CHAPTER 1

Innovative conceptual design technologies for an energy-efficient diesel-generator power system of a transport vehicle

Dmytro Kulagin
Igor Maslov

Abstract

The paper investigates innovative conceptual design technologies for an energy-efficient diesel-generator power system of transport vehicles. The relevance of the work lies in the necessity of integrated energy utilization within internal transport networks to minimize energy losses and consequently minimize the cost of generated energy, which forms the foundation for constructing an energy-efficient system. Solving this problem requires the development of control principles that include: creating a mathematical model of the static and dynamic processes within the power system; establishing an economic model for evaluating the cost and efficiency of electricity generation and consumption; and implementing system control aimed at minimizing costs based on the economic assessment. The primary causes of active power losses in the AC electric power system of a transport vehicle are analyzed, particularly system imperfections and reactive power flow, which induces additional losses. Measures for reactive power compensation are proposed as a method to eliminate or reduce these power flows. A system of energy efficiency evaluation criteria is defined, where the main objective is the maximal reduction of the energy loss level. The methodology for enhancing energy efficiency is based on the sequential formation of a set of possible measures, their techno-economic selection, and ranking based on economic feasibility. To forecast losses, a mathematical model of the transport power system has been developed. The model is built on the principles of decomposition and hierarchy, allowing the power system to be broken down into levels (from individual consumers to the generator system busbars) and enabling the calculation of the total effective active energy losses across all sections. This approach ensures the system's adaptation to changing operating conditions, optimizes energy consumption, and improves its overall efficiency.

DOI: 10.21303/000-0000-0000-0-0.ch1

Keywords

Energy efficiency, power system, electric transport, power supply design, energy, mathematical model, economic model, optimization, electric machines, electric apparatus, mathematical problems in power engineering.

1.1 Introduction

The problem of integrated energy utilization in internal transport networks, considering the necessity of minimizing energy consumption and the corresponding minimization of generated energy cost, forms the basis for constructing an energy-efficient transport power system [1–3].

Solving this problem requires the development of appropriate control principles, which must be based on the sequential execution of the following stages:

– development of a mathematical model for static and dynamic processes corresponding to both the entire power system and its individual component nodes [4–6];

– establishment of an economic model for evaluating the cost and efficiency of electric power generation and consumption within transport networks [7–9];

– implementation of power system control aimed at minimizing energy consumption and the corresponding minimization of generated energy cost based on the evaluation using the established economic model [10–12].

A significant number of works have been devoted to the issues of developing a mathematical model for static and dynamic processes corresponding to both the entire power system and its individual component nodes [13–15].

The evaluation of the cost and efficiency of energy generation and consumption in transport networks provides an understanding of how economically effective the operation of the power system is, provided that the operational indices of the traction system and the power quality indices in the electrical network for the corresponding power supply to consumers are fully ensured. This approach can be implemented by combining the mathematical model of static and dynamic energy processes with approaches from modern economic theory [16–18].

An Integrated Electric Power System is a complex of electrical installations for the conversion, transmission, and distribution of electrical energy, the functional purpose of which is to supply electric power to transport electricity consumers [19–21].

1.2 Principles of designing an energy-efficient diesel-generator power system of transport vehicles

The modern electric power system must comply with the following basic requirements: reliability – ensuring uninterrupted operation of the system in various operating modes; economic efficiency – effective use of resources, minimization of costs for electricity generation and distribution [22–24]; safety – guaranteeing safety for the transport vehicle, crew, and the environment during system operation; convenience of technical operation – simplicity in system management, maintenance, and repair [25–27]; ensuring the established level of power quality – maintaining stable voltage and frequency, and the absence of disturbances and distortions in the electrical energy supply [28–30].

Recently, in the transport industry, one of the leading tasks has been the optimization of energy losses during its generation and transmission through electrical networks [31], which has introduced another key requirement: energy efficiency.

In the classic approach to constructing a transport power system, the following levels of the specified system are distinguished:

– individual energy consumers;
– distribution points;
– distribution networks;
– main switchboard;
– generator system busbars.

Individual levels use their own method for calculating electrical parameters, and the design characteristics may differ for the same type of electrical element [32].

When calculating active power losses in system elements, in the presence of power meters at each level, this approach allows for a realistic assessment of losses in system components when transitioning from one level to another. Considering the integrated power system as a transport subsystem, it is clear that the electric energy losses during its transmission are determined by the resistance and the power flow transmitted by the system itself [33].

It is possible to conditionally divide the unified electric power system into the following fragments (which provide power supply to each specified system level):

– electrical networks of individual electricity consumers;
– internal electrical networks;
– power sources.

This classification is based on the principle of electric power transfer from the source to the reception point, which allows for analyzing the stage of transfer where the most electric energy is lost. At the same time, it is also necessary to adhere to technical principles, according to which the part of the network supplying electricity to each technical unit (section, compartment, etc.) or any of its groups is taken into account. For the purpose of further analysis of the electrical system's energy efficiency, it is possible to consider the schematic and component implementation of the elements of these electrical system fragments. The type of transport power supply is determined by the following main factors [34]:

– system voltage;
– presence of auxiliary power plants;
– requirements for the reliability of uninterrupted power supply.

The electrical network of a transport vehicle is a set of elements designed to transmit electrical energy from the main switchboard to connected distribution points that supply isolated or high-voltage electrical equipment.

In some cases, measuring equipment is also directly connected to the main switchboard (depending on the power source). The transmission elements of such networks are lines (usually cables or busbars). Depending on the specific requirements for the power supply of electricity consumers in the aforementioned transport networks, it is expedient to apply mainline and radial transport power supply schemes.

Unlike the radial scheme, the mainline scheme is characterized by less reliable power supply but is cheaper to install due to the reduction in the length of power lines and the number of high-voltage devices used [35, 36]. In order to preserve the advantages of mainline schemes and increase reliability, various improvements have been made, including transit mainline schemes. For example, large and important electricity consumers are served by radial circuits, while others are grouped together and served by mainline circuits. The electrical networks of individual transport electricity consumers are intended for the distribution and direct supply of most electricity consumers. The components of such an electrical network are:

– a power plant (often of pre-fabricated design);
– a system with various protective devices;
– a power circuit.

Structurally, the communication lines are insulated wires or cable lines, and busbars are also used for mainline circuits. In practice, the mixed network system, which combines the advantages of radial and mainline systems, has become the most widespread. The principle of studying the transport electrical system should be based on an approach used in energy auditing practice, which is based on considering the elements of the transport network. This is logical when compiling energy balances across the transport vehicle as a whole, assessing the total losses in the elements, and developing general energy saving measures. However, such an approach, firstly, excludes the integrity of the transport system. This integrity is manifested in the fact that its elements are interconnected, and the processes of electrical energy conversion and consumption are inseparable. Secondly, the energy saving recommendations proposed in this case are independent of themselves and provide only a general direction.

Moreover, the uniqueness of each transport subsystem is not taken into account. Therefore, the division of the transport power system into such fragments in the study must be related to its structure and specific technical processes in each compartment or power consumer. This does not contradict the general principles of energy research but rather supplements and improves them.

The integration of Energy Storage Systems into marine traction networks fundamentally establishes a bi-directional energy flow, moving beyond conventional unidirectional power schemes to achieve the maximal reduction of energy loss levels. Primary power is generated by the Onboard Power Generation System, typically comprising diesel-generator sets, which supply energy via the main switchboard and power converters to the propulsion drives for vessel movement. The Energy Storage System functions as a dynamic energy buffer, optimizing this flow. Energy charging primarily occurs via two channels. Firstly, the Energy Storage System instantaneously absorbs regenerative braking energy recovered from the propulsion motors during deceleration, preventing its dissipation as heat and serving as the most direct mechanism for loss minimization. Secondly, the Energy Storage System can draw power from the diesel-generator sets during low-load periods, facilitating their sustained operation within the highest efficiency band and thereby reducing the overall cost of energy generation. The reverse flow, Energy Storage System discharging, is triggered during high transient peak loads, such as those encountered during maneuvering or rapid acceleration. The Energy Storage System rapidly injects stored energy into the traction network, effectively relieving the diesel-generator sets and mitigating severe load transients that cause significant active power losses due to high impulse currents. Furthermore, the Energy Storage System's fast-response capability actively contributes to voltage stabilization and reactive power compensation within the network, which is crucial for enhancing power quality, improving network throughput, and curtailing auxiliary losses. Consequently, the Energy Storage System transforms the highly volatile propulsion load profile into a stable, efficient demand for the Onboard Power Generation System, significantly improving the vessel's overall fuel efficiency.

1.3 Identification of the causes of main energy losses in the AC electric power system

The transmission of energy through the electrical networks of a transport vehicle is accompanied by active electric energy losses caused by electromagnetic and thermal processes occurring in their elements and technological electrical equipment. The classification of electric energy losses existing in the theory of general power supply is based on their underlying causes.

The first segment of losses is determined by two main factors: fundamental losses, which are defined by the nominal operating mode of the power system elements and the operating conditions with selected justified parameters, and additional losses, caused by deviations in the operating mode and parameters from the specified nominal values. The second segment of losses is caused by various types of reasons and can be divided into the following groups:

- imperfection of the power system;
- reactive power transfer through the power system elements;
- irrationality of technological processes in the compartments;
- deterioration of electric power quality;
- defects in the organization of the entire power system.

The imperfection of the transport power system from the perspective of increased electric energy losses is due to the lack of rational approaches that consider the energy-saving factor when solving the primary tasks of building the transport system. This also applies to the comprehensive implementation of such approaches during the design process. These tasks include, but are not limited to, selecting the quantity and capacity of electrical equipment, determining the optimal locations for power sources, choosing conductor cross-sections, and forming the overall circuit topology, all of which influence the system's overall efficiency and energy saving capacity.

Reactive power transfer through the elements of the transport electrical network that possess active resistance leads to additional power and electric energy losses. Increased reactive power flows also cause other undesirable phenomena, such as a reduction in the throughput capacity of transport lines and distribution devices, as well as a decrease in the voltage level in the network. The magnitude of these flows can be reduced or completely eliminated through reactive power compensation. The problem of reactive power compensation includes a number of techno-economic tasks, such as:

- implementing measures to reduce the reactive power of transport electricity consumers;

– selecting the location and model for installing transport reactive power compensation devices;
– optimizing the operating modes of transport reactive power compensation devices;
– improving methods for calculating and minimizing reactive power.

Measures aimed at reducing the reactive power consumption by the electrical equipment itself are widely used in operational practice and may include the following actions:

– increasing the loading of transport technological units and their operating time;
– using no-load limiters on asynchronous motors and transport repair units;
– modernization of the lighting system;
– replacement, relocation, and disconnection of electrical equipment under load;
– replacement of asynchronous motors with synchronous ones in new electric drives, if acceptable based on techno-economic comparisons;
– performing high-quality motor repair;
– using rational converter circuits;
– applying individual reactive power compensation means.

1.4 Definition of the system of evaluation criteria for an energy-efficient diesel-generator power system of a transport vehicle

The main objective in constructing and enhancing the energy efficiency of a transport power system is the maximal reduction of the energy loss level. The solution to the problem of selecting appropriate means to increase energy efficiency must be performed sequentially:

– formation of a set of all possible means and measures for enhancing the energy efficiency of the transport power system;
– selection of subsets of combinations of options for means and measures for increasing the energy efficiency of the transport power system;
– establishment of a corresponding objective function for enhancing the energy efficiency of the transport power system, and determination of boundary conditions and specific requirements.

The set of all circuit solutions that correspond to the defined objective function for enhancing the energy efficiency of the transport power system, and also satisfy the defined constraints and boundary conditions, allow for the energy efficiency of the transport system and constitute the set of measures and means that must be implemented for the maximally effective transfer of energy and its consumption by the corresponding electricity consumers. The specified list of measures and means depends on the results of solving the optimization problem for increasing energy efficiency and the corresponding technological features of the overall transport system's functioning.

The application of a dynamic process for determining the structure and parameters of the power system during the formation of these measures and means, based on the comprehensive solution of all defined tasks for developing a system of energy efficiency enhancement measures, allows for achieving a dynamic transformation of the power system. This facilitates the system's adaptation to changing operating conditions, optimizes energy consumption, and improves its overall efficiency. The main aspect when implementing the proposed dynamic changes in the system (determination of the structure and parameters of the power system) is their mutual influence.

The complete simultaneous replacement of the entire nomenclature of electrical equipment in the power system and the use of new circuits is generally not economically feasible during the modernization of a transport power system, despite the possible maximal energetic benefits from loss reduction. This is explained by the high price level of fuel and electrical equipment. Therefore, the task arises of finding optimal measures and means that can maximally approximate the power system to energy loss minimization while remaining economically justifiable. Given that existing power systems have similar structure and parameters for certain classes of transport vehicles (based on the typification and unification of design solutions), the operational parameters can significantly differ due to the technological features of each specific transport vehicle. This requires the application of different approaches to enhance energy efficiency depending on the specifics of each system. To achieve maximal energy efficiency of the transport power system, a set of control actions aimed at optimizing its operation is necessary.

The magnitude of the energy efficiency reserve also depends on the number of electricity consumers, which determines the redistribution of loads and the change in the supply circuit topology. Changes in the system topology or other influences aimed at increasing energy efficiency may be accompanied by additional costs. However, these costs do not always lead to a mandatory increase in total costs within a group of electricity consumers with the same functional purpose. For the effective solution of the energy efficiency enhancement problem, a list of basic sets of technically feasible modifications of the power system should be created, which will form the basis for further analysis of the feasibility of implementing the defined measures. Each action must involve the recalculation of the power system's operational indicators, as changes in the energy consumption characteristics of some electricity consumers may affect others, requiring verification of the admissibility of these changes. The formation of the initial set of technically feasible variants of combinations of means and measures for enhancing energy efficiency is based on comparing their parameters with the existing system indicators. First, independent groups of electricity consumers are identified, the change of which does not affect other subsystems. Then, groups of dependent measures are determined, the implementation of which requires interaction between components. The sequence of implementation of each measure and means should be based on their economic and technical feasibility.

Economic feasibility is assessed under the condition that the cost price of the saved energy should not exceed the capital investments for the implementation of the specific measure.

Technical feasibility is determined through engineering analysis of each specific transport vehicle and its power system. It is obvious that to maximize energy efficiency, the sequence of implementation of economically feasible measures and means can be determined by ranking them by the amount of cost savings. Therefore, the methodology for organizing the implementation program for enhancing the energy efficiency of a transport vehicle's power system consists of the following stages:

1. Formation of the set of all possible technical measures and means, which implementation is permissible under the defined operating conditions of the respective transport vehicle. This includes considering all possible options that can improve the energy efficiency of the transport power system without violating technological and operational norms.

2. Determination of economically and technically permissible measures and means for enhancing energy efficiency. At this stage, an evaluation of the measures is conducted, taking into account that the cost price of the saved energy should not exceed the capital investments in their implementation. In addition, a technical analysis is carried out to ensure the feasibility of each measure in the context of the specific operating conditions of a particular transport unit, which determines whether the proposed measures are technically realistic.

3. Sorting the refined list of permissible measures and means for enhancing energy efficiency by decreasing cost of saved energy. This stage involves prioritizing the implementation of measures that most effectively lead to energy savings. Thus, the sequence of implementation will depend on which measures provide the greatest economic benefit per unit of investment.

Various indicators are typically used to assess the effectiveness of such projects, allowing for a comprehensive evaluation of the results of energy efficiency enhancement programs. Among these indicators may be the economic effect.

Thus, the selection of a specific set of measures for enhancing the energy efficiency of a transport vehicle's power system depends on the defined goal and objectives and the financing scheme. The selection of the set of measures and means for reducing losses in the transport vehicle's power system should be based on the principle of economic feasibility, i.e., the implementation of measures that allow for obtaining the maximal energy effect with minimal costs. This approach ensures the optimal use of energy saving potential while maintaining economic benefits.

From the perspective of an investor interested in the maximal return on invested funds, the effectiveness of energy efficiency enhancement measures is evaluated through Net Present Value (NPV). This indicator allows for assessing the real benefit of investments, considering the time and possible risks associated with the implementation of the measures. The selection of such measures that yield the maximal Net Present Value is key to increasing the economic efficiency of the energy saving process in the transport vehicle's power system. Consequently, the effectiveness of the energy efficiency enhancement program will be achieved when measures that provide the maximal economic effect are combined with technical feasibility and ensure minimal costs with maximal energy savings. The implementation of measures and means for enhancing the energy efficiency of a transport vehicle's power system is associated with costs for their realization, which obviously requires a separate consideration of this process from the perspective of economic feasibility. The selection of economically effective measures is based on performing techno-economic calculations, i.e., determining the following proposed techno-economic indicators:

– capital (initial) investments;

– current (annual) costs.

For transport power systems, the current (annual) costs represent the costs of electric energy generation, maintenance of transport service personnel, and current repair of electrical equipment, depreciation deductions, and auxiliary costs. Analogous to making technical decisions during the design of a transport power system, the selection of these measures is carried out using the following criteria:

– project payback period or its reciprocal, the capital investment efficiency ratio in the project;

– annual discounted costs [23].

The share of cost savings per USD 1 of capital investments is reflected by the efficiency ratio, the reciprocal of the payback period.

Based on the recommendations in [23], that the implementation of measures for electric energy saving does not significantly affect the change in depreciation deductions and other costs, it is proposed to calculate this ratio only from the perspective of reducing the cost of consumed electricity (expected electricity savings). Annual discounted costs are most often used in the design of a transport power system, where the economic efficiency of projects is determined by its minimal value. The components of this criterion are analogous to the payback period criterion, among which the specific weight of the energy loss cost during its transmission through internal networks is still small, so the potential for energy efficiency in the resulting engineering studies is practically not utilized.

The latter is also due to the fact that capital investments in the power system are a component of the techno-economic justification for the construction or reconstruction of the entire transport vehicle, determined by the estimated cost of the designed object based on consolidated indicators. Hence the desire to reduce the cost of the transport power system, and therefore the focus on reducing capital investments first when choosing technical solutions, which also leads to a decrease in operating costs (for depreciation and current maintenance), since they are normalized by a certain percentage of the capital investments in the power system. This focus in the given criterion is mathematically realized as an element of the sum of the techno-economic projects of the transport system, among which the cost of electrical equipment has predominant significance.

One of the main criteria for the effectiveness of energy saving as a complex of organizational, technical, and technological solutions is the additional gain that remains as a result of their implementation. In the presence of losses, the degree of reduction of these losses as a result of specific organizational and technical measures to enhance the energy efficiency of transport vehicles is taken into account. At the same time, a constraint for the development of design options for increasing the energy efficiency of transport vehicles is that the transport vehicle as a whole must comply with pre-defined technical, technological, social, and environmental performance indicators. The main effects from the implementation of energy saving measures and tools in the power systems of transport vehicles as a complex of organizational, technical, and technological solutions are calculated based on the principle of isolating from the total volume of benefits received the part that is directly caused by the implementation of these measures and tools and remains undistributed. Logically, this should be defined as

$$\Delta P_i = P_{2i} - P_{1i}, \tag{1.1}$$

where P_{1i} and P_{2i} – the profit indicators for the i-th calculation period before and after the implementation of the complex of measures aimed at reducing energy losses in the transport vehicle's power system.

In transport power systems, the real processes of energy generation, conversion, and transmission, and the corresponding losses, are determined by the energy consumption modes of transport electricity consumers and the parameters of the transport power system itself. It makes sense to consider the appropriate technical process of energy transmission through the system so that the total losses in the system elements are as small as possible, while satisfying all technical requirements for the overall operation of the transport vehicle. Therefore, the overall evaluation of the energy saving potential *ESP* in the transport vehicle's power system is proposed to be performed as the difference in active electric energy losses corresponding to the parameters of the transport power system over a specified time interval W_p and the forecasted active electric energy losses in the proposed power system W_n

$$ESP = W_p - W_n. \tag{1.2}$$

Unlike other criteria for evaluating the energy efficiency of transport power systems, the latter explicitly define the maximally technically possible energy saving reserve in transport power systems and identify measures aimed at the direct reduction of energy losses within the transport systems. These measures are based on the calculation and analysis of specific values of energy savings determined after making changes to the transport vehicle's power system. However, the implementation of measures to reduce energy losses in transport power systems must be technically and economically justified. Therefore, a detailed assessment of the forecasted energy efficiency of the transport power system is necessary.

1.5 Defining general requirements for the diesel-generator power system model of transport vehicles

The application of computational methods for investigating electromechanical and electromagnetic processes in transport electric power systems requires a mathematical analogue, constructed with consideration for the research objectives (forecasted parameters and the factors influencing them). A systematic and effective influence on the magnitude of electric energy losses during transmission through the transport vehicle's electrical network first requires the determination of these losses. Therefore, it is proposed to develop a mathematical model of the transport power system. In this model, the parameters subject to forecasting are the total effective electric energy losses across all sections and levels of generation, transmission, and consumption on board the transport vehicle over a certain period.

The selection of the synthesized model structure and the relationships between power values, transport power system parameters, and the load of the transport electricity consumer is determined by the permissible forecasting error (loss estimation). The latter is defined by the requirements for the accuracy class of the transport measuring equipment that records the electricity consumption mode indicators of the consumers.

One of the goals of using the developed model is also the forecasting of losses when changing the structure and parameters of the transport power system itself over a certain period of time, and the use of the resulting values in subsequent techno-economic analysis.

The selection of the method for calculating effective energy losses in the power system is determined by the data used regarding the parameters of its elements (resistances). The latter are very stable and not difficult to obtain. The magnitude of the existing or projected electrical load can be determined by known methods applied in the operation of transport vehicles, or calculated by methods applied in the design of transport vehicles. Depending on the type and completeness of information about the load, deterministic, probabilistic, or statistical models and methods that satisfy the conditions of information uncertainty (fuzziness) can be used to calculate effective power losses. If the parameters of the transport network elements and the electrical load of transport electricity consumers are used as initial data, it is recommended to use the first of these. When calculating losses in the transport vehicle's power system, a simple deterministic method is recommended, which takes into account the duration of intervals with maximal power loss values, according to which the active electric energy losses ΔW are determined by the formula [23]

$$\Delta W_a = \Delta P \cdot \tau \,, \tag{1.3}$$

where ΔP – active power losses in the maximal load mode of the transport network; τ – the duration of time intervals with maximal power losses in the transport vehicle's power system.

The theory of designing complex technical objects utilizes the principles of decomposition and hierarchy in object descriptions. The latter involves division into levels, typically functional ones, depending on the level of detail of the properties and characteristics displayed by the object as a whole.

The principle of decomposition consists of dividing each hierarchy into several parts (blocks), which allows objects to be designed block by block at each level of the hierarchy. It is obvious that the considered approach is also suitable for modeling transport power systems. It is possible to transfer the principles outlined above to the immediate task, which is the construction of an energy efficiency model for a transport power system. To construct such a model, the power system is broken down into subsystems, and the structure of the model itself is determined considering its hierarchical structure:

– individual electricity consumers;
– distribution points;
– distribution electrical networks;
– main switchboard;
– generator system busbars.

Then, the total active energy losses in the system W will be determined by the formula

$$W = W_1 + W_2 + W_3 + W_4 + W_5, \tag{1.4}$$

where W_1 – active energy losses in the generator system busbars; W_2 – active energy losses in the main switchboard; W_3 – active energy losses in the distribution electrical networks; W_4 – active energy losses in the distribution points; W_5 – active energy losses in the individual electricity consumers.

Typification and unification of design solutions are also important principles in the design of complex technical systems. Therefore, the structure of the model should correspond to the typical diagram of the transport power system and can be easily adapted to other diagrams by removing sections or elements that do not exist, or by their additional inclusion at various levels of the power system using appropriate connections. Thus, the development of models for transport power systems is based on mathematical dependencies for calculating effective power losses in the transport subsystems specified in the model. These model components must be self-contained computational units, suitable for the further effective implementation of the energy efficiency research model of the transport power system not only for the transport vehicle as a whole, but also separately for each compartment and complex electricity consumer.

Let there be a set of distribution nodes N for a certain compartment or group of compartments of the transport vehicle. The number N includes everything that must be powered from the j-th transformer of the transport power system. These nodes are further presented as distribution points (DP_i, $i = \overline{1,N}$), with calculated loads for active power P_i and reactive power Q_i, and coordinates of the locations in the plan of the vehicle section ((x_i, y_i), m). The active electric energy losses in the vehicle's network when supplying the distribution points DP_i from the j-th transformer are calculated as the sum of losses on the ij-th section w_{ij}

$$W_c = \sum_{j}^{M} \sum_{i}^{N} w_{ij} = \sum_{j}^{M} \sum_{i}^{N} w_i \cdot l_{ij}. \tag{1.5}$$

The current load of the i-th node of the transport network at nominal voltage U

$$I_i = \frac{\sqrt{P_i^2 + Q_i^2}}{\sqrt{3} \cdot U}, \tag{1.6}$$

and the specific resistance of the ij-th section of the transport network is determined by the conductor cross-section s_{ij} and the specific resistance of its core material ρ_{ij}, considering the number of conductor strands in the transport network for each section n_{ij} (units)

$$r_{ij} = \frac{1000 \cdot \rho_{ij}}{s_{ij} \cdot n_{ij}}. \tag{1.7}$$

The length of the transport network section l_{ij} can be calculated based on the coordinates of the j-th transformer (x_j, y_j) and the i-th distribution points (x_j, y_j), using the principle of the shortest possible distance

$$D = \frac{\sqrt{\left(y_i - y_j\right)^2 + \left(x_i - x_j\right)^2}}{1000}, \tag{1.8}$$

or based on a detailed layout plan of the electrical equipment in the corresponding compartment or group of compartments of the transport vehicle, i.e., by correcting the section length according to the proposed transport route for laying the electrical network.

It is possible to establish the initial constraints and assumptions that must be taken into account when defining the general requirements for the model of the transport integrated power system.

1. The number of transport transformers N, the range of variation of which will be determined as follows

$$\frac{S}{SH^{\max}} \le N \le \frac{M}{m}, \tag{1.9}$$

where S – the electrical load of the compartment or group of compartments of the transport vehicle; $SH^{\max}$ – the maximal nominal power of the transport transformer that meets the established requirements; m – the number of connections to the busbars; M – the number of electricity consumers connected to the transport transformer.

2. The electrical load S_1 on each transport vehicle transformer must relate to the nominal power of the transformer S_N as follows

$$S_N \geq \frac{S_1}{n \cdot k}, \tag{1.10}$$

where n – the number of transport transformers; k – the transformer loading factor.

3. The coordinates of impermissible placement of each transport transformer (x_T, y_T) from the perspective of the transport vehicle's technological and territorial conditions are constrained as follows:

$$\begin{gathered} x_{\min} \leq x_T \leq x_{\max}, \\ y_{\min} \leq y_T \leq y_{\max}, \\ (x_T, y_T) \notin Z_i,\ i = \overline{1, T}, \end{gathered} \tag{1.11}$$

where ($x_{\min}$, $y_{\min}$), ($x_{\max}$, $y_{\max}$) – the limiting values of the abscissa and ordinate for placement on the transport vehicle; Z_i – the set of abscissa and ordinate of all transport vehicle area sections that belong to the i-th closed region of impermissible placement; T – the indicator of impermissible placement zones on the transport vehicle.

4. The cross-sections of conductors for all sections of the transport electrical network must be selected considering the main technical constraints:

– maximum permissible heat dissipation, taking into account normal and post-fault conditions;

– thermal stability of cables to short-circuit currents;

– performing tests for economic current density.

All checks against these requirements concern the previously selected (according to one of the conditions) increase in the cross-sectional area s. The latter value in the range of change of such a parameter as the cross-sectional area of the network transmission section F defines its minimum limit. The maximum value of this range is limited by the number of cable lines m_1 permitted for connection in the design of the distribution device. The constraint for the cross-sectional area of conductors for all sections is then defined by the following inequality

$$s \leq F \leq m_1 \cdot s_1. \tag{1.12}$$

5. The maximal nominal power of the reactive power compensator connected to the distribution device busbars must not exceed the reactive power load value for each bus section, taking into account reactive losses.

6. The short-circuit current of the power bus, relative to its level in the hierarchy of the transport electrical network, must not exceed the switching capacity of the distribution device used.

The parameters of the components of the transport electrical network determine their layout, as they are the connecting elements between the supply and distribution parts of the transport vehicle. Such parameters include:

– coordinates of the installation locations of the nodes under consideration;

– number of nodes and distribution of electrical loads among the nodes, which determines the scheme (topology) of the transport power system;

– design characteristics of individual nodes.

Thus, the efficiency of electric power transmission through the network will directly depend on its topology.

A characteristic feature of transport power systems is the presence of sections where cable laying is impossible. Therefore, difficulties arise in setting topology problems related to the mathematical description of constraints on the location of possible power sources and the routing of transport electrical network cables. Depending on how these constraints are introduced, the complexity of the problem can significantly vary. The method of domain plane recognition of the transport vehicle allows for dividing the image space of the transport vehicle into non-overlapping regions, each corresponding to one class of images, which enables an elementary analytical description and significantly simplifies the description of unacceptable regions of the transport vehicle.

Then, the entire unacceptable zone is described by a purely logical separation function of the form

$$\psi(\vec{x}) = \bigvee_{\mu=1}^{m} \zeta(\vec{x}), \tag{1.13}$$

where *m* – the number of non-intersecting regions into which the transport vehicle's image-space is divided; $\zeta(\vec{x})$ – the analytical description of the region of the selected class.

It is obvious that the most acceptable region for the task under consideration is the elementary region in the form of a hyperparallelepiped (a rectangle on a plane), the simplest analytical description of which is the signature function of the form [5, 6]

$$\zeta_{\mu}\left(\vec{x}_j\right)=\frac{1}{2^n}\prod_{\gamma=1}^{n}\left\{1+\operatorname{sgn}\left[\left(x_{j\gamma}-x_{j\gamma\min}\right)\left(x_{j\gamma\max}-x_{j\gamma}\right)\right]\right\}. \tag{1.14}$$

If the point, which is the placement location of the *j*-th element of the electrical network, falls within the hyperparallelepiped $\left(x_{\gamma\min}\ldots x_{\gamma\max}, \gamma=\overline{1,n}\right)$, then $\phi_{\mu}\left(\vec{x}_j\right)=1$. Otherwise, $\phi_{\mu}\left(\vec{x}_j\right)=0$.

1.6 Conclusions

~~1.~~ The general principles for designing an energy-efficient transport integrated AC power system have been defined. It is shown that the problem of integrated electric energy utilization in transport networks, taking into account the need for minimization of energy losses and the corresponding minimization of the cost of generated energy, is the foundation for constructing an energy-efficient transport integrated power system. Solving this problem requires the development of appropriate control principles, which must be based on the sequential execution of stages such as: the development of a mathematical model of static and dynamic processes corresponding to both the entire electric power system of the transport vehicle and its individual component nodes; the establishment of an economic model for evaluating the cost and efficiency of electric power generation and consumption in transport networks; and the implementation of control over the integrated electric power system of the transport vehicle to minimize energy consumption and the corresponding minimization of the cost of generated energy based on the evaluation using the established economic model. The principle of investigating the transport electrical system should be appropriately based on the consideration of individual elements of the transport network, which is logical when compiling energy balances for the transport vehicle as a whole, assessing total losses in the elements, and developing general energy-saving measures. In the course of the study, it was determined that the division of the transport power system into these fragments must be related to its structure and specific technical processes in each compartment or electricity consumer. This does not contradict the general principle of energy research but merely supplements and improves it.

~~2.~~ The causes of major energy losses in the integrated AC electric power system of a transport vehicle have been identified. Specifically, energy transmission through the electrical networks of the transport vehicle is accompanied by active electric energy losses caused by electromagnetic and thermal processes occurring in their elements and the technological electrical equipment of the transport vehicle. It is shown that the transfer of reactive power through the active resistances in the elements of the transport electrical network causes additional power losses and a corresponding increase in electric energy consumption. Increased reactive power flows can also lead to other undesirable phenomena, such as a reduction in the throughput capacity of transport lines and distribution devices, and a decrease in the voltage level. The reduction or complete elimination of power flows can be achieved by implementing reactive energy compensation measures. In marine transport, the issue of reactive power regulation involves a complex of techno-economic aspects, including: reducing the consumption of reactive energy by on-board electricity consumers; determining the optimal type and location for installing compensating devices; setting up effective operating modes for these devices; and improving methods for calculating and reducing the level of reactive power. Measures aimed at reducing reactive power consumption by the consumers themselves are usually applied in operational practice and may include actions such as: increasing the loading of transport technological units and increasing their utilization time; using no-load limiters on asynchronous motors and transport welding units; replacement, rearrangement, and disconnection of lightly loaded electrical equipment; replacement of asynchronous motors with synchronous ones in new electric drive installations, if acceptable based on techno-economic comparisons; performing high-quality motor repair; utilizing rational converter circuits; and applying means for individual reactive power compensation.

~~3.~~ A system of evaluation criteria for an energy-efficient transport integrated AC power system has been established. It is specifically shown that the main objective in constructing and enhancing the energy efficiency of a transport power system is the maximal reduction of the energy loss level. The solution to the problem of selecting appropriate means to increase energy efficiency must be performed sequentially: forming the set of all possible means and measures for enhancing the energy efficiency of the transport power system; selecting subsets of combinations of options for means and measures to increase the energy efficiency of the transport power system; and establishing a corresponding objective function for enhancing the energy efficiency of the transport power system, as well as defining boundary and additional conditions. The set of solutions that correspond to the defined objective function for enhancing the energy efficiency of the transport power system, and also satisfy the defined constraints and boundary conditions, enable the energy efficiency of the transport system and constitute the set of measures and means that must be implemented for the maximally effective energy transmission through the transport vehicle's systems and its consumption by the corresponding electricity consumers.

~~4.~~ The general requirements for the model of the transport integrated power system have been defined. Specifically, the model is based on the principle of decomposition, which means dividing each level into a number of parts (blocks) with the possibility of block-by-block design of the object at each hierarchical level. It is obvious that the considered approach should be appropriately implemented when modeling the transport power system to solve the problem of forming an energy efficiency model for the transport power system, the core idea of which is the development of a power system that operates with minimal energy losses within it. For the synthesis of this model, the transport vehicle's power system is broken down into subsystems, taking into account its hierarchical structure and defining the structure of the model itself: individual electricity consumers; distribution points; distribution electrical networks; main switchboard; generator system busbars.

The corresponding requirements for each subsystem and the initial values and constraints have been established.

Conflict of interest statement

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

Use of artificial intelligence statement

The authors declare that they did not use artificial intelligence tools in preparing this manuscript.

References

1. Lee, H.-W., Kim, K.-C., Lee, J. (2006). Review of maglev train technologies. IEEE Transactions on Magnetics, 42 (7), 1917–1925. https://doi.org/10.1109/tmag.2006.875842
2. Mi, C. C., Buja, G., Choi, S. Y., Rim, C. T. (2016). Modern Advances in Wireless Power Transfer Systems for Roadway Powered Electric Vehicles. IEEE Transactions on Industrial Electronics, 63 (10), 6533–6545. https://doi.org/10.1109/tie.2016.2574993

3. Arefifar, S. A., Mohamed, Y. A.-R. I., El-Fouly, T. H. M. (2012). Supply-Adequacy-Based Optimal Construction of Microgrids in Smart Distribution Systems. IEEE Transactions on Smart Grid, 3 (3), 1491–1502. https://doi.org/10.1109/tsg.2012.2198246
4. Giuntoli, M., Poli, D. (2013). Optimized Thermal and Electrical Scheduling of a Large Scale Virtual Power Plant in the Presence of Energy Storages. IEEE Transactions on Smart Grid, 4 (2), 942–955. https://doi.org/10.1109/tsg.2012.2227513
5. Maslov, I., Tymoshchuk, O., Kulagin, D. (2025). Determining the causes of major energy losses in a ship's unified AC power system. Modern automotive industry, transport and road infrastructure '2024 (MAITRI2024), 3428, 020021. https://doi.org/10.1063/12.0038611
6. Kulagin, D., Maslov, I. (2024). Mathematical Model of Electromagnetic Transients of a Frequency-Controlled Propeller's Induction Motor. 2024 IEEE 5th KhPI Week on Advanced Technology (KhPIWeek). IEEE 1–5. https://doi.org/10.1109/khpiweek61434.2024.10877991
7. Choi, S., Huh, J., Lee, W. Y., Lee, S. W., Rim, C. T. (2013). New Cross-Segmented Power Supply Rails for Roadway-Powered Electric Vehicles. IEEE Transactions on Power Electronics, 28 (12), 5832–5841. https://doi.org/10.1109/tpel.2013.2247634
8. Choi, S. Y., Jeong, S. Y., Gu, B. W., Lim, G. C., Rim, C. T. (2015). Ultraslim S-Type Power Supply Rails for Roadway-Powered Electric Vehicles. IEEE Transactions on Power Electronics, 30 (11), 6456–6468. https://doi.org/10.1109/tpel.2015.2444894
9. Kulahin, D. O. (2016). Rolling electrical complex on the basis of the criterion of minimizing the area under the curve of motion. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2, 60–67.
10. Kulagin, D. O. (2014). The mathematical model of asynchronous traction motor taking into account the saturation of magnetic circuits. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 6, 103–110.
11. Fathy, A., Kaaniche, K., Alanazi, T. M. (2020). Recent Approach Based Social Spider Optimizer for Optimal Sizing of Hybrid PV/Wind/Battery/Diesel Integrated Microgrid in Aljouf Region. IEEE Access, 8, 57630–57645. https://doi.org/10.1109/access.2020.2982805
12. Arai, J., Iba, K., Funabashi, T., Nakanishi, Y., Koyanagi, K., Yokoyama, R. (2008). Power electronics and its applications to renewable energy in Japan. IEEE Circuits and Systems Magazine, 8 (3), 52–66. https://doi.org/10.1109/mcas.2008.928420
13. Kulagin, D. O. (2014). Mathematical model of asynchronous traction motor taking into account the saturation. Technical Electrodynamics, 6, 49–55.

14. Kulagin, D. O., Fedosha, D. V., Nitsenko, V. V., Shevchenko, S. Yu., Danylchenko, D. O. (2019). Using a phase-differential busbar protection for switchgears of power system facilities. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 4, 63–67. https://doi.org/10.29202/nvngu/2019-4/10
15. Holtz, J., Lotzkat, W., Werner, K.-H. (1988). A high-power multitransistor-inverter uninterruptable power supply system. IEEE Transactions on Power Electronics, 3 (3), 278–285. https://doi.org/10.1109/63.17945
16. Sitzman, A., Surls, D., Mallick, J. (2007). Design, Construction, and Testing of an Inductive Pulsed-Power Supply for a Small Railgun. IEEE Transactions on Magnetics, 43 (1), 270–274. https://doi.org/10.1109/tmag.2006.887685
17. Liu, Z., Zhang, W., Ji, X., Li, K. (2012). Optimal Planning of charging station for electric vehicle based on particle swarm optimization. IEEE PES Innovative Smart Grid Technologies. IEEE, 1–5. https://doi.org/10.1109/isgt-asia.2012.6303112
18. Nitsenko, V., Kulagin, D. (2017). Improvement implementation methods of relay busbars protection of switchgears. Tekhnichna Elektrodynamika, 6, 61–71. https://doi.org/10.15407/techned2017.06.061
19. Nitsenko, V. V., Kulahin, D. O. (2017). Research on effect of differential-phase protection of busbars system with voltage of 110–750 kV. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 4, 72–79.
20. Mansor, M. A., Hasan, K., Othman, M. M., Noor, S. Z. B. M., Musirin, I. (2020). Construction and Performance Investigation of Three-Phase Solar PV and Battery Energy Storage System Integrated UPQC. IEEE Access, 8, 103511–103538. https://doi.org/10.1109/access.2020.2997056
21. Amei, K., Takayasu, Y., Ohji, T., Sakui, M. (1989). A maximum power control of wind generator system using a permanent magnet synchronous generator and a boost chopper circuit. Proceedings of the Power Conversion Conference-Osaka 2002 (Cat. No.02TH8579). IEEE, 3, 1447–1452. https://doi.org/10.1109/pcc.2002.998186
22. Korobko, B., Kivshyk, A., Kulagin, D.; Onyshchenko, V., Mammadova, G., Sivitska, S., Gasimov, A. (Eds.) (2021). Experimental Study of the Efficiency of the Differential Pump of Electromagnetic Action on the Basis of Mathematical Modeling of the Parameters of Its Operation. Proceedings of the 3rd International Conference on Building Innovations. Cham: Springer, 203–213. https://doi.org/10.1007/978-3-030-85043-2_20
23. Bratkovska, K., Makhlin, P., Shram, A., Kulagin, D., Fedosha, D. (2022). Estimation of Optimization Approaches of the Energy Intensive Equipment's Power-Time Diagrams of Industrial Enterprises. 2022 IEEE 8th International Conference

on Energy Smart Systems (ESS). IEEE, 277–281. https://doi.org/10.1109/ess57819.2022.9969248

24. Yekimov, S., Nianko, V., Kulagin, D., Lunkina, T., Haponenko, S. (2021). The importance of environmental education for effective environmental management. E3S Web of Conferences, 296, 08002. https://doi.org/10.1051/e3sconf/202129608002
25. Lee, F. C., van Wyk, J. D., Boroyevich, D., Guo-Quan Lu, Zhenxian Liang, Barbosa, P. (2002). Technology trends toward a system-in-a-module in power electronics. IEEE Circuits and Systems Magazine, 2 (4), 4–22. https://doi.org/10.1109/mcas.2002.1173132
26. vanWyk, J. D., Lee, F. C., Liang, Z., Chen, R., Wang, S., Lu, B. (2005). Integrating Active, Passive and EMI-Filter Functions in Power Electronics Systems: A Case Study of Some Technologies. IEEE Transactions on Power Electronics, 20 (3), 523–536. https://doi.org/10.1109/tpel.2005.846553
27. Crisostomi, E., Liu, M., Raugi, M., Shorten, R. (2014). Plug-and-Play Distributed Algorithms for Optimized Power Generation in a Microgrid. IEEE Transactions on Smart Grid, 5 (4), 2145–2154. https://doi.org/10.1109/tsg.2014.2320555
28. Kulagin, D., Maslov, I., Lysechko, V., Prokopenko, V., Shram, A., & Pastushenko, V. (2023). Analysis Of Current Approaches to Modernizing the Electric Power Scheme of Diesel Generator Transport. 2023 IEEE 4th KhPI Week on Advanced Technology (KhPIWeek). IEEE, 1–6. https://doi.org/10.1109/khpiweek61412.2023.10312881
29. Kelley, A. W., Owens, W. R. (1989). Connectorless power supply for an aircraft-passenger entertainment system. IEEE Transactions on Power Electronics, 4 (3), 348–354. https://doi.org/10.1109/63.39124
30. Mesbahi, T., Khenfri, F., Rizoug, N., Bartholomeus, P., Moigne, P. L. (2017). Combined Optimal Sizing and Control of Li-Ion Battery/Supercapacitor Embedded Power Supply Using Hybrid Particle Swarm-Nelder-Mead Algorithm. IEEE Transactions on Sustainable Energy, 8 (1), 59–73. https://doi.org/10.1109/tste.2016.2582927
31. Wang, C.-N., Nguyen, N.-A.-T., Dang, T.-T., Bayer, J. (2021). A Two-Stage Multiple Criteria Decision Making for Site Selection of Solar Photovoltaic (PV) Power Plant: A Case Study in Taiwan. IEEE Access, 9, 75509–75525. https://doi.org/10.1109/access.2021.3081995
32. Cella, R., Giangaspero, G., Mariscotti, A., Montepagano, A., Pozzobon, P., Ruscelli, M., Vanti, M. (2006). Measurement of AT Electric Railway System Currents at Power-Supply Frequency and Validation of a Multiconductor Transmission-Line

Model. IEEE Transactions on Power Delivery, 21 (3), 1721–1726. https://doi.org/10.1109/tpwrd.2006.874109

33. Luo, P., Li, Q., Zhou, Y., Ma, Q., Zhang, Y., Peng, Y., Sun, J. (2021). Multi-Application Strategy Based on Railway Static Power Conditioner With Energy Storage System. IEEE Transactions on Intelligent Transportation Systems, 22 (4), 2140–2152. https://doi.org/10.1109/tits.2020.3048362
34. Kulaghin, D., Maslov, I. (2025). Synthesis of Automatic Control System of Traction Asynchronous Motor of Transport Diesel-Generator Power Plant. Problems of the Regional Energetics, 4, 18–31. https://doi.org/10.52254/1857-0070.2025.4-68.02
35. Dyke, K. J., Schofield, N., Barnes, M. (2010). The Impact of Transport Electrification on Electrical Networks. IEEE Transactions on Industrial Electronics, 57 (12), 3917–3926. https://doi.org/10.1109/tie.2010.2040563
36. Zhang, H., Hu, Z., Song, Y. (2020). Power and Transport Nexus: Routing Electric Vehicles to Promote Renewable Power Integration. IEEE Transactions on Smart Grid, 11 (4), 3291–3301. https://doi.org/10.1109/tsg.2020.2967082