction in thermal stress on power modules, improved output voltage quality of voltage source inverters, and a decrease in electromagnetic interference in the overhead contact line. Thus, the use of SiC converters is considered one of the most effective ways to modernize next-generation traction drives.

Further improvements in the energy efficiency and reliability of traction drives are associated with the use of multilevel inverters, which provide output voltage with lower harmonic distortion and reduced torque ripples. The advantages of multilevel structures in locomotive drives include reduced stress on the insulation of traction motors, improved electromagnetic compatibility with the traction network, smoother traction force, and the possibility of constructing modular systems with enhanced maintainability [125, 126]. The modular design principle of power converters also contributes to higher operational reliability through redundancy and simplified maintenance [127–129].

A significant potential for improving the energy efficiency of locomotives is associated with the integration of energy storage systems, in particular supercapacitors and lithium-ion batteries, into the intermediate direct current link. Such solutions enable enhanced efficiency of regenerative braking when the network's capacity to absorb energy is limited, reduce peak loads on the contact network during traction, provide partial autonomous power supply during short-term voltage drops, and optimize the energy operation modes of the traction drive under variable operating conditions. Combined systems with energy storage are considered an important component of prospective energy-saving technologies in railway traction [130, 131].

Improving the reliability of traction electric drives is impossible without the development of modern methods of technical condition monitoring and adaptive control [132, 133]. Changes in motor parameters, temperature effects, insulation aging, and load non-uniformity require the use of algorithms capable of correcting operating modes in real time. Promising directions are sensorless control with the use of state observers, prediction of failures of power modules based on diagnostic models, integration of digital monitoring systems and elements of artificial intelligence for optimization of traction and regenerative braking modes [134–137]. The development of such approaches will contribute to increasing operational safety and reducing maintenance costs of locomotives.

Thus, the considered promising directions for the development of traction electric drives of locomotives indicate a gradual transition from traditional control schemes to integrated energy-efficient systems of a new generation. Modern trends are determined by the active introduction of high-frequency power converters based on SiC technologies, the development of multilevel and modular inverter structures, as well as the use of energy storage to increase the efficiency of regenerative braking. At the same time, adaptive control algorithms and digital diagnostic methods are becoming of significant importance, which allow ensuring stable operation of the traction electric drive under conditions of variable loads and complex operating modes. Thus, the combination of innovations in power electronics and intelligent control approaches forms the basis for increasing the energy efficiency, reliability, and competitiveness of modern railway transport.

Conclusions.

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

– the design and energy characteristics of brushless traction motors of locomotives are generalized. It is established that asynchronous machines are characterized by high mechanical reliability and resistance to overloads; however, their electromechanical parameters depend on rotor slip and temperature changes of the windings, which requires an adaptive control approach. Permanent magnet synchronous motors provide increased energy efficiency and stable torque over a wide speed range, but require accurate determination of rotor position and control of the state of the magnetic system under significant loads. The energy operating modes of these motors in traction systems are characterized by bidirectional flow of electrical energy in traction and regenerative braking modes, which determines the features of drive dynamics and torque control processes. Thus, asynchronous and permanent magnet synchronous motors have different design and energy characteristics, which justify the need to apply specialized control methods to ensure high efficiency, reliability, and dynamic performance in railway traction;

– the main structural configurations of brushless traction electric drives of electric locomotives are systematized and their operating modes are considered: traction and electric braking. It is established that in the schemes of direct current and alternating current electric locomotives the key elements are the intermediate direct current link and the voltage source inverter, which provides the formation of controlled voltage for asynchronous and permanent magnet synchronous motors. For alternating current systems a transformer with a thyristor rectifier or a transformer with an active four-quadrant converter are used. Modern systems also provide the use of multilevel inverters to improve the quality of the output voltage and reduce harmonic distortions. In addition, intermediate DC-DC stages are used for voltage stabilization and integration of energy storage, as well as combined schemes with electrical energy storage systems. The features of the use of asynchronous and permanent magnet synchronous motors in these schemes for the implementation of traction and braking modes are generalized. It is shown that the choice of structural configuration determines the possibilities of organizing bidirectional energy flow, provides increased control flexibility and stability of operation of the traction electric drive, and also allows the energy to be used as efficiently as possible during regenerative braking, which is critically important for modern electric locomotives;

– it is established that the configuration of power converters is a determining factor for the formation of traction and regenerative braking modes in brushless traction electric drives of locomotives. It is confirmed that the voltage source inverter provides effective torque control and bidirectional energy flow in direct current systems, while in alternating current systems the use of thyristor rectifiers, active 4QS converters, and cascaded multilevel inverters allows improving the quality of the supply voltage, implementing precise torque control and optimizing regeneration. The introduction of DC-DC intermediate stages and combined schemes with energy storage systems provides increased system flexibility, allows matching voltage levels, and enables efficient use of regenerated energy for repeated supply of the motors;

– modern approaches to electromagnetic torque control in brushless traction electric drives of locomotives based on asynchronous motors and permanent magnet synchronous machines are considered and generalized. It is shown that the most widespread methods are vector control and direct torque control, which ensure the implementation of traction and regenerative braking modes over a wide range of speeds and loads. It is established that FOC is characterized by high control accuracy and efficiency in steady-state modes, while DTC provides increased speed of response and stability in transient processes. It is noted that the choice of control method is determined by the type of traction motor, the requirements for drive dynamics, and the structure of the power converter. The application of modern torque control algorithms in combination with voltage source inverters and active converters is a necessary condition for increasing the energy efficiency and reliability of traction electric drives of electric locomotives;

– it is determined that the prospects for increasing the energy efficiency and reliability of control systems of traction electric drives of locomotives are associated with the comprehensive improvement of power converters, the introduction of SiC semiconductor technologies, the development of multilevel inverter structures and modular solutions, as well as the integration of energy storage into the intermediate direct current link. An additional important direction is the implementation of control methods based on digital adaptive algorithms and diagnostic systems, which ensure stable operation of the electric drive under real operating conditions of railway traction.

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Нерубацький В. П. Дослідження методів і засобів керування безколекторними тяговими двигунами локомотивів на основі сучасних силових перетворювачів.

Анотація. *Об'єктом дослідження є електромеханічні та енергетичні процеси перетворення і керування енергією в безколекторних тягових електроприводах локомотивів під час реалізації режимів тяги і рекуперативного гальмування. У роботі розглянуто підходи щодо підвищення енергоефективності та експлуатаційної надійності тягових систем через обґрунтований вибір структурних конфігурацій силових перетворювачів і сучасних методів керування електромагнітним моментом тягових двигунів.*

Узагальнено конструктивні та енергетичні особливості асинхронних двигунів і синхронних двигунів із постійними магнітами як основних об'єктів керування у складі безколекторного електропривода локомотива. Визначено, що функціонування тягових систем у залізничних умовах має широкий діапазон швидкостей, значні коливання навантаження та необхідність забезпечення двонапрямного енергетичного обміну з тяговою мережею.

Систематизовано основні режими роботи тягового електропривода, зокрема тяговий режим і режим електричного гальмування, а також встановлено структурні вимоги щодо їх реалізації. Узагальнено типові конфігурації силових перетворювальних комплексів електровозів постійного та змінного струму, зокрема рішення з проміжною ланкою постійного струму, автономними інверторами напруги, багаторівневими перетворювачами, проміжними каскадами перетворення енергії та комбінованими схемами з накопичувальними системами.

Показано, що ефективність рекуперативного гальмування і стабільність енергетичних процесів визначені переважно можливостями двонапрямного перетворення енергії, параметрами проміжної ланки та узгодженням електропривода з характеристиками контактної мережі. Встановлено, що застосування сучасних методів векторного і прямого керування моментом дає змогу забезпечити високі динамічні показники тягового електропривода, точність регулювання моменту і зниження енергетичних втрат у силових перетворювачах.

Перспективність розглянутих підходів пояснено інтеграцією напівпровідникових перетворювальних систем нового покоління, використанням накопичувачів енергії та адаптивних *алгоритмів керування, здатних функціонувати в умовах змінних експлуатаційних режимів. Використання результатів оглядового дослідження буде корисним для проєктування та модернізації систем керування тяговими електроприводами локомотивів, оптимізації режиму рекуперативного гальмування і забезпеченні надійної роботи локомотивів у широкому діапазоні навантажень.*

Ключові слова: *безколекторні тягові двигуни, тяговий привод, локомотив, силові перетворювачі, автономний інвертор напруги, рекуперативне гальмування, методи керування, багаторівневі інвертори.*

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