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ВЛИЯНИЕ ТОКОВ КУСОЧНО-ЛИНЕЙНОЙ ФОРМЫ НА ОСТАЮЩЕЕСЯ НАПРЯЖЕНИЕ НЕЛИНЕЙНОГО ОГРАНИЧИТЕЛЯ ПЕРЕНАПРЯЖЕНИЙ

Приведены результаты исследования динамической модели нелинейного ограничителя перенапряжений. Моделирование выполнено с помощью демонстрационной версии программы Micro-Cap 11. Установлено, что для быстрой оценки величины остающегося напряжения на нелинейном ограничителе перенапряжений можно использовать кусочно-линейное описание коммутационных и грозовых импульсов тока без существенной потери точности результатов.

Ключевые слова: схемотехническое моделирование, нелинейный ограничитель перенапряжений, остающееся напряжение, кусочно-линейная форма.

Trotsenko Yevgeniy, *PhD, Associate Professor, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: y.trotsenko@kpi.ua, ORCID: http://orcid.org/0000-0001-9379-0061*

Brzhezitsky Volodymyr, *Doctor of Technical Sciences, Professor, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: v.brzhezitsky@kpi.ua, ORCID: http://orcid.org/0000-0002-9768-7544*

Masluchenko Igor, *PhD, Associate Professor, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: i.masluchenko@kpi.ua, ORCID: http://orcid.org/0000-0001-6073-9649*

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**Kulagin D.,
Yatsenko D.**

INVESTIGATION OF PECULIARITIES OF DECOMPOSITION OF TRACTION ELECTRIC DRIVES OF MOBILE ELECTROTECHNICAL COMPLEXES

Досліджено особливості проведення декомпозиції систем тягових електроприводів для різних видів та конструкцій рухомих електротехнічних комплексів. Проведено аналіз практичного досвіду декомпозиції систем тягових електроприводів та узагальнення методики визначення структури та параметрів при заданих вимогах з боку рухомого електротехнічного комплексу. Запропоновано метод підвищення енергоефективності дизель-генераторної електромеханічної системи транспортного засобу за статичними та динамічними характеристиками.

Ключові слова: *декомпозиція електроприводу, електротехнічний комплекс, тяговий привод, автономна система, дизель-генераторна система.*

1. Introduction

A significant amount of work has been devoted to improving the individual elements of the diesel-generator electromechanical system. For example, in [1–4] the mutual influence of separate groups of elements of common industrial electric drives, in particular the redactor-traction motor, the traction motor-reducer on the general potential of energy efficiency according to static characteristics is shown. However, electric drives of vehicles are more complex in structure, contain a larger number of groups of interconnected elements. So they can have a greater energy potential in the case of a mutual influence between groups of these elements with static characteristics.

Solving the problem of increasing the energy potential of an electromechanical system is possible only in a complex manner. At the same time, it is necessary to consider the established mode of operation of the entire system as a whole, taking into account the conditions for the rational operation of its individual components, provided that the relationship between them is taken into account. After all, a fairly frequent practical situation is when a rational operating mode of individual elements of an electromechanical system and optimal control of them does not lead to the operation of the entire system on the economic characteristics. This, as a consequence, increases the consumption level of diesel fuel. Conversely, the artificial compulsion of diesel operation on the economic characteristics leads to the operation of these electrical elements of the whole electromechanical system with significant power losses.

The use of an integrated, interrelated approach, in which the most energy efficient mode of operation of the entire system is selected, will solve this problem. And each element of the system will work in the most energy saving mode, which is only possible with this position of the electromechanical system. This can be done taking into account the synergetic properties of the electromechanical system.

2. The object of research and its technological audit

The object of research is the traction electric drive systems of mobile electrotechnical systems based on various types of motors.

When choosing the structure of the traction electric drive of the mobile electrotechnical complex, it is necessary to proceed from the premise that the primary power unit, traction generator, traction gearbox, system of own needs, traction motor and reducer-wheel pair are considered not as separate components or subsystems to increase their energy potential. They are integral parts of the entire traction electric drive, the energy potential of which should be maximized according to the chosen principles only in general. In this case, the solution of individual tasks for these subsystems is necessary only to ensure the selection of rational performance of the entire traction electric drive.

It is known that the electromechanical system is synergetic [1]. The synergetic concept of improving the energy efficiency of the diesel-generator system of a vehicle is based on the fact that in this system each power element is intended to maximize its technical and economic performance. In this case, each element must compensate for each other's disadvantages, and increase the energy potential of the entire diesel-generator electromechanical system. Task of the reverse decomposition of the electromechanical system and establishing the relationship between the energy potential of the received subsystems and the entire system as a whole are a priority to establish the boundaries of increase of the energy potential of the system.

According to the synergetic approach and the decomposition method, let's consider the elements of a complex hierarchical structure of the electromechanical system – a synchronous generator, a gearbox, a traction motor, a redactor, a wheel, a control system as separate subsystems. These subsystems are subordinate to each other and there is a mutual influence between them.

To use the synergetic properties of the electromechanical system, it is necessary to consider internal interactions between the elements of a common closed system in order to achieve the maximum effect of the operation of the entire system, and not just a single object or subsystem. That is, the construction of the structure of such system must be considered in the direction of taking into account the mutual influences between the components decomposed by the electromechanical structure.

So, in the future we will consider methods for ensuring the energy-efficient operating mode of each of the elements of the hierarchical structure of the electromechanical system alone and in combination. This is necessary to achieve the most rational level of diesel fuel consumption in setting the technological performance of the entire vehicle. Let's perform the decomposition of a typical sequential structure of the diesel-generator electromechanical system of the vehicle, shown in Fig. 1.

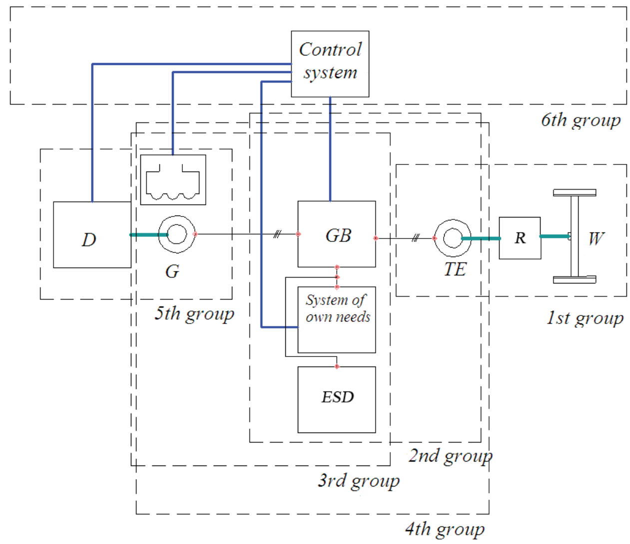

Fig. 1. Block diagram of the diesel-generator electromechanical system of the vehicle

In Fig. 1 *D* – diesel, *G* – generator, *ESD* – energy storage device, *R* – reducer, *TE* – traction motor, *GB* – gearbox, *W* – wheelset.

3. The aim and objectives of research

The conducted research is aimed at determining the specifics of the decomposition of traction electric drive systems for various types and designs of mobile electrical systems.

To achieve this aim, the following tasks are accomplished:

1. Analysis of practical experience of decomposition of traction electric drive systems.
2. Generalization of the technique of decomposition of the structure and parameters of traction electric drives with specified requirements from the mobile electrotechnical complex.

4. Research of existing solutions of the problem

The basic idea of the theory of complex systems is that the behavior of the whole can't be predicted from the properties of its parts. Similarly, acting on each part of the system separately, one can't achieve the maximum effect for the entire system as a whole. The interaction between the elements of the system makes a significant impact on the operation of the entire system. This property of systems is called «emergence»: the whole is different from the sum of its constituent parts, because the main thing is how the interaction between the parts proceeds. Moreover, these interactions can be governed by very simple rules. Therefore, complex systems must be considered only in aggregate, using a method for optimizing complex systems-a synergetic method that has recently been used singly but very efficiently for mechatronic systems. Thanks to the wide application of research results on mechatronics, a special direction of development of this branch of science – transport mechatronics can be identified today in transport [1]. It is devoted to the analysis of problems of communication and organization of interaction of transport electromechanical and electronic components, units and telematic devices and systems in the process of operation of transport vehicles for obtaining synergetic effect [2]. Therefore, mechatronics and telematics based on synergetics of transport vehicles and systems is the main component of the latest information and communication technologies.

Any transport vehicle or system is a set of devices, assemblies and units that combine technical means to provide technology:

- mechanical (the process of movement of vehicles in space and time);
- electronic (motion control process);
- information (the process of processing data on the state of the traffic environment).

Accordingly, transport systems and technologies, such as mechatronic systems and facilities, should be considered. This line of research is exploring a new scientific direction – mechatronics [3], which has found wide application in road transport [4]. Not every transport vehicle or system at a sufficient level corresponds to the definition of the mechatronic system. First, such system must have the property of autonomy. Secondly, the mechatronic system is distinguished by intelligent (Smart) behavior. The property of the mechatronic system, transport vehicle or car to be «smart» can be achieved or obtained through the use of modern technologies of artificial intelligence based on neural networks [1, 5].

Competitive vehicle today can be developed only by the scheme of a hybrid electric vehicle with a synergetic power plant, which includes an internal combustion motor, an electric motor and a buffer energy storage element [4, 6]. Specialists' studies [4, 7] confirm the feasibility of creating such a synergetic electric vehicle, which in more than two cases is more economical than a base vehicle with a traditional internal combustion motor. However, the promising synergetic principle is still not developed for diesel-generator electromechanical systems of a wide range of capacities

A characteristic feature of the research of leading scientific schools in recent decades is the indispensable development of control problems in parallel with traditional research of means of transformation, constitutes a sufficient condition for performing synergetic optimization measures [8, 9]. In [4, 10, 11], the concept of a system study of the energy parameters of a control object is proposed as a necessary condition for solving optimization problems, based on the following provisions:

- autonomous transport power supply systems with DC voltage converters are closed structures. They have to be analyzed in the whole aggregate of mutual influences and interconnections of all structural components. That is, the basic structure is subject to investigation: «accumulator battery – impulse converter – traction motor»;
- research and analysis of traction electrical equipment systems should be covered by a single mathematical description, containing a functional relationship of the regime characteristics, control parameters and energy indicators of these systems;
- from the energy indicators (efficiency, power consumption, power losses, etc.), which dependence on control parameters is studied, the preference should be given precisely to efficiency. After all, the most common indicator of the energy efficiency of both individual components and the drive system as a whole.

The main directions of the synergetic increase in the efficiency of the functioning of autonomous electric vehicles and the improvement of their operational characteristics are the rational organization of the primary energy source conversion processes and the provision of effective overall energy exchange in transport energy supply systems. With this formulation of the problem, its solution is based on a comprehensive study of the dependencies of energy indicators of transport energy supply systems on the control and load parameters with mandatory consideration of the constraints imposed by primary sources.

Researches, existing methods and means of increasing efficiency are mainly concern individual components of such systems and do not always provide a synergetic increase in the efficiency of systems as a whole, which hinders the development of autonomous electric transport [4]. From this follows the need for further development of scientific research on energy indicators of energy supply systems on the basis of a synergetic system analysis of transport electric drives, development of a synergetic methodology for rational construction of their structure, synergetic methods and means of controlling the elements of such systems. This will ensure a reduction in specific energy costs, an increase in efficiency, improvement of operational, reliable and ergonomic indicators of autonomous electric transport [1, 4].

A great contribution to the solution of the problem of increasing the efficiency of electric power systems of autonomous electric transport was made by scientists of the laboratory of electric vehicles of the Institute of Electrodynamics (Kyiv, Ukraine). Here, a methodology has been developed that makes it possible to perform studies on the energy efficiency of power supply systems of such vehicles from the point of view of efficiency both element-wise and at the system level. With the help of this methodology, a number of schemes have been analyzed for the quality of traction and auxiliary electrical equipment for electric vehicles [12]. In particular, the authors of [12] with the help of this methodology carried out an analysis of the power indicators of the power supply systems of the autonomous electric transport of the combined pulse-width regulator and the power converter for the power supplies of low-voltage on-board consumers. Dependences of the efficiency of individual elements and power supply systems of autonomous electric transport as a whole on the control parameters and load are obtained. The recommendations on the optimal, from the point of view of the overall efficiency of power supply systems of autonomous electric transport, control of such systems are also determined.

The main directions of increasing the efficiency of functioning of autonomous electric vehicles, improving their operational characteristics is the rational organization

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of processes for converting the energy of the primary source and ensuring effective overall energy exchange in transport energy supply systems. With this formulation of the problem, its solution is based on a comprehensive study of the dependencies of energy indicators of transport energy supply systems on the control and load parameters with mandatory consideration of the constraints imposed by primary sources.

The main issue in the construction of energy-efficient structures of diesel-generator systems is the optimization of the power consumption used by the system from the diesel. This will reduce the level of losses and ensure the power consumption of the entire electromechanical system at a minimum. Reducing the level of losses, that is, increasing the efficiency in such systems attracts the attention of many researchers [1–7]. Various methods for solving it are proposed, and numerous inventions are patented enough to reduce the power loss in some cases. However, the fact that none of these methods is widely used in the practice of diesel-generator systems indicates that many attempts to improve the level of energy efficiency have a low effect. As a rule, the gain in efficiency is acquired at the cost of a significant complication in the design of the electromechanical system, the introduction of additional links. The limits of applicability of these methods also remain unknown. Practical implementation of many methods is based on the inability to predict some side effects that are critical to use this method.

To date, there is no classification system for diesel-generator electromechanical systems in terms of capacity. It is necessary to study the performance of vehicles for static characteristics. For the vast majority of transport vehicles and rolling stock railways, the question arises about the need for its creation. As a basis, let's adopt the traction classification, which is used in the tractor industry.

According to the old GOST 27021-86 or ST SEV 628-85 the standard row of agricultural tractors included 10 traction classes. It was a growing sequence of dimensionless numbers (0.2...8), each of which expressed the value of the nominal tractor traction power (P_{cr}) in tones [13].

In international practice, according to ISO 730/1 and ISO 730/3-82, the classification of tractors is based on the maximum traction power $N_{cr.\max}$. It is obtained when testing an energy source on a smooth horizontal and dry concrete surface or a surface covered with crooked/uncut grass [13]. Tractors are divided into four categories, each corresponding to the classification of energy resources in accordance with the international standard GOST 27021-86 (ST SEV 628-85) [13].

Practice shows that the classification in accordance with GOST 27021-86 (ST SEV 628-85) gives a more accurate idea of the operational properties of the tractor [13]. And this, in turn, allows to correctly determine a complex of agricultural machinery and tools. However, in order to generalize and classify the main measures for increasing the energy potential for elements decomposed by structures, this classification of diesel-generator vehicles is too detailed, since the approaches will be the same in most of these classes. This detailed classification is useful for the correct selection of a complex of agricultural machines and tools for the relevant tractor and for carrying out appropriate design and traction calculations. It will also be needed in determining the appropriate operating weight of the tractor, the nominal tractive effort and tolerance for its oscillation, the rate of slipping of the power tool when determining its nominal tractive effort.

5. Methods of research

To achieve the task of control of complex electromechanical system, the important potential is not every individual element of the electric drive, but the potential of their aggregate in the interaction. With a successful combination of interaction and operating modes of each element and the whole structure in general, the total energy saving potential of the whole is greater than the sum of the energy saving potentials of individual elements of the electric drive. As a result, we get a synergy effect. Synergy (Greek synergos), means coordinated, interacting. The law of synergy states that the sum of the properties of an organized whole is greater than the arithmetic sum of the properties of its elements. The resulting overall effect is called synergetic. The task of the control algorithm is to optimize the interaction of resources to obtain a positive synergy effect, the effect of reducing the level of losses in the system.

The main reserves of synergetic increase in energy efficiency of diesel-generator electromechanical systems are methods of increasing the efficiency of electromechanical structure elements, vehicle control modes and control algorithms for structural elements.

Let's determine that based on the approach of a synergetic increase in the energy efficiency of the diesel-generator electromechanical system of a vehicle, the primary measure for improving energy efficiency is the development of a concept for selecting the structure of the system using a synergetic approach. The main means of increasing the energy efficiency of the diesel-generator electromechanical system is the application of electric braking with the use of recuperative accumulation or energy redistribution. The main reserves of energy efficiency increase are the corresponding complex control algorithms based on the synergetic principle. At the same time, increasing the accuracy and adequacy of the control systems of diesel-generator electromechanical systems makes it possible to ensure the fulfillment of the task of creating reference motion parameters that satisfy the optimal one for any particular criterion of motion. Special attention should also be paid to the means of implementing the developed control algorithms, which will allow the most accurate development of control algorithms.

The techniques used to optimize the energy systems are rather complex, most of them are based on the condition of equality of relative increments in fuel consumption, which is only a necessary condition for the existence of an extremum. To account for restrictions, the method of penalty functions is applied. It allows for the possibility of calculations only with the use of a computer. The methods of dynamic programming, branches and boundaries are also quite complex and require the use of a computer. The most known method for optimizing parallel running diesel motors is the method [1, 4]. The method is easily applied to motors with identical loading characteristics and quite complex for units with different characteristics. In addition, when developing the criterion of optimality, this method does not impose restrictions on the power of the aggregates. The method does not provide a mathematical justification for the choice of the composition of operating aggregates [1, 4].

6. Research results

The maximum effect on increasing the energy potential can be achieved by considering the subsystem group of electromechanical vehicle system. In these groups, certain types of energy are converted into other and corresponding adjustments of the physical characteristics of these types of energy. To do this, let's perform the decomposition of the structural scheme of the electromechanical system, shown in Fig. 1, to the appropriate groups:

Group 1: traction motor – reducer – wheelset.

Group 2: converter (gearbox) – traction motor.

Group 3: generator – converter (gearbox).

Group 4: generator – converter (gearbox) – traction motor.

Group 5: diesel – generator.

Group 6: general control system for all links and the system as a whole.

To analyze and generalize the means of increasing the energy potential by static characteristics, let's perform the classification of diesel-generator electromechanical systems depending on the power (Table 1).

Table 1

Classification of diesel-generator electromechanical systems by traction categories

Power category	Traction power, kW	Part of the total power consumption for own needs	Types of diesel-generator vehicles belonging to this power category
I	< 70	4–30 % (power mainly from auxiliary generators)	– mini tractors; – loaders; – light self-propelled chassis; – tractors to class 2; – light construction equipment; – light road equipment; – auxiliary machines and self-propelled devices of railways
II	70–300	6–25 % (power from the auxiliary generators, or DC bus)	– tractors of classes 3–8; – building and road machinery; – rail buses; – auxiliary machines and self-propelled devices of railways; – rail cars; – auxiliary quarry vehicles; – locomobiles; – urban transport
III	> 300	8–20 % (power mainly from DC bus)	– tractors of classes more than 8; – combines; – locomobiles; – heavy building and road machinery; – quarry dump trucks; – suburban rolling stock; – shunting rolling stock

The proposed classification covers all the main categories of diesel-generator electromechanical systems according to traction classes for which some unified approaches are characteristic.

The accepted structure of the electromechanical system and the classification according to traction categories is given, which is typical for both AC systems and DC systems.

Let's perform a generalization of the basic structures of the elements of the decomposed system in accordance with the proposed classification, the relationship between which allows maximum use of the synergetic properties of the electromechanical system.

Variants of the structures of «traction motor – reducer» group are given in Table 2.

Table 2

Variants of the structures of «traction motor – reducer» group

Structure of the elements of the group	Power category		
	I	II	III
Reducer with variable number of degrees – Traction motor			
Gearless system (motor-wheel)			Not typical for this class
Traction motor of special design – Reducer	Not typical for this class		

Variants of the structures of «reducer – traction motor» group are given in Table 3.

Table 3

Variants of the structures of «reducer – traction motor» group

Structure of the elements of the group	Power category		
	I	II	III
Frequency converter – Traction motor of special design			
Multi-level frequency converter – AC traction motor	Not typical for this class		
4q-converter – Traction motor	Not typical for this class		
Using an energy storage device			

Variants of the structures of «generator – converter» group are given in Table 4.

Table 4

Variants of the structures of «generator – converter» group

Structure of the elements of the group	Power category		
	I	II	III
Generator – Converter – Common DC bus			
Generator – Direct frequency converter			Not typical for this class
Generator – Storage system – Converter			

Variants of the structures of «generator – converter – traction motor» group are given in Table 5.

Table 5

Variants of the structures of «generator – converter – traction motor» group

Structure of the elements of the group	Power category		
	I	II	III
Generator – Traction motor (without traction converter with power supply of own needs from auxiliary generator)		Not typical for this class	Not typical for this class
Generator – Converter – Common DC bus			
Generator – Converter – Common DC bus with storage system			

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Variants of the structures of «diesel-generator» group are given in Table 6.

Table 6

Variants of the structures of «diesel – generator» group

Structure of the elements of the group	Power category		
	I	II	III
Diesel – High-speed synchronous generator	Not typical for this class		
Diesel generator with combined windings			Not typical for this class
Diesel with supercharging or boosting – Generator	Not typical for this class		
Diesel-compressor – Generator with the ability to work in motor mode			

The above classification of structures shows the unity between approaches to diesel-generator electromechanical systems of alternating and direct currents that allows to unify the proposed measures and extend them to a wider class of vehicles. Considering the prospects of constructing electromechanical systems based on alternating current, we will further consider the relationship between these groups based on an electric drive with an asynchronous motor.

Let's suppose that P is the set of all possible means to improve the energy efficiency of the electromechanical system. Moreover, the set P has the property that some of its constituent subsets can be used simultaneously, and the other subsets only alone, which is explained by the incompatibility of simultaneous execution of certain organizational and technical measures. Therefore, let's divide the set P into definite subsets:

– subset P_1 includes the means that will be introduced in the subsystem «traction motor – reducer – wheel-set» (Table 2);
– subset P_2 includes the means that will be introduced in the subsystem «converter – traction motor» (Table 3);
– subset P_3 includes the means that will be introduced in the subsystem «synchronous generator – converter» (Table 4);
– subset P_4 includes the means that will be introduced in the subsystem «synchronous generator – converter – traction motor» (Table 5);
– subset P_5 includes the means that will be introduced in the subsystem «diesel – synchronous generator» (Table 6);
– subset P_6 includes the means that will be introduced in the subsystem «general control system of all links and the system as a whole».

Each means is put in line with the effect of its implementation, which in general is expressed in a reduction in the specific consumption of the diesel motor. Let:

– subset P_1 includes z_1 means (Table 2);
– subset P_2 includes z_2 means (Table 3);
– subset P_3 includes z_3 means (Table 4);
– subset P_4 includes z_4 means (Table 5);
– subset P_5 includes z_5 means (Table 6);
– subset P_6 includes z_6 means.

Let's introduce the notation: n – the number of the means for improving energy efficiency. Then consider the arrays $V(n)$ and $E(n)$, which contain the cost and the output effects from the introduction of the corresponding activities of certain subsets. Let's suppose that the vector $M(n)$ contains elements that are equal to 0 in the case that the corresponding measure for increasing the energy potential is rejected or 1 otherwise.

The solution of the problem of choosing the means to increase the energy potential of the diesel-generator electromechanical system must be consistently, firstly forming the set of all possible means to improve the energy efficiency of the electromechanical system. Secondly, it is necessary to choose combinations of variants of subsets of means. Thirdly, it is necessary to establish the appropriate objective function, as well as define constraints and boundary conditions.

Let's formulate a mathematical model for the indicated problem of searching for means of increasing the energy potential of a system using static characteristics in the following form:

$$\begin{cases} P = P_1 \cap P_2 \cap P_3 \cap P_4 \cap P_5 \cap P_6; \\ \Phi(x) = \sum_{s=1}^{z_1} V_1(n)\cdot x_1(n) + \sum_{s=1}^{z_2} V_2(n)\cdot x_2(n) + \\ + \sum_{s=1}^{z_3} V_3(n)\cdot x_3(n) + \sum_{s=1}^{z_4} V_4(n)\cdot x_4(n) + \\ + \sum_{s=1}^{z_5} V_5(n)\cdot x_5(n) + \sum_{s=1}^{z_6} V_6(n)\cdot x_6(n) \to \min; \\ \sum_{s=1}^{z_1} E_1(s)\cdot x_1(n) + \sum_{s=1}^{z_2} E_2(n)\cdot x_2(n) + \\ + \sum_{s=1}^{z_3} E_3(n)\cdot x_3(n) + \sum_{s=1}^{z_4} E_4(n)\cdot x_4(n) + \\ + \sum_{s=1}^{z_5} E_5(n)\cdot x_5(n) + \sum_{s=1}^{z_6} E_6(n)\cdot x_6(n) \le E. \end{cases}$$

Arrays $E(n)$ as parameters of efficiency contain the following parameters: specific cost index, current value of specific fuel consumption, minimum specific fuel consumption, nominal efficiency of the system, duration of start.

As a specific value indicator, the dependence of the cost of an electromechanical system on power is proposed.

The combination of all technical and schematic modifications of each group of decomposed structure is a necessary list of activities that need to be implemented for maximum fuel economy. This list will depend on the solution results of the optimization task and the technological features of the system processes. The application of the process of determining the structure and parameters of the system, based on a complex solution of all the main tasks of developing a system of measures to increase the energy potential, during the formation of these measures, allows to obtain a correct transformation of the latter. That is, with the potential implementation of the proposed changes in the system, is their mutual influence.

Complete replacement of the entire equipment of the system and arrangement of new schemes simultaneously can be economically impractical, despite the maximum effect from reducing fuel losses. This is due to the existing policy of prices for energy resources and equipment. Thus, there is a task of identifying the initial event or part of those measures that maximally brought the system closer to the maximum energy potential, but would be permissible for economic reasons.

Existing systems of vehicles are similar in their structure and parameters, as they are created on the principles of typification and unification of design solutions. However, the regime parameters may differ, which is due to technological peculiarities. So, there will be different benchmarks in the process of increasing the energy potential.

It should be understood that in order to obtain the maximum value of the increase in the energy potential in the system, according to the results of the development, a certain set of impacts on it is needed. Also, the limiting value of the reserve in systems is affected by the number of electromechanical systems on a single vehicle, which causes the redistribution of loads between them, that is, a change in the overall scheme.

These effects on the electromechanical system or any other changes in it will be accompanied by other additional costs. And these costs do not always lead to their mandatory increase within the group of elements of an electromechanical system of one functional purpose.

To further solve the task, it is necessary to determine the list of basic variants of technically possible modifications of the electromechanical system as a basis for analyzing the feasibility of implementing certain activities. In this case, the sequence of actions to change the existing parameters of the electromechanical system to certain during the solution of the task at this stage does not matter. However, each such operation must be accompanied by a recalculation of the system performance indicators, as a likely change in the consumption characteristics of adjacent groups of the electromechanical system. This, in turn, requires testing it for the permissibility of operation in accordance with technical specifications specific to the transport process, and also to determine the additional costs for these activities. This is due to the fact that the formation of such list involves only a part of the possible variations of the system according to the most rational from the point of view of the energy potential, which includes only a certain part of its parameters. Partial measures are defined here to ensure the implementation of a system of approaches to increase the energy potential in general to the following actions that contribute to reducing losses in the electromechanical system.

Formation of the initial list of technically possible combinations of means for changing the electromechanical system is based on a comparison of their parameters with existing ones. At first it makes sense to single out independent groups which change is not related to others. Then groups of dependent funds are considered, since the independent realization of each of them is impossible without the others.

The sequence of implementation of each activity should be established only for those of them that are economically viable. The latter is ensured by the fulfillment of the condition: the cost of the saved fuel should not exceed the capital investments for the implementation of the measure.

Obviously, in order to obtain the greatest possible effect, the sequence of the already economically feasible measures to increase the energy potential can be determined by ranking them by such indicator as the amount of savings.

Thus, the methodology for organization of the program for increasing the energy potential will consist of the following stages:

1. A list of all possible technical measures is formed, the implementation of which is permissible under the conditions of vehicle operation.

2. On the basis of the obtained list, economically feasible measures are determined, proceeding from the condition that the economic effect should not exceed investments in the sale of funds.

3. The specified list of permissible measures is sorted by reducing the amount of saved fuel, which determines the sequence of their implementation during modernization.

To assess the effectiveness of such projects, a list of the following indicators is recommended [4, 15].

Economic effect:

$$\Delta_E = \frac{\Delta C}{P_{dep} + E_n},$$

where ΔC – the constant in the years of the calculation period profit from the resulting measures to increase the energy potential; P_{dep} – the rate of renovation for depreciation; $E_n = 0.1$ – the norm of investments efficiency.

The rate of renovation for depreciation is calculated as follows:

$$P_{dep} = \frac{E_H}{\left(1+E_n\right)^{\tau_s} - 1},$$

where τ_s – the service life of the electrical complex of the vehicle (15 years according to the standards).

Then for the period of 15 years:

$$\Delta_E = \frac{\Delta C}{0.1315}.$$

Thus, the choice of an economically feasible system of measures to increase energy potential depends on the goals and schemes for financing the energy saving process.

7. SWOT analysis of research results

Strengths. The strength of the study is the use of synergetic properties of the system in combination with providing an energy-efficient operating mode and controlling each of the elements of decomposed structure of the electromechanical system. In comparison with the known methods, this leads to:

– achievement of the most rational specific level of fuel consumption;
– efficiency maximization of the electromechanical system.

Weaknesses. The weak side of the research is the complications of the technical design of the electric drive control system. It is explained by:

– complication of technical algorithms;
– increase in the number of deliverers.

Opportunities. The opportunity of further research is the development of more advanced control algorithms for electrical facilities.

Threats. In the world there are analogues of the object of research used in electric vehicles. However, they are unsuitable for use in diesel-generator systems, due to the specific nature of this power source, which is shown in this research.

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8. Conclusions

1. Analysis of practical experience of decomposition of traction electric drive systems is carried out, which allowed to systematize modern approaches to this issue and determine:

– the most problematic places (the lack of a logical system for selection of groups for decomposition and a mathematical description of the algorithm of this process);

– typical approaches (separation of electromechanical systems with traction classes).

2. The generalization of decomposition technique of the structure and parameters of traction electric drives is carried out under the given requirements from the mobile electrotechnical complex. This made it possible to achieve the most rational specific level of fuel consumption and maximize the efficiency of the electromechanical system by selecting the operating mode of each element in such way that the overall efficiency of the system is at the maximum level.

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ИССЛЕДОВАНИЕ ОСОБЕННОСТЕЙ ПРОВЕДЕНИЯ ДЕКОМПОЗИЦИИ ТЯГОВЫХ ЭЛЕКТРОПРИВОДОВ ПОДВИЖНЫХ ЭЛЕКТРОТЕХНИЧЕСКИХ КОМПЛЕКСОВ

Исследованы особенности проведения декомпозиции систем тяговых электроприводов для различных видов и конструкций подвижных электротехнических комплексов. Проведен анализ практического опыта декомпозиции систем тяговых электроприводов и обобщения методики определения структуры и параметров при заданных требованиях со стороны подвижного электротехнического комплекса. Предложен метод повышения энергоэффективности дизель-генераторной электромеханической системы транспортного средства по статическим и динамическим характеристикам.

Ключевые слова: декомпозиция электропривода, электротехнический комплекс, тяговый привод, автономная система, дизель-генераторная система.

Kulagin Dmitro, *PhD, Professor, Department of Power Supply of Industrial Enterprises, Zaporozhye National Technical University, Ukraine, e-mail: kulagindo@gmail.com, ORCID: http://orcid.org/0000-0003-3610-4250*

Yatsenko Dmitro, *Department of Power Supply of Industrial Enterprises, Zaporozhye National Technical University, Ukraine, e-mail: 19yatsenko94@mail.ru, ORCID: http://orcid.org/0000-0001-6702-569X*