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Prospective methods for enhancing the energy efficiency of multi-motor traction electric drive systems for rail vehicles

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Abstract. The relevance of the study is determined by the need to improve the energy efficiency of the multi-motor traction electric drive of commuter electric trains by reducing electricity consumption and losses in traction equipment, power converters, the overhead contact system and auxiliary systems. The aim of the study was to determine the most appropriate technical solutions for improving the energy efficiency of a multi-motor traction electric drive based on a comprehensive analysis of the structure of energy losses, types of traction electric motors, control methods and approaches to optimising movement modes. The study used a multicriteria analysis method applying the Harrington desirability function. The results established that the main reserves for improving energy efficiency are concentrated in reducing losses in the traction electric drive, power converters and the mechanical part of the drive, which account for the largest share of the total energy losses of an electric train. It was determined that the asynchronous traction motor is the most appropriate option for use in a multi-motor traction electric drive, as it provides a rational combination of energy efficiency, reliability, ease of maintenance and acceptable weight and dimensional characteristics. A comparison of asynchronous electric drive control methods showed the advantage of vector control, which ensures high accuracy in regulating electromagnetic torque, stable operation under variable loads and improved energy characteristics of the drive. Among the methods for optimising the movement modes of electric trains, dynamic programming was identified as the most promising, as it enables the formation of energy-saving movement trajectories while taking into account speed limits, track profile and variable operating conditions. The obtained results confirm the feasibility of the integrated combination of an asynchronous traction motor, vector control and dynamic programming algorithms as a basis for creating energy-efficient traction electric drive systems for modern rail rolling stock

Keywords: induction traction motor; vector control; dynamic programming; electric train; energy losses; optimisation of operating modes; multicriteria analysis

Introduction

Rail transport is traditionally regarded as one of the most energy-efficient modes of mass transportation due to the low rolling resistance of steel wheels on rails, high carrying capacity, and centralised power supply for rolling stock. However, the rising cost of electrical energy, stricter environmental requirements, and the need to reduce operating costs make further improvement of traction rolling stock energy efficiency an urgent task. This issue is particularly important for suburban multiple-unit trains, which operate over short interstation distances with frequent stops and repeated acceleration-braking cycles. Under such conditions, a considerable part of the consumed electrical energy is spent not only on useful train movement, but also on covering losses in traction electric drives, power converters, catenary systems, and auxiliary equipment. Therefore, improving the efficiency of multi-motor traction electric drive systems is of significant scientific and practical importance.

A typical operating cycle of an electric train between adjacent stations consists of acceleration, cruising, coasting, and braking before stopping. The highest electricity consumption is observed during acceleration, when traction

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motors operate under high-current conditions and significant electromagnetic loads. During this period, instantaneous power consumption may exceed average values, leading to increased losses in converters, electric machines, and the catenary system. Since electricity costs constitute a significant component of operating expenses, even a slight reduction in the specific energy consumption of electric trains can provide a substantial economic effect. In research, improving the energy efficiency of rail rolling stock is regarded as a multidimensional problem that includes energy-efficient train operation, reduction of losses in traction power supply systems, rational use of braking energy, and optimisation of traction drive performance. Y. Rao *et al.* (2022) considered energy-efficient train control taking into account traction system efficiency and concluded that rolling stock energy consumption should be assessed through train motion and traction equipment efficiency. I. Riabov *et al.* (2023) considered the energy efficiency of a multi-motor traction electric drive and emphasised that energy savings can be achieved through rational load distribution between traction motors and adaptation of drive operation to actual traction demand.

A separate group of studies is devoted to traction motors and traction electric drive structures. S. Paul *et al.* (2022) reviewed railway traction motors for distributed traction systems and showed that induction motors and permanent magnet synchronous motors are among the most promising solutions for modern rail vehicles. Y. Peng *et al.* (2024) compared energy-efficient train control based on permanent magnet synchronous motors and induction motors, confirming that motor type influences the attainable energy-saving effect. However, these studies mainly focus either on motor design or on particular operating conditions, while an integrated multicriteria comparison of traction motor types for suburban multi-motor rolling stock remains insufficiently developed.

The choice of the control method for induction traction drives is also widely discussed in the literature. S. Goolak *et al.* (2023) analysed traction drive control systems of electric locomotives with asynchronous traction motors and showed that vector control and direct torque control have different sensitivity to supply voltage and load disturbances. These results are important for multi-motor traction systems, where uneven load distribution, supply asymmetry, and variations in wheel-rail adhesion may reduce overall drive efficiency. Therefore, the effectiveness of a control method should be assessed by its ability to maintain stable and energy-efficient operation under variable traction loads. Another important research direction is the optimisation of train operating modes and speed trajectories. D. Kouzoupis *et al.* (2023) proposed a direct multiple shooting approach and showed that this method provides flexibility in problem formulation and sufficient computational efficiency for complex energy-efficient train control tasks. Z. Xing *et al.* (2023) developed an improved brute-force search approach and concluded that transforming the problem into the search for optimal turning points can reduce the solution space and improve computational speed.

Thus, individual aspects of rail rolling stock energy efficiency have been studied in sufficient depth, ranging from traction motor selection to train driving algorithms. However, the integrated multicriteria selection of ways to improve multi-motor traction electric drive efficiency, simultaneously taking into account motor type, control method, operating conditions, and train operating mode optimisation, remains insufficiently explored. The purpose of the study was to substantiate promising approaches to improving multi-motor traction electric drive energy efficiency through comparison of traction motor types, induction drive control methods, and electric train operating mode optimisation approaches.

Materials and Methods

The study was conducted as a comparative analytical investigation based on the systematisation of scientific publications, technical characteristics of traction equipment, and expert evaluation of alternatives. The factual material consisted of twenty peer-reviewed scientific sources devoted to traction motors, induction-drive control, energy-efficient train operation, and railway trajectory optimisation. The publications were selected because they directly addressed distributed or multi-motor traction, induction and permanent-magnet machines, vector and direct torque control, dynamic programming, model predictive control, genetic algorithms, and optimal-control methods. The main sources used for the comparison of traction-machine types were the works by S. Nategh *et al.* (2020), I. Riabov *et al.* (2023), and H.J. Kaleybar *et al.* (2023). The comparison of induction-drive control methods was based mainly on B. Liubarskyi *et al.* (2017), A. Fathy Abouzeid *et al.* (2020), and S. Goolak *et al.* (2023). The analysis of train-motion optimisation methods relied on Y. Rao *et al.* (2022), D. Kouzoupis *et al.* (2023), Z. Zhang *et al.* (2023).

The research sequence consisted of four stages. At the first stage, the structure of energy losses in a suburban electric train was generalised from the literature and from the typical energy chain of an electric train: catenary system – power converter – traction machine – gearbox – wheelset – wheel-rail contact. At the second stage, the main alternatives for the traction machine were selected: DC motor, induction motor, permanent magnet synchronous motor, and switched reluctance motor. At the third stage, three control methods for induction drives were compared: scalar control, vector control, and direct torque control. At the fourth stage, four approaches to train-motion optimisation were compared: model predictive control, Pontryagin's maximum principle, genetic algorithms, and dynamic programming.

A multicriteria evaluation was used because the alternatives differed by parameters that could not be reduced to a single physical dimension. For each group of alternatives, five criteria were selected. For traction motors, the criteria were efficiency factor, control-system complexity, reliability, weight-and-size characteristics, and operating costs. For induction-drive control, the criteria were energy efficiency, torque control accuracy, control-system response speed, implementation complexity, and operational stability. For train-motion optimisation, the criteria were optimisation accuracy, computational complexity, real-time implementation, solution stability, and versatility. For the criteria related to cost and complexity, a higher desirability value corresponded to a more favourable state, that is, lower cost or lower complexity.

The numerical values in the tables were obtained through expert scoring and subsequent normalisation. The expert group included seven specialists: four academic researchers in electric traction and electric drives and three engineers with experience in operation or maintenance of electric rolling stock. The research involving respondents was conducted on a voluntary basis. All participants were informed about the purpose of the study, the nature of their participation, and the intended use of the obtained results. Written informed consent was obtained from all respondents, including consent to publish the generalised research results. The confidentiality and anonymity of the participants were ensured, and no personal data allowing the identification of respondents were disclosed. Participation in the study did not involve any form of discrimination, coercion, pressure, or unequal treatment. The ethical principles of the study were consistent with the Code of Ethics of the American Sociological Association (2018), the ICC/ESOMAR International Code on Market, Opinion and Social Research and Data Analytics (2025).

Each expert evaluated every alternative on a 10-point scale for each criterion. The individual scores were averaged, after which the averaged values were transformed into partial desirability indices on the Harrington scale. The interpretation of the desirability index was as follows: values from 0.80 to 1.00 corresponded to a very good level, 0.63 to 0.80 to a good level, 0.37 to 0.63 to a satisfactory level, 0.20 to 0.37 to a low level, and values below 0.20 to an unacceptable level. This procedure made it possible to convert heterogeneous technical judgments into comparable dimensionless indicators. The generalised Harrington desirability function was used to obtain an integral indicator for each alternative. The partial desirability for the *i*-th criterion was defined as:

$$d_i = exp[-\exp(-y_i)], \quad (1)$$

where y_i is a normalised coded value of the corresponding criterion. When an expert-score scale was used, the coded value was formed from the averaged expert score after accounting for whether the criterion was beneficial or cost-type. The generalised desirability index was calculated as:

$$D_j = \sqrt[n]{d_{1j} \cdot d_{2j} \cdot \ldots \cdot d_{nj}}, \quad (2)$$

where n is the number of criteria. The geometric form of the aggregation was chosen because it penalised alternatives with one very weak criterion and therefore better reflected the requirements of traction systems, where high efficiency cannot compensate for insufficient reliability or excessive implementation complexity.

Results

A typical operating cycle of an electric train between two adjacent stations consists of acceleration, cruising at constant speed, coasting, and braking before stopping. The highest electricity consumption is observed during acceleration, when traction motors operate under high-current conditions and significant electromagnetic loads (Haahr *et al.*, 2017). During this period, instantaneous power consumption may considerably exceed average values, leading to increased losses in power converters, electric machines, and the catenary system (Feng *et al.*, 2013; Rao *et al.*, 2022). Electricity costs constitute one of the most significant components in the structure of operating expenses of multiple-unit rolling stock. According to estimates by railway operating services, their share may reach 25-35% of total passenger transportation costs. Under such conditions, even a slight reduction in the specific energy consumption of electric trains can provide a substantial economic effect on the scale of the entire transport system (Liu & Golovitcher, 2003; González-Gil *et al.*, 2014). Analysis of the energy performance of suburban electric train operation shows that the pattern of electricity consumption has a pronounced cyclical structure. Each operating cycle between adjacent stops includes a period of intensive acceleration, a phase of motion at limited or steady speed, and a braking stage. Within this cycle, the electrical energy supplied from the catenary system is used both to produce the useful mechanical work required for train movement and to cover losses in various elements of the energy chain. During acceleration, traction motors operate under high-current conditions, which is accompanied by increased electrical losses in their windings as well as increased switching losses in power converters. In addition, high traction currents cause extra losses in the catenary system and in the power cables of the electric train. As a result, the actual efficiency of the entire electric traction system is significantly lower than the efficiency of its individual components.

For assessing the energy efficiency of an electric train, the analysis of the structure of energy losses during traction operation is of particular importance. Energy losses in an electric train are formed in several major subsystems. A significant share of these losses arises in the traction electric drive, which includes traction motors, power converters, and elements of the electrical circuits. Another part is associated with mechanical losses in gearboxes, bearing assemblies, and the wheel-rail contact. Additional losses occur in the catenary system and current collection equipment, as well as in the auxiliary systems of the electric train. A generalised distribution of the energy losses of an electric train is shown in Figure 1. The presented values are average values for modern DC electric trains and may vary depending on the type of traction equipment, operating conditions, and track profile.

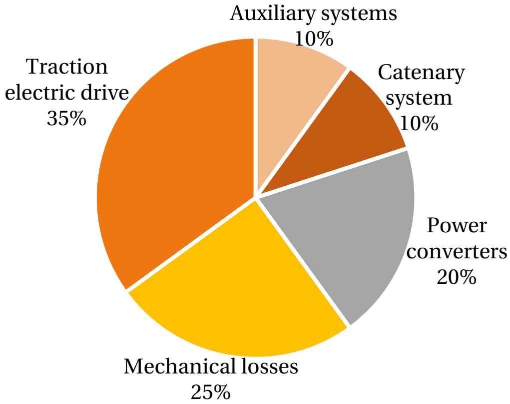

Figure 1. Approximate distribution of energy losses in an electric train

Source: developed by the authors

A conventional distribution of energy losses may be represented by the following shares. Approximately one third of the total losses is attributed to the traction electric drive, where electrical and magnetic losses occur in the motors and power converters. A significant portion of the losses is also formed in the mechanical part of the system, including losses in gearboxes, bearings, and the wheel-rail contact. Some of the energy is dissipated in the catenary system due to voltage drops and conductor heating. A separate group consists of losses in the auxiliary systems of the electric train, including ventilation units, compressors, heating systems, and lighting. The analysis of the loss structure shows that the greatest reserve for improving the energy efficiency of electric trains is associated with the enhancement of the traction electric drive and the optimisation of its operating modes. It is precisely in this subsystem that the most intensive energy processes occur, determining the level of electricity consumption during train acceleration and motion. For this reason, improving the energy efficiency of electric trains requires an integrated approach involving simultaneous enhancement of the traction electric drive design, optimisation of its control algorithms, and rational formation of train operating modes. Such an approach makes it possible to consider the electric train as a unified energy system in which electrical and mechanical processes are closely interconnected (Rao *et al.*, 2022). Structurally, an electric train consists of motor cars and trailer cars. The motor cars are equipped with traction motors, power converters, and auxiliary electrical equipment, whereas the trailer cars primarily perform a transport function. Such a configuration ensures a rational distribution of train mass and makes it possible to provide sufficient adhesion between the wheels and the rails (Paul *et al.*, 2022).

The energy process in an electric train can be represented as a sequence of conversions of electrical energy from the catenary system into the mechanical energy of wheelset rotation. In general, this sequence includes several main stages. Electrical energy is supplied through the current collector to the power converters, where it is converted into the parameters required to supply the traction motors. Then, in the motors, electromagnetic energy is converted into mechanical energy, which is transmitted through the gearbox to the wheelsets, generating the traction force required to move the train (Nategh *et al.*, 2020). An important feature of electric trains is the presence of a multi-motor traction drive structure. Each motor bogie may have one or two traction motors operating in parallel and producing the total traction torque. This arrangement makes it possible to ensure a more uniform distribution of traction effort among the train axles and improves the utilisation of adhesive weight. At the same time, the multi-motor drive structure complicates the control system and increases the requirements for synchronisation of the individual traction motors. Uneven load distribution among the motors may lead to increased energy losses and a reduction in the overall efficiency of the system. Under actual operating conditions, the power levels of individual drives may differ due to variations in axle load, wheel-rail contact conditions, and control system parameters. This leads to additional energy losses associated with the uneven distribution of traction torque (Goolak *et al.*, 2023). An increase in the efficiency of traction motors makes it possible to directly reduce electricity consumption during train operation. In modern induction traction motors, this efficiency can exceed 0.9 over a wide load range, which makes them attractive for application in multiple-unit rolling stock (Peng *et al.*, 2024). At the same time, the selection of the optimal type of traction motor cannot be based on a single parameter alone. For an objective comparison, it is necessary to take into account a whole set of criteria, among which energy efficiency, weight and dimensional characteristics, reliability, control system complexity, and operating costs are of primary importance. Given the heterogeneity of these indicators, it is advisable to use multicriteria evaluation methods that make it possible to integrate different technical characteristics into a single generalised criterion. One of the most widely used approaches for solving such problems is the Harrington desirability function method (Harrington, 1965). Since different types of traction motors are characterised by a combination of technical and operational indicators, the selection of the most appropriate option for use in the electric traction system of an electric train should be carried out using multicriteria analysis methods.

One effective approach to solving such problems is the use of the generalised Harrington desirability function, which makes it possible to transform heterogeneous technical characteristics into dimensionless indicators and combine them into a single integral criterion. The desirability function method is based on transforming each technical parameter into a partial desirability index ranging from zero to one. Values close to zero correspond to unsatisfactory characteristics, whereas values close to one indicate a high level of technical excellence of the respective parameter. For each type of traction motor, the corresponding values of the partial desirability functions are determined. After that, based on the given relationship, a generalised indicator is calculated that characterises the overall efficiency of using a particular type of motor in the electric traction system. Several main types of traction electric motors are used in modern electric traction systems. Each of these motor types has its own technical and operational characteristics, which necessitates their comprehensive comparison. The choice of these motor types and comparison criteria is consistent with the works by S. Paul *et al.* (2022), who emphasised the prospects of induction and permanent magnet synchronous motors for distributed traction systems, and S. Nategh *et al.* (2020), who identified efficiency, reliability, thermal loading, mass-dimensional parameters, and manufacturability as important factors in traction motor design. DC motors remained the principal type of traction motor for electric trains for a long time. Their widespread use was due to the relative simplicity of speed control and the ability to develop a high starting torque. At the same time, the presence of a commutator-brush assembly results in increased operating costs associated with maintenance and brush replacement. In addition, electrical losses in the commutator assembly reduce the efficiency of such machines.

Induction traction motors became widely used with the development of power semiconductor technology. They are characterised by a simple design, the absence of a commutator-brush assembly, and high operational reliability. The squirrel-cage rotor of an induction motor does not require special maintenance, which reduces operating costs. Furthermore, modern control systems make it possible to provide effective control of the speed and torque of such motors. I. Riabov *et al.* (2023) showed that the energy efficiency of a multi-motor traction electric drive depends on rational load distribution between traction motors, which confirms the importance of considering induction motors in such systems. Permanent magnet synchronous motors are distinguished by high efficiency and high specific power. The use of permanent magnets makes it possible to reduce excitation losses and improve the energy efficiency of the motor. However, such machines are characterised by a more complex design and the high cost of magnetic materials, which limits their widespread application in multiple-unit rolling stock. Switched reluctance motors attract the attention of researchers due to their simple rotor design and high reliability. The absence of rotor windings provides increased mechanical strength and overload resistance. At the same time, the complexity of the control system and the increased torque ripple are factors that limit the use of such machines in the traction drives of electric trains. H.J. Kaleybar *et al.* (2023) confirmed the relevance of multicriteria and optimisation approaches for rail vehicle systems, which supports the use of comparative evaluation when selecting traction equipment. The initial values of the desirability indices for different types of traction motors are presented in Table 1.

Table 1. Values of partial desirability indices for different types of traction motors

Criterion	DC motor	Induction motor	Permanent magnet synchronous motor	Switched reluctance motor
Efficiency factor	0.90	0.95	0.96	0.94
Control system complexity	0.80	0.63	0.63	0.37
Reliability	0.37	0.80	0.80	0.80
Weight and dimensional characteristics	0.37	0.80	0.90	0.85
Operating costs	0.37	0.80	0.70	0.80

Source: developed by the authors

These values were obtained on the basis of expert evaluation and subsequent normalisation of the criteria according to the Harrington desirability scale. The partial desirability indices were determined using formula 1, while the generalised assessment of each motor type was performed using formula 2. The data presented in Table 1 show that the permanent magnet synchronous motor has the highest values for efficiency factor and weight-and-dimensional characteristics. However, its operating costs are lower in desirability than those of the induction motor and switched reluctance motor. The induction motor demonstrates the most balanced combination of efficiency, reliability, weight-and-dimensional characteristics, and operating costs. DC motors are characterised by relatively favourable control simplicity, but their reliability, weight-and-dimensional characteristics, and operating costs have lower desirability values. Switched reluctance motors show acceptable reliability and operating costs, but their practical application is limited by the complexity of the control system. Therefore, taking into account the partial desirability indices calculated by formula 1 and their generalised aggregation according to formula 2, the induction motor can be considered the most rational option for use in a multi-motor traction electric drive of an electric train. For a more illustrative comparison of the technical characteristics of different motor types, the evaluation results should be presented in the form of a radar chart (Fig. 2), which makes it possible to graphically represent the relationship among the individual evaluation criteria. The chart presents the values of the partial desirability indices according to the following criteria: efficiency, control system complexity, reliability, weight and dimensional characteristics, and operating costs. Each motor type is represented by a separate curve, which makes it possible to visually assess the relationship among the different technical parameters. Thus, the results of the multicriteria analysis show that the most appropriate option for application in the traction electric drive system of electric trains is the induction traction motor. It is this type of electric machine that provides the optimal combination of energy efficiency, reliability, and operational suitability. Determining the feasibility of using an induction traction motor in the electric traction system of an electric train necessitates a detailed analysis of possible control methods for such a drive. The efficiency of an induction electric drive largely depends on the control algorithms that ensure the formation of the required electromagnetic torque and motor speed operating modes. Unlike DC motors, in which speed control is achieved by varying the supply voltage or field current, induction motors require more sophisticated control systems. Similarly, to the previous analysis of traction motor types, the Harrington desirability function method is used to compare control systems. This approach makes it possible to take into account several technical characteristics of control systems and combine them into a single integral indicator.

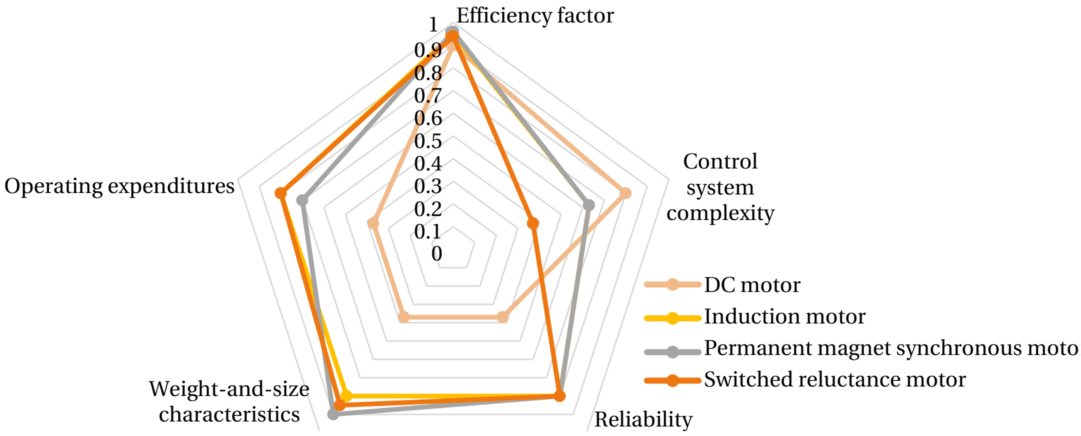

Figure 2. Radar chart of desirability indices for different types of traction motors

Source: developed by the authors

The evaluation criteria for induction drive control systems include energy efficiency, electromagnetic torque control accuracy, control system response speed, implementation complexity, and operational stability under different load conditions. The choice of these criteria is determined by their direct influence on the operational and energy performance of the electric train. Scalar control is based on maintaining a specified relationship between the supply voltage and frequency of the electric motor. This approach is relatively simple to implement and does not require complex computational algorithms. At the same time, the torque control accuracy of scalar systems is limited, which reduces their effectiveness in traction electric drives, where precise control of traction effort is of great importance. Vector control of an induction electric drive is based on the independent regulation of the stator current components responsible for generating the magnetic flux and the electromagnetic torque. This approach makes it possible to achieve control characteristics similar to those of a DC motor, thereby ensuring high torque and speed control accuracy. The direct torque control method involves the direct regulation of the electromagnetic torque and magnetic flux of the motor based on the analysis of instantaneous values of currents and voltages. This method is characterised by high dynamic response and makes it possible to react quickly to load changes. At the same time, its implementation requires the use of high-speed computing devices and sophisticated signal processing algorithms. For each of the considered control methods, the corresponding values of the partial desirability indices are determined. The normalised values of the criteria for the three main control methods are presented in Table 2.

Table 2. Values of partial desirability indices for different control systems of an induction electric drive

Criterion	Scalar control	Vector control	Direct torque control
Energy efficiency	0.63	0.90	0.85
Torque control accuracy	0.50	0.90	0.85
Control system response speed	0.50	0.85	0.90
Implementation complexity	0.90	0.63	0.63
Operational stability	0.63	0.90	0.85

Source: developed by the authors

The values were obtained by averaging expert scores and converting them into partial desirability indices using formula 1. The overall comparison of the considered control methods was carried out using the generalised Harrington desirability function according to formula 2. The results presented in Table 2 indicate that vector control provides the most favourable combination of energy efficiency, torque control accuracy, control system response speed, and operational stability. Direct torque control is characterised by a high response speed and good energy performance, but its implementation complexity reduces its overall desirability. Scalar control has the highest desirability value for implementation complexity because of its relative simplicity, but it is inferior to vector control and direct torque control in terms of energy efficiency, torque control accuracy, and dynamic response. Thus, based on the partial desirability indices calculated by formula 1 and their generalised evaluation according to formula 2, vector control is the most appropriate method for induction traction drives operating under variable load conditions typical of suburban electric trains. Figure 3 shows the values of the partial desirability indices for each control method, which makes it possible to visually assess their advantages and disadvantages. The analysis of the graphical representation confirms that vector control provides the most optimal combination of energy efficiency, control accuracy, and operational stability.

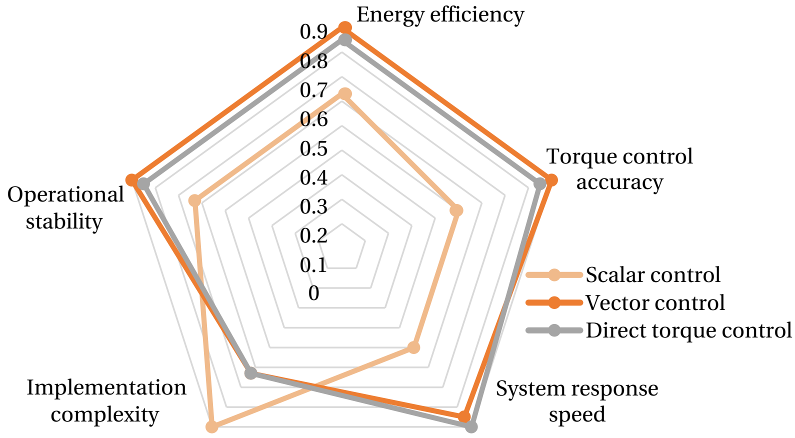

Figure 3. Radar chart of desirability indices for induction electric drive control systems
Source: developed by the authors

Various mathematical approaches may be used to optimize the operating modes of electric trains. Each of them has its own advantages and limitations, which become apparent depending on the operating conditions, the required calculation accuracy, and the feasibility of implementation in real-time control systems. Therefore, it is advisable to carry out a comprehensive evaluation of different train motion optimisation methods using a multicriteria approach. To perform such an analysis, the Harrington desirability function is used, making it possible to integrate heterogeneous characteristics of optimisation methods into a single generalised indicator. As in the previous cases, each evaluation criterion is transformed into a partial desirability index ranging from zero to one. The higher the value of the index, the more desirable the corresponding characteristic of the method. The following train motion optimisation methods are considered in the evaluation process: dynamic programming, Pontryagin's maximum principle, genetic algorithms, and model predictive control. The normalised values of the criteria for train motion optimisation methods are presented in Table 3.

Table 3. Values of partial desirability indices for train motion optimisation methods

Criterion	Model predictive control	Pontryagin's maximum principle	Genetic algorithms	Dynamic programming
Optimisation accuracy	0.90	0.85	0.80	0.90
Computational complexity	0.37	0.63	0.63	0.63
Real-time implementation	0.37	0.50	0.63	0.75
Solution stability	0.80	0.80	0.63	0.90
Versatility	0.63	0.63	0.90	0.85

Source: developed by the authors

These values were formed on the basis of expert evaluation of the methods according to optimisation accuracy, computational complexity, real-time implementation, solution stability, and versatility. The averaged expert scores were transformed into partial desirability indices using formula 1, and the integral comparison of the optimisation methods was performed using the generalised desirability index calculated by formula 2. The data in Table 3 show that model predictive control has a high value for optimisation accuracy, but its practical use is limited by high computational complexity and difficulties in real-time implementation. Pontryagin's maximum principle demonstrates satisfactory values for most criteria, but its versatility and real-time implementation are lower than those of heuristic and dynamic programming approaches. For a more illustrative comparison of the different optimisation methods, the evaluation results should be presented in the form of a radar chart (Fig. 4).

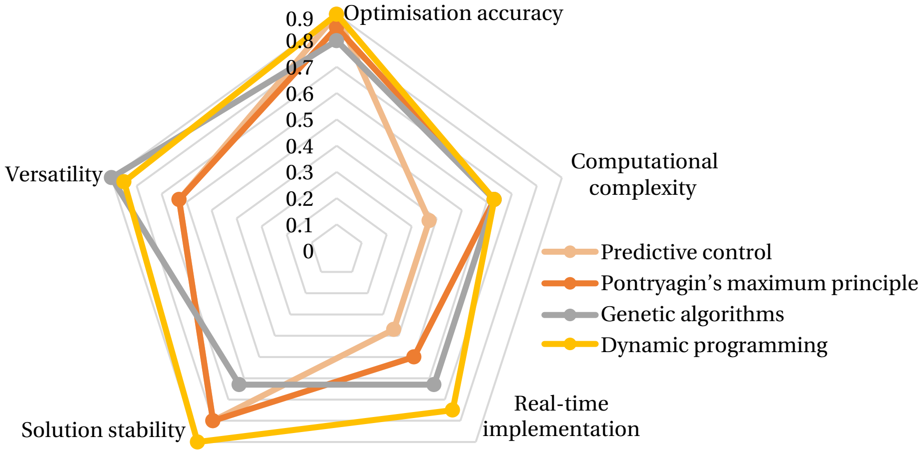

Figure 4. Radar chart of desirability indices for electric train motion optimisation methods

Source: developed by the authors

The chart shows the values of the partial desirability indices for each optimisation method, which makes it possible to graphically assess their advantages and limitations. Thus, the conducted analysis indicates the expediency of using dynamic programming methods for the formation of energy-efficient operating modes of electric trains. The application of this approach makes it possible to take into account changes in operating conditions in real time and to generate optimal control actions for the traction electric drive. The results of the performed analysis of the traction electric drive of an electric train, control methods for induction motors, and optimisation algorithms for train operating modes make it possible to formulate general principles for constructing a control system that ensures improved energy efficiency of rolling stock. Such a system should combine the functions of traction electric drive control, optimisation of train operating modes, and interaction with the railway power supply system. The general operating principle of the control system may be described as a sequence of interactions among several functional modules. First, the motion parameters and electrical quantities are measured. The obtained information is then transmitted to a data processing unit, where the current state of the system is assessed. After that, the optimisation unit determines the optimal control actions, which are transmitted to the traction electric drive control system. The implementation of such a control system structure makes it possible to adapt the operating modes of the traction electric drive to changing train operating conditions. As a result, more efficient use of electrical energy is achieved, and losses in the electric traction system are reduced.

Discussion

In contemporary research, improving the energy efficiency of rail rolling stock is regarded as a multidimensional problem that includes energy-efficient train operation, reduction of losses in traction power supply systems, rational use of regenerative braking energy, and optimisation of traction drive performance. X. Feng *et al.* (2013) systematised the main directions of traction energy saving in rail transport and showed that energy consumption depends not only on rolling stock parameters, but also on driving strategy, timetable constraints, traction and braking modes, and infrastructure conditions. V.I. Shynkarenko *et al.* (2016) focused on the modelling of recovery energy distribution zones in DC traction systems and demonstrated the importance of assessing the conditions under which regenerated energy can be reused within the traction power network. Y. Rao *et al.* (2022) further developed this research direction by considering the efficiency of the traction system itself in energy-efficient train control. These studies confirm that the energy performance of rail rolling stock should be evaluated as the result of interaction between the vehicle, traction drive, power supply system, and operating conditions.

A separate group of studies is devoted to the design of traction motors and the structure of multi-motor traction electric drives. I. Riabov *et al.* (2023) considered the problem of increasing the energy efficiency of a multi-motor traction electric drive and emphasised that energy savings can be achieved through rational distribution of load between traction motors and adaptation of the drive operating mode to actual traction demand. S. Nategh *et al.* (2020) analysed the main aspects of traction motor design for railway applications, including efficiency, thermal loading, reliability, mass and dimensional parameters, and manufacturability. S. Paul *et al.* (2022) reviewed the state of railway traction motors for distributed traction systems and showed that induction motors and permanent magnet synchronous motors are among the most promising solutions for modern rail vehicles. Y. Peng *et al.* (2024) compared energy-efficient train control based on permanent magnet synchronous motors and induction motors, confirming that the choice of motor type has a direct influence on the attainable energy-saving effect. However, these studies mainly focus either on motor design or on particular operating conditions, while an integrated multicriteria comparison of traction motor types for suburban multi-motor rolling stock remains insufficiently developed.

The choice of the control method for induction traction drives is also widely discussed in the literature. A. Fathy Abouzeid *et al.* (2020) analysed control strategies for induction motors in railway traction applications and showed that vector control and direct torque control provide better dynamic and energy performance than scalar control, although they require more complex control algorithms and higher computational resources. B. Liubarskyi *et al.* (2017) studied optimal operating modes of induction traction drives and substantiated the need to coordinate motor operating conditions with the control algorithm of the semiconductor converter. These results are especially important for multi-motor traction systems, where uneven load distribution, supply asymmetry, and variations in wheel-rail adhesion may reduce the overall efficiency of the drive. Therefore, the effectiveness of a control method should be assessed not only by its theoretical accuracy, but also by its ability to maintain stable and energy-efficient operation under variable traction loads.

Another important research direction is the optimisation of train operating modes and speed trajectories. J.T. Haahr *et al.* (2017) proposed a dynamic programming approach for optimising train speed profiles under speed restrictions and passage point constraints, which is directly relevant to railway sections with complex operating limitations. P. Wang & R.M.P. Goverde (2019) extended this problem to multi-train trajectory optimisation for energy-efficient timetabling, showing that energy consumption should be minimised while taking into account the interaction between trains. D. He *et al.* (2021) applied an improved differential evolution algorithm and a multi-particle train model to energy-efficient trajectory optimisation, while Z. Xing *et al.* (2023) proposed an improved brute-force search approach for energy-saving train operation. These studies indicate that different optimisation methods can provide significant energy savings, but their practical applicability depends on computational complexity, stability of the obtained solution, and the possibility of real-time implementation.

Studies increasingly focus on real-time and onboard optimisation methods. D. Kouzoupis *et al.* (2023) proposed a direct multiple shooting approach aimed at improving the computational efficiency of train trajectory optimisation. A. Liebhold *et al.* (2023) considered onboard train speed optimisation using the prediction of block clearing times under real-time rescheduling conditions. A. Yildiz *et al.* (2023) analysed traction energy optimisation with regard to passenger comfort, which is particularly important for urban and suburban rail systems with frequent stops. D. Wang *et al.* (2024) investigated the use of deep reinforcement learning for energy-saving operation in urban rail transit. At the same time, H.J. Kaleybar *et al.* (2023) showed that genetic algorithms and their variants are widely used in rail vehicle optimisation problems, mainly as heuristic tools for complex multi-parameter tasks. Thus, the available studies confirm the effectiveness of modern optimisation methods, but they do not fully solve the problem of jointly selecting the traction motor type, induction drive control method, and train motion optimisation algorithm within a single multicriteria framework.

The results of the study were generally consistent with the conclusions of previous investigations, but they also extended them by integrating three decision levels into one multicriteria framework. I. Riabov *et al.* (2023) demonstrated that the energy efficiency of a multi-motor traction drive could be improved by rationally disconnecting or loading traction motors in accordance with the operating mode. The present study reached a comparable conclusion in a broader form: the highest energy effect should be expected not only from the drive topology itself, but also from the coordinated selection of machine type, control method, and trajectory optimisation algorithm. The conclusion regarding the preference for the induction machine partially coincided with the findings of S. Nategh *et al.* (2020) and S. Paul *et al.* (2022). These authors emphasised that permanent magnet synchronous machines offer very high efficiency and high specific power, whereas induction machines remain attractive because of their robustness, simpler rotor design, and lower maintenance sensitivity. In the present study, the permanent magnet synchronous machine also received the highest partial score for efficiency and compactness. However, after the inclusion of reliability and operating-cost criteria, the induction machine obtained a slightly more rational position for suburban rolling stock. This difference showed the importance of multicriteria evaluation: the most efficient component by one criterion is not necessarily the most appropriate component for a fleet with intensive operation and high maintainability requirements.

The obtained preference for vector control was supported by the results of A. Fathy Abouzeid *et al.* (2020), who showed that advanced induction-motor control strategies were required in railway traction because the drive often operated at low switching frequencies and in nonlinear inverter modes. S. Goolak *et al.* (2023) also showed that the control system of asynchronous traction motors should be assessed under disturbances and asymmetrical supply conditions. The present study agreed with these conclusions and indicated that vector control provided the best compromise between energy efficiency, torque-control accuracy, and operational stability. Direct torque control remained competitive because of its high response speed, but the multicriteria score reflected the need to limit ripple and ensure predictable operation in a multi-motor system. The results concerning train-motion optimisation corresponded with the findings of Y. Rao *et al.* (2022), who proved that traction-system efficiency had to be included in train-control models. M. Nold & F. Corman (2024) similarly demonstrated that more realistic modelling of energy losses could change the optimal control strategy. In the present study, this idea was reflected in the use of loss distribution and drive-specific criteria before selecting the optimisation method. Y. Peng *et al.* (2024) emphasised that braking characteristics and reduced-power operation should be included in the control model; this supported the conclusion that a universal energy-saving algorithm must account for actual vehicle limitations rather than only the theoretical speed profile.

The choice of dynamic programming as the most promising basic method should be interpreted with regard to alternative modern approaches. D. Kouzoupis *et al.* (2023) showed that direct multiple shooting could provide high computational efficiency for some trajectory optimisation problems. Z. Zhang *et al.* (2023) and D. Wang *et al.* (2024) demonstrated the advantages of model predictive control for online and cooperative train operation. J. Liu *et al.* (2025) showed that deep reinforcement learning could reduce dependence on an exact mathematical model. These methods are promising, but they require either higher computational resources, extensive operational data, or more complex validation procedures. Dynamic programming was therefore evaluated as the most balanced method for the considered task because it provided stable solutions, transparent interpretation, and compatibility with discretised representations of speed, position, and operating constraints.

The main limitation of the study was that the quantitative values of the desirability indices were based on expert scoring and generalised data from the literature rather than on direct experimental measurements from a specific electric-train type. Therefore, the obtained integral indicators should be regarded as a substantiated comparative assessment rather than as universal numerical constants. Thus, the obtained results summarise the approach to improving the energy efficiency of a multi-motor traction electric drive as an interconnected system of decisions, in which the choice of motor type, converter control algorithm and speed trajectory optimisation method should be made not separately, but comprehensively. For commuter electric trains, this approach is particularly important, since frequent acceleration and braking cycles require coordination between traction drive control and the optimisation of operating modes as a key condition for reducing energy consumption.

Conclusions

The conducted study confirmed that improving the energy efficiency of the multi-motor traction electric drive of rail rolling stock should be considered as a comprehensive task associated not only with the improvement of individual drive components, but also with the optimisation of the entire system of energy conversion and utilisation. It was established that a significant share of energy losses is generated precisely in the traction electric drive, especially during acceleration and operation under variable load conditions typical of suburban electric trains. This confirms that the main reserve for reducing energy consumption is associated with the rational selection of the traction motor type, an efficient control method, and an appropriate train motion optimisation approach. According to the results of the multicriteria analysis, it was found that the induction motor is the most appropriate option for use in the traction electric drive system of electric trains, as it provides the most balanced combination of energy efficiency, reliability, and operational suitability. The comparison of control methods for the induction drive showed the advantage of vector control, since it offers the best combination of high control accuracy, operational stability, and energy efficiency. The analysis of train motion optimisation methods demonstrated the expediency of applying dynamic programming as the most promising approach for forming energy-saving control actions under variable operating conditions.

Thus, a promising way to improve the energy efficiency of the multi-motor traction electric drive of rail rolling stock is the integrated combination of an induction traction motor, vector control, and dynamic programming methods, which makes it possible to reduce energy losses, improve the efficiency of traction power utilisation, and enhance the operational performance of electric trains. Further research should be aimed at developing and validating a mathematical model of the proposed integrated control system under real operating conditions, taking into account train mass, track profile, interstation distances, speed restrictions, traction power supply parameters, and the dynamic redistribution of load between traction motors.

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Conflict of Interest

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Перспективні шляхи підвищення енергоефективності багатодвигункового тягового електроприводу рейкового рухомого складу

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Анотація. Актуальність дослідження зумовлена необхідністю підвищення енергоефективності багатодвигункового тягового електроприводу приміських електропоїздів шляхом зниження витрат електроенергії та втрат у тяговому обладнанні, силових перетворювачах, контактній мережі й допоміжних системах. Метою роботи було визначення найбільш доцільних технічних рішень щодо підвищення енергоефективності багатодвигункового тягового електроприводу на основі комплексного аналізу структури енергетичних втрат, типів тягових електродвигунів, методів керування та способів оптимізації режимів руху. У роботі використано метод багатокритеріального аналізу із застосуванням функції бажаності Харінгтона. У результаті дослідження встановлено, що основні резерви підвищення енергоефективності зосереджені у зменшенні втрат у тяговому електроприводі, силових перетворювачах і механічній частині привода, які формують найбільшу частку загальних енергетичних втрат електропоїзда. Визначено, що найбільш доцільним для використання у складі багатодвигункового тягового електроприводу є асинхронний тяговий двигун, оскільки він забезпечує раціональне поєднання енергоефективності, надійності, простоти експлуатаційного обслуговування та прийнятних масогабаритних показників. Порівняння методів керування асинхронним електроприводом показало перевагу векторного керування, яке забезпечує високу точність регулювання електромагнітного моменту, стійкість роботи за змінних навантажень і покращення енергетичних характеристик привода. Серед методів оптимізації режимів руху електропоїздів найбільш перспективним визначено динамічне програмування, що дає змогу формувати енергоощадні траєкторії руху з урахуванням обмежень швидкості, профілю колії та змінних умов експлуатації. Отримані результати підтверджують доцільність комплексного поєднання асинхронного тягового двигуна, векторного керування та алгоритмів динамічного програмування як основи для створення енергоефективних систем тягового електроприводу сучасного рейкового рухомого складу

Ключові слова: асинхронний тяговий двигун; векторне керування; динамічне програмування; електропоїзд; енергетичні втрати; оптимізація режимів руху; багатокритеріальний аналіз