ABSTRACT
of the dissertation work
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«Research on the effectiveness of the use of energy storage devices on electric rolling stock», submitted for the degree of Doctor of Philosophy (PhD) in the specialty 6D071300 – Transport, transport equipment and technologies

Introduction

Railway transport is one of the main consumers of fuel and energy resources (TER) in the energy market of Kazakhstan. In modern conditions of economic development, energy conservation and energy efficiency are the most important factors in increasing the competitiveness of railway transport in the domestic and international transport services markets. The main share of fuel and energy resources consumed by the transportation process falls on traction rolling stock (over 500 thousand tons per year), therefore, the reduction in the specific energy consumption for train traction is expressed, first of all, in increasing the energy efficiency of traction rolling stock (hereinafter - TPS). One of the most important sources of energy saving on electrified sections of railways is the recovery of braking energy, the efficiency of which is one of the main directions of technical measures to reduce the specific energy consumption for train traction [2].

With a busy train schedule, the share of recovered electrical energy used inefficiently is significant.

Studies by many authors have been devoted to various options for the recovery of electricity during braking of the TPS, but this task has not found a successful solution to date. The main difficulty of using the regenerative braking mode is not the ability of the electrical network to accept regenerative braking energy. Traction power supply systems (hereinafter referred to as STE) of railways have not yet been equipped with energy recovery reception devices.

Due to the difficulties, and sometimes the impossibility, of direct recovery of braking energy into the contact network in recent years, research aimed at developing energy storage systems in storage devices with subsequent use of energy during the start-up, acceleration of trains and for powering their own needs of the TPS is of particular importance.

The purpose of this work is to increase the energy efficiency of the TPS by reducing energy consumption for the traction needs of electric rolling stock (hereinafter - EPS) by accumulating regenerative braking energy in storage devices and using it for the locomotive's own needs.

To date, a lot of experience has been accumulated in the study of energy conversion issues in electric transport. A significant contribution to the solution of the issue related to the development of energy-efficient traction drives and the development of methods for reducing energy consumption for train movement was made by scientists: I.S. Efremov, V.E. Rosenfeld, K.G. Marquardt, V.P. Feoktistov, V.V. Shevchenko, M. V. Shevlyugin, A. Ruffer, D.A. Booth, N.I.

Shchurov, V.I. Sopov, A.A. Shtangov, V.N. Anosov, M. Zolot, K.J. Kelly, T.Markel, A.Burke, etc.

The relevance of the dissertation research is due to the exclusion of those drawbacks of electric traction that are associated with uneven electricity consumption by electric rolling stock, as well as with ensuring the guaranteed possibility of implementing regenerative braking. The solution of this problem is of particular importance for suburban electric motor-car trains, as well as for mainline electric locomotives. The full use of regenerative braking energy reduces the energy consumption for train traction by 7-18% [3].

The purpose and objectives of the study is to create methods for calculating parameters and determining the energy characteristics of storage devices in an electric rolling stock system, as well as to develop circuit solutions aimed at improving the efficiency of using the energy of electrodynamic braking, taking into account the influence of random factors.

In accordance with the goal , there is a sequence of the following tasks:

1) to conduct a comprehensive assessment of the effectiveness and main issues of the use of regenerative braking, taking into account the influence of random factors, and to justify solutions related to the installation of energy storage devices on EPS, ensuring the effective use of braking energy of rolling stock;

2) determining the size of the excess recovery energy and the average capacity of the energy storage unit (NE) capable of fully accepting all this excess recovery energy, using a comprehensive research method that includes methods of mathematical analysis and simulation modeling, methods of processing mathematical statistics;

3) perform an analysis of the existing types of storage devices and formulate the requirements imposed on them by the system of railway electric rolling stock.

4) to develop methods and circuit solutions to improve the efficiency of the use of storage devices in the system of electric rolling stock, based on the experimental and quantitative assessment of the electrical energy generated in braking mode;

5) to determine the main parameters of the storage device that meets the requirements of its use in the electric transport system, to develop a methodology for calculating the parameters of the energy storage device for placing it on an electric rolling stock, as well as to make a technical and economic assessment of the use of NE.

The object of the study is the system of the main electric locomotive and electric rolling stock.

The subject of the study is the energy characteristics of an electric rolling stock equipped with energy storage devices and the redistribution of energy flows in the EPS system when using electric energy storage devices.

Research methods. To solve the tasks set, a comprehensive research method was used, including analysis and generalization of scientific and technical literature data, theoretical and experimental methods. Theoretical research is based on methods of mathematical, structural and simulation modeling using applied software packages, methods of the theory of electrical circuits. The reliability of

the results obtained is ensured by the parallel use of various models, as well as their confirmation in the course of experimental studies.

Calculations and mathematical models are performed both using computational software complexes written in the environment of "Kortes" (complex of traction calculations of power supply), "Vectrum", and using mathematical modeling in the environment of "Matlab – Simulink".

The main provisions submitted for protection:

1. The necessity and expediency of creating and implementing storage devices based on supercapacitors and a lithium-ion battery that allow the most efficient use of electric braking energy in the EPS system.

2. The results of experimental studies of the energy consumption of traction and own needs of EPS and the determination of the leveling functions of the distributions of specific thrust energies and electrical braking of EPS.

3. The main provisions justifying the most effective use of storage devices in the EPS system, mathematical description and modeling of the processes of EPS movement, allowing to determine the nature of the distribution of energy of electric braking.

4. Ways to increase the efficiency of using the braking energy of rolling stock in the regenerative braking mode instead of recovery.

5. Developed schematic diagrams of NE for use in mainline electric locomotives and suburban electric trains, as well as methods for determining indicators that determine the effectiveness of their work, with an assessment of technical and economic indicators.

Scientific novelty of the dissertation work.

- It has been established that the most effective is the use of energy storage devices on an electric rolling stock, and not in the power supply system.
- A comprehensive analysis was performed and a quantitative assessment of the reduction in power consumption when installing energy storage devices in various parts of the system under consideration, determining the energy balance of an electric rolling stock equipped with storage devices, was given.
- Circuit solutions have been developed and a calculation method has been created that allows evaluating the efficiency of using a storage device on an EPS and determining its parameters. The expediency of using and implementing energy storage devices directly on an electric rolling stock is shown.
- A mathematical model has been created, implemented with the use of a PC, which allows calculating the electrical processes occurring in the power circuit of an EPS equipped with a storage device.
- The rational placement of the storage device is determined and its schematic solution is proposed when used in the EPS system.
- Developed methods for assessing the technical and economic effect of the use of NE

The practical significance of the results of the work lies in solving the urgent complex task of using storage devices aimed at reducing power

consumption in the EPS system. Engineering calculation methods have been developed that allow designing energy efficient storage devices.

Implementation of the results of the work. Theoretical and practical materials on the use of energy storage devices and methods of effective use of regenerative braking in EPS, developed in the dissertation work, are used in the educational process as part of the study of the disciplines "Theory of locomotive traction" and "Locomotives" in the preparation of students for the educational program 6B07117 - "Locomotives" in ALiT, and are also used as an additional methodological instructions in the operational locomotive depots of the Almaty and Zhambyl branches of KTZ – Freight Transportation LLP.

Approbation of the work. The results of the study were reported at: XLII International Scientific and Practical Conference "Innovative Technologies in Transport: education, science, practice", KazATK, Almaty, April 18, 2018; International Scientific and practical conference "The Potential of Modern Science", Prague, Czech Republic, November 30, 2018; XLIII International Scientific and Practical Conference "Innovative technologies in transport: education, science, practice", KazATK, Almaty, April 17, 2019; VI International Scientific and Technical Conference "Locomotives. Electric transport. XXI Century", St. Petersburg, Russia, November 13-15, 2018; at the expanded meeting of the Department "Rolling stock", ALiT, 10.10.2022, Almaty.

Publications. According to scientific work, 1 article was published in the journal "Transport Problems", included in the Scopus database (percentile – at least 25), 6 articles in journals included in the database of the Committee for Quality Assurance in Education of the Ministry of Education of the Republic of Kazakhstan (KKSON), 3 articles in journals – collections of materials of international scientific and technical conferences and 2 utility model patents were obtained.

The structure and scope of the dissertation. The dissertation work consists of an introduction, content, the main part of 5 sections, conclusions and conclusions, appendices. The content of the work is presented on 142 pages of typewritten text, includes 65 tables, 89 figures, a list of used sources from 84 titles, 2 appendices on 8 pages.

The main material of the dissertation is presented in five chapters.

The introduction reflects the relevance of the topic and the direction of scientific research. The goals, tasks of the work and the proposed solutions are formulated. Research methods are described. The main provisions submitted for defense are given, information about the scientific significance, novelty and practical value of the results of research, implementation and approbation of the work is presented.

In the first chapter, electric transport is considered as a complex electrical complex, in which two main subsystems are identified: power supply and electric rolling stock. Currently, the main problem has become the solution of issues related to improving the energy efficiency of the use of regenerative braking. As a result of numerous studies and analyses, today the main way to efficiently use regenerative energy is the use of energy storage devices at power supply

substations or in the EPS system. The main reason for the lack of widespread use of energy storage in mainline electric locomotives and electric trains is due to the discrepancy in its weight and size characteristics. But at present, the scientific and technical development of energy storage devices is dynamically underway, efficient energy storage devices with excellent weight and size characteristics are being introduced (for example, lithium–ion batteries, supercapacitors). The energy balance is presented, which determines the energy of the movement of an electric rolling stock.

In the second chapter, the energy recovery potential for electrified railway sections is calculated using simulation modeling. A complete analysis of electrified railway sections was carried out according to the quantitative indicator of the energy received from regenerative braking. The calculation was carried out in even and odd directions of railway sections. As a result, it was found that the recuperative energy received (relative to the total energy spent on train traction) in percentage terms is 10% in the even direction and 7% in the odd direction. It follows from these indicators that there is a great possibility of using a regenerative braking system to reduce the specific energy consumption for train traction, but this method of calculating energy for EPS movement due to complete or partial neglect of the random nature of movement does not fully reflect the real processes of energy consumption on electric rolling stock.

It is shown that the specific energy consumption of braking and traction are random variables. This is due to the presence of a significant number of random factors affecting the processes of movement. It is established that the gamma distribution can be taken as the basic law of probability distribution of specific thrust and braking energies. Due to the constant growth of the energy component and a large reserve of unused energy generated in the electric braking mode, the use of storage devices is profitable and expedient.

The third chapter analyzes various types of energy storage devices: electrochemical, inductive, superconducting, hybrid types of storage devices, capacitive, capacitors with a double electric layer and hybrid electrochemical capacitors. As a result of the analysis, it was found that the most promising and satisfying the basic requirements for introduction into the electric transport complex is a storage element based on double-layer capacitors (supercapacitors) and electrochemical (lithium-ion batteries). This type of storage elements is capable of providing, at low weights and sizes, high energy indicators necessary for the implementation of the specified traction characteristics by electric motors.

Criteria for comparative evaluation of storage devices have been developed, on the basis of which a detailed analysis of energy storage devices has been performed, the advantages and disadvantages of their use in the electric transport complex have been identified

Energy storage devices based on a supercapacitor combine: high specific power of the order of 104 -105 W / kg with a stored specific energy of up to 50 kJ / kg; a large number of charge-discharge cycles ranging from one hundred thousand to one million; charge time up to 30 seconds; operation in a wide temperature range of -50 ... +100 °C; high efficiency exceeding 95%; long storage time of

stored energy amounting to hundreds of hours; almost constant discharge rate over the entire operating temperature range. The modular design of the supercapacitor withstands currents in kiloamps and voltages of hundreds of volts.

Energy storage devices based on lithium-ion batteries combine: they have a higher energy density compared to other batteries of the same type. They can produce energy up to 150 watts/hour/kg, low discharge rate. Thus, they have more reliable and stable charging capabilities, which allows them to work for extended periods of time between two consecutive charging periods, and lithium-ion batteries can work with or without minimal maintenance. They do not require frequent and additional maintenance and priming, are available in various types and sizes.

The fourth chapter shows that it is most effective to use a storage device on an electric rolling stock, for the purpose of operational use of the energy of electric braking with accumulation, short-term storage and implementations in traction mode. It is recommended to use the energy of the storage device for its own needs of EPS (motor fans, motor compressors, electric locomotive motor pumps). Schematic solutions of the EPS power circuit with a storage element are proposed. Experimental measurements were carried out with the electric locomotive's own needs, the power consumption and current indicators of voltage and current were determined. With the help of mathematical equations, the capacity of the energy storage for the electric locomotive's own needs was determined and a schematic computer model of an EPS with an energy storage was developed on the software package "Matlab-Simulinik". This model work will help to match the application of the energy storage device, the correctness of its mathematical calculations and electrical circuits.

An assessment of the change in energy consumption for the needs of EPS and the amount of excess energy recovery, taking into account the introduction of storage devices, was carried out.

In the fifth chapter, it is shown that the energy of electric braking is most effectively used in the electrical complex when installing a storage device on an electric rolling stock and the preliminary conditions for placing an energy storage device in the EPS system are formulated. Studies have been conducted on the possibility of placing energy storage devices on existing EPS, as a result of which it has been established that the placement of an energy storage device on an existing electric rolling stock is carried out only by carrying out modernization work. The effective locations of energy storage devices on EPS have been determined. It is established that the storage device has a mass not exceeding 3% of the mass of the EPS and allows the full use of the energy of electric braking.

The technical and economic efficiency of the introduction of NE on existing electrified railways was calculated, which showed that the payback period of NE can be 4.5 – 5 years, with the service life of lithium-ion batteries reaches up to 9-10 years (the service life can reach supercapacitors – up to 25-30 years), which indicates a possible increase in the efficiency of the offer.

The conclusion contains a description of the main results on the theoretical and practical development of the problem associated with increasing the efficiency of energy use in electric rolling stock using storage devices.

- The main criteria for evaluating the effectiveness of the use of NE in EPS are determined.
- The analysis of the existing types of NE made it possible to select storage devices of capacitive and electrochemical types that determine the relevance of the tasks.
- A comparative analysis of existing energy storage devices made it possible to work out the requirements for EPS storage devices and choose lithium-ion batteries and supercapacitors as such a device, allowing the most rational use of the energy of electric braking of vehicles.
- A methodology has been developed for determining the main performance indicators of EPS, which determines the feasibility of using NE.
- The polygons of the most efficient use of NE in EPS have been identified to date with a preliminary assessment of efficiency, which allows to reveal the possible potential of energy saving on the existing electrified railways of the Republic of Kazakhstan
- The use of storage devices on electric rolling stock can give a total energy savings of 7 to 14% in the railway electric transport system.
- Various variants of circuit implementations and the use of storage devices are considered, the rationale for their rational introduction into the EPS system is carried out.
- Schematic diagrams have been developed, the weight and size indicators of the main types of NE for use in EPS have been determined, and the potential possibility of their use has been assessed.
- Simulation models were used to calculate the parameters of EPS, which allow mathematically reproducing all the processes accompanying energy exchange and calculating the electric power performance of the studied objects.
- A methodology has been developed to assess the effectiveness of the introduction of NE on existing railway lines with NE, which showed that the payback period of NE is 4.5 – 5 years. However, given the prospects for the development of technologies for the manufacture of molecular capacitors, it can be assumed that their costs will be significantly reduced.

Further research on the problem under consideration should be aimed at a deeper analysis of the processes occurring during the joint operation of the battery and storage device, optimization of their parameters, as well as improvement of circuit solutions of power electrical circuits of EPS with storage devices.