METHOD FOR ESTIMATING THE USE OF REGENERATIVE ENERGY

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ABSTRACT

With an annual increase in the volume of energy regenerated by rolling stock, an assessment of the use of such energy becomes particularly topical. The article defines the regenerative energy efficiency indicators for braking and its components. The influencing factors and the empirical coefficients determining the degree and nature of the energy distribution of regeneration at the railway section, are determined. The initial data are listed, preparatory calculations and the algorithm of the method of evaluating the efficiency of regeneration are presented. A method is proposed for distributing the energy returned to traction substations according to the components of its beneficial use.

Keywords: *railway, regeneration, energy efficiency, traction power supply system, traction substations.*

Background. *The experience of using regenerative braking on the electrified sections of the world's railways shows a high degree of energy efficiency in the use of regenerative energy [1–3]. For example, in the UK, the share of recovery of regenerative energy in the contact network is 7,2 % of energy consumption by traction substations. The percentage of recovery to the system of external power supply is 1,7 %. Spain, Sweden have comparable results.*

The study of the flow distribution of regenerative energy in the traction power supply system (TPSS) allows to make technical decisions on equipping the electrified sections with additional receivers of excess energy (energy storage devices or inverters), determine their characteristics, develop approaches to creating energy-optimal train schedules.

To determine the measure of efficiency and directions of use of regenerative energy, specialists of Omsk State Transport University offer to evaluate:

– the absolute value of beneficial use of regenerative energy generated by TPSS;

– the relative amount of beneficial use of regenerative energy (in percents) from its absolute value according to the indications of the regeneration calculators of TPSS.

The effective use of regenerative energy begins with its consumption for the own needs of the regenerating TPSS. This energy is not taken into account by the counters, however, the method proposed by the authors of the article [6] makes it possible to calculate the value of this energy in accordance with the operational and technical conditions on the section.

Objective. *The objective of the authors is to consider a method for estimating the use of regenerative energy.*

Methods. *The authors use general scientific and engineering methods, comparative analysis, evaluation approach, simulation.*

Results.

Initial data and preparation for calculation

The user of the methodology collects the initial information from the reports and analytical forms available in JSC Russian Railways for the accounting period separately for each section of DC and AC. Thus, the reporting form TXO-125 serves as a source of information on the amount of regenerative energy, linear mileage, average technical and section speed of ERS. Automated system of management of the track facilities ASU-P acts as a source of information on the number of main tracks and characteristics of the track profile, and an automated system for maintaining and analyzing the schedule of the train sheet GID Ural-VNIIZhT is a source of data on the average masses and the size of train traffic.

Automated control system of the electrification and power supply system ACS-E gives:

– number of traction substations and secondary power sources (for DC sections);

– types of catenary and degree of its wear;

– lengths and power schemes of inter-station zones of the section;

– power losses of idling and short-circuit transformers of traction substations.

The initial indicators for determining the amount of regenerative energy returned to the traction substations of the calculation section, broken down into components, are systematized on the basis of Transenergo [a branch of JSC Russian Railways in charge of providing electric power to some of corporate facilities] statistics obtained from ASKUE automated information and monitoring system. For the constant current section, they are analyzed and recorded in a special table for each substation, comprising:

– the amount of energy return by input counters of secondary power sources on the AC side;

– the amount of energy return from the input counters of the step-down transformers 6 (10) kV;

– the amount of energy return by the counters of high voltage inputs of the step-down transformers;

– the amount of power consumption by the counters of high voltage inputs of step-down transformers.

For calculation regarding AC sections, the following data are analyzed and entered into a special table for each traction substation:

– energy recovery on the counters of the feeder connections of the contact network (FCC);

– energy recovery by counters installed at the inputs of 27,5 kV of step-down transformers;

– energy consumption for traction of trains on the input counters of 27,5 kV;

– energy recovery on the counters installed on the inputs on the high voltage side of the step-down transformers;

– electricity consumption on counters installed on the inputs on the high voltage side of the step-down transformers;

– electricity consumption according to counters installed at 6/10/35 kV inputs of the step-down transformers.

Then the analysis of the track profile is carried out to determine the direction of the calculation section (even or odd) that is more energy-consuming for movement of trains, which is called «complex direction» in the methodology. This is done by calculating the value of the equivalent slope of the section in an even and odd direction using the formula:

$$i_{eq} = \frac{\sum_{j=1}^{J} i_j \bullet S_j}{\sum_{j=1}^{J} S_j}, \quad (1)$$

where i_j – slope of the j-th element of the track profile of the calculation section,‰; S_j – length of the j-th element of the track profile of the calculation section in the odd direction, m; J – number of elements of the profile of the calculation section.

A direction with a larger value of the equivalent slope is taken as a complex direction.

In the following calculation, the average masses of freight trains as factors influencing the energy efficiency of recovery are taken into account separately for the complex and easy direction of train traffic.

The influence of the types of contact suspension, the degree of its wear, as well as the lengths and power schemes of the inter-substation zones (ISZ) in the method is taken into account through the value of relative resistance of the traction network. After that, the average values for the area of relative resistance of the traction network are determined, depending on the length of the contact suspension of a certain type and the length of ISZ with different power circuits, which are used in the future calculation as input data. In addition, the average idle and short-circuit power losses of the step-down substations of the traction substations of AC sections and rectifier transformers of DC sections, which are also initial data, are also pre-calculated

Methodology algorithm

The methodology for estimating the efficiency of the use of regenerative energy, a general algorithm and basic calculation formulas are presented in [6].

1. At the first stage of calculations, from the amount of regenerative energy generated by ERS and transferred to the contact network in the sector during the calculation period, the share of regenerative energy is deducted, in its turn taking into account the deduction caused by the energy losses in the contact network. This is done by calculating the coefficient of the efficiency of use of regenerative energy $k^{KN}_{reg.eff.}$. At the same time, such data as the average masses of freight trains are taken into account, separately in complex and easy directions, average technical speed in freight traffic, average daily train traffic (and separately freight trains), the type of contact suspension, average wear of the contact wire, the power scheme of the section, etc. The coefficient $k^{KN}_{reg.eff.}$ calculated for the section by multiplying it by the reported value of regenerative energy W^{KN}_{reg} generated by ERS makes a value that no longer contains the energy loss in the contact network $W^{KN}_{reg.eff.}$.

2. On the basis of the same initial data and using the empirical formulas [5], the coefficients of recovery of regenerative energy for each traction substation of the section k^{ECE}_{reg} are determined, and for DC sections, the energy loss coefficients of regenerative energy in the converter units of the substations k^{ECE}_{pot} are determined as well. With the help of these coefficients, the amount of regenerative energy is defined, comprising the amount of the energy returned to the traction substations of the section W^{ECE}_{reg}, and also the volume of energy losses in the transformers with such energy transfer ΔW^{SPS}_{reg} for the sections of direct current.

3. The regenerative energy generated by ERS and transmitted to the contact network is determined, with the allowance taking into account the energy losses in the contact network and the return of energy to the traction substations. It forms a share of regenerative energy, consumed by traction of trains in the calculation section $W^{ERSdr.}_{reg}$.

4. Two components are calculated, the determination of which allows to more fully and objectively evaluate the efficiency of the use of regenerative energy in the calculation section, namely:

1) the difference in energy losses in TPSS for cases with and without the use of regenerative braking – the calculation algorithm is described in detail in [9];

2) the amount of regenerative energy, consumed for own needs of regenerating ERS.

The second component is based on the coefficient of use of ERS auxiliary equipment and the time factor in the regenerative mode, which is determined by the formula:

$$k_{t\,reg} = t + \sum_i \left(s_i \bullet X_i^{t\,reg} \right), \quad (2)$$

where t, s_i are the empirical coefficients for the corresponding number of main tracks and the influencing factor $X_i^{t\,reg}$; $X_i^{t\,reg}$ – values of factors affecting the time factor in the regenerative mode.

The values of the factors in this case are the numerical reflection of such initial data as the masses of trains, technical and sectoral speeds, and the size of movement of trains.

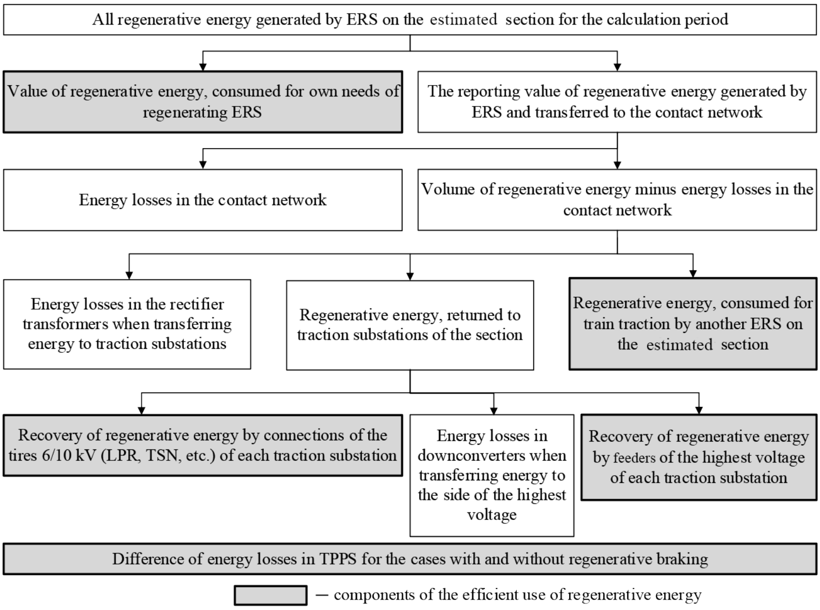
5. Determination of the amount of regenerative energy, returned to each traction substation of the calculation section, broken down by its use, is carried out separately for the sections of direct and alternating current.

5.1. In DC sections, the calculation is made only for cases with secondary power sources in traction substations and the presence of energy recovery from the secondary power sources and using the entry counters for the calculated period in the following order.

Based on the total recovery of regenerative energy according to the input counters of secondary power sources of each traction substation in the calculation section $W^{ECEn}_{rec(count.)}$ and the total value of energy return according to the input counters of secondary power sources of all traction substations of the section $\sum_{n=1}^{N} W^{ECEn}_{rec(count.)}$, the share of recovery of regenerative energy from the inputs of secondary power sources of each substation is determined:

$$\gamma^{ECEn}_{reg} = \frac{W^{ECEn}_{rec(count.)}}{\sum_{n=1}^{N} W^{ECEn}_{rec(count.)}}, \quad (3)$$

where n is number of the traction substation of the calculation section; N –number of traction substations of the calculation section.



Pic. 1. Scheme of the components of the use of regenerative energy in the areas of direct current.

Further, the share of the regenerated energy returned from the traction network to each traction substation along the secondary power sources inputs of the considered section is allocated, which is found by the formula:

$$W_{reg}^{ECEn} = W_{reg}^{ECE} \bullet \gamma_{reg}^{ECEn}, \quad (4)$$

where W_{reg}^{ECE} is the amount of regenerative energy, returned to the traction substation of the section in accordance with point 2 of the algorithm.

The share of recovery of regenerative energy by the lower voltage inputs of the step-down transformers of each traction substation of the considered section is determined:

$$\gamma_{reg}^{NNn} = \frac{W_{rec(count.)}^{NNn}}{W_{rec(count.)}^{ECEn}}, \quad (5)$$

where $W_{rec(count.)}^{NNn}$ is the energy return according to the lower voltage input counters of the step-down transformer of each traction substation of the section.

The value of regenerative energy recovery through voltage inputs of the step-down transformer of each traction substation in the considered section is calculated by the formula, kW·h:

$$W_{reg}^{NNn} = W_{reg}^{ECEn} \bullet \gamma_{reg}^{NNn}. \quad (6)$$

The volume of recovery of regenerative energy through the connections of 6/10 kV tires (LET, TSN, etc.) is calculated for the i-th traction substation of the considered section, kW•h:

$$W_{reg}^{(6/10)n} = W_{reg}^{ECEn} - W_{reg}^{NNn}. \quad (7)$$

The share of regenerative energy recovery through the top-voltage inputs of the step-down transformer into the external power supply system of each traction substation in the considered section is determined by the formula:

$$\gamma_{reg}^{VNn} = \frac{W_{rec(count.)}^{VNn}}{W_{rec(count.)}^{NNn}}, \quad (8)$$

where $W_{rec(count.)}^{VNn}$ is energy return according to the counters of the high voltage inputs of each traction substation in the considered section.

The value of recovery of regenerative energy through the input of the higher voltage of the step-down transformer of each traction substation of the calculation section, kW•h:

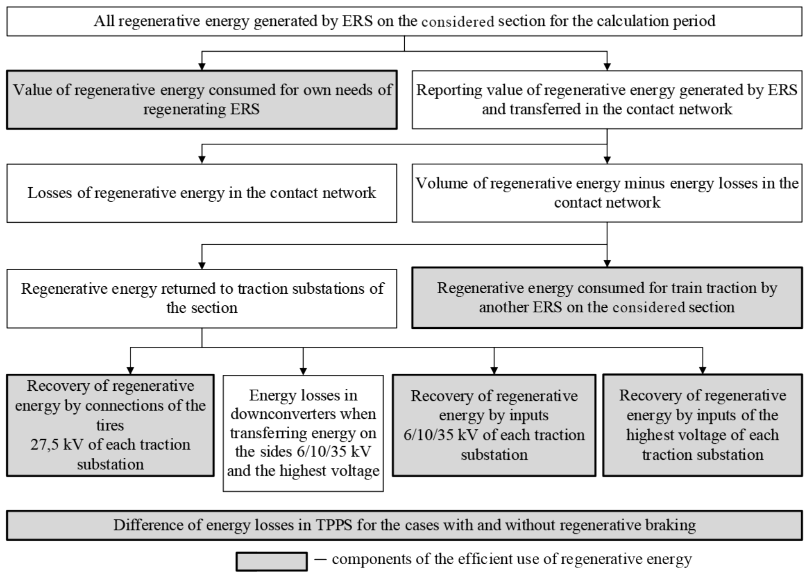
$$W_{reg}^{VNn} = W_{reg}^{NNn} \bullet \gamma_{reg}^{VNn}. \quad (9)$$

In the absence of accounting information on the return of energy through the inputs and connections of any of the traction substations of the section (for example, in the absence of energy accounting for connections or inputs), calculations using formulas that involve unknown quantities are not performed for such a traction substation. This introduces some error in the distribution of regenerative energy within the traction substations of the section, but is an inevitable assumption and simplification. It should be noted that there will be no error in calculating the total amount of beneficial use of regenerative energy for the sections and the test section as a whole. In accordance with the presented methodology, the total return amount for all 6/10 kV connections and for the high voltage inputs of all traction substations will be determined correctly, and the error will only appear in the distribution of return volumes between connections of specific traction substations.

Thus, the components of the use of regenerative energy at the sections of direct current, determined by the method, can be illustrated in the form of a block diagram (Pic. 1).

5.2. In AC sections, the calculation of the regenerative energy value returned to each traction substation of the considered section, broken down by components, is performed for the cases of availability of energy return according to FCC interconnection counters in the following order.

Immediately there is a reservation: as in the case of DC sections, in the absence of reporting information on the return of energy for any inputs and connections of one or several traction substations of the section,



Pic. 2. The scheme of the components of the use of regenerative energy in the areas of alternating current.

calculation using formulas that involve unknown quantities should not be performed for these substations.

In addition, it is obvious that in the volume of energy return on FCC there may be the energy of the equalizing currents flowing into TPSS of alternating current. It is possible to set this value in a calculated way, but for this it is necessary to perform a number of additional operations, including using simulation of the section operation during the considered period. A similar question for any area of alternating current can be solved with the use of synchronous measurements on FCC of traction substations and ERS. In the proposed method, the amount of energy transfer is not determined, but only noted that this circumstance introduces an error in calculation and is an unavoidable assumption. It should be understood that, like in the case of missing information on connections and inputs of traction substations on the consumption and return of energy, this error extends only to the distribution of the volumes of recovery of regenerative energy between the connections of specific traction substations without harming the evaluation of the efficiency of the use of regenerative energy on the section and the test section as a whole.

Based on the share of recovery of regenerative energy through the connections of FCC of each traction substation of the considered section $\gamma_{reg}^{FCC-ECEn}$, *defined as the ratio of energy return through all FCC counters of the traction substation n* $\sum_j W_{rec(count.)}^{FCCj-ECEn}$ *to the total energy recovery value for all FCC feeding the considered section of all traction substations* $\sum_{n=1}^{N} W_{rec(count.)}^{FCC-ECEn}$, *the value of the energy returned to each traction substation of the section is calculated:*

$$W_{reg}^{ECEn} = W_{reg}^{ECE} \cdot \gamma_{reg}^{FCC-ECEn}. \qquad (10)$$

The share of return of regenerative energy by the inputs of 27,5 kV of each traction substation of the considered section is determined by the formula:

$$\gamma_{reg}^{input\,27,5n} = \frac{W_{rec(count.)}^{input\,27,5n}}{\sum_j W_{rec(count.)}^{FCCj-ECEn}}, \qquad (11)$$

where $W_{rec(count.)}^{input\,27,5n}$ *is the energy return according to the input counters of 27,5 kV of each substation of the section.*

The value of recovery of regenerative energy through the input of 27,5 kV of each traction substation of the section is determined according to the formula, kW•h:

$$W_{reg}^{input\,27,5n} = W_{reg}^{ECEn} \cdot \gamma_{reg}^{input\,27,5n}. \qquad (12)$$

Further, the amount of recovery of regenerative energy from the connection of 27,5 kV tires (DPR, TSN, GRSH, etc.) of each traction substation of the calculation section, kW•h is determined:

$$W_{reg}^{27,5n} = W_{reg}^{ECEn} - W_{reg}^{input\,27,5n}. \qquad (13)$$

The relative amount of energy losses in the reducing power transformers of traction substations is:

$$\delta^{PT} = \frac{(W_{cons(count.)}^{VNn} - W_{rec(count.)}^{VNn}) - (W_{cons(count.)}^{input\,27,5n} - W_{rec(count.)}^{input\,27,5n}) - W_{cons(count.)}^{6/10/35n}}{W_{cons(count.)}^{VNn} - W_{rec(count.)}^{VNn}}, \qquad (14)$$

where $W_{cons(count.)}^{VNn}$ *is energy consumption according to the counters of high voltage inputs of each traction substation of the section;* $W_{rec(count.)}^{VNn}$ *– energy recovery according to the counters of high voltage inputs of each traction substation of the section;* $W_{cons(count.)}^{input\,27,5n}$ *– energy consumption according to input counters of 27,5 kV of each traction substation of the section;* $W_{cons(count.)}^{6/10/35n}$ *– power consumption according to input counters 6/10/35 kV (inputs of winding of the district load) of the reducing power transformers of each traction substation of the section.*

The share of recovery of regenerative energy at the inputs of 6/10/35 kV of each traction substation of the considered section is:

$$\gamma_{reg}^{6/10/35n}=\frac{W_{rec(count.)}^{input\,27,5n}(1-\delta^{PT})-W_{rec(count.)}^{VNn}}{W_{rec(count.)}^{input\,27,5n}}. \quad (15)$$

The amount of recovery of regenerative energy through the inputs 6/10/35 kV of each traction substation of the section, kW • h is:

$$W_{reg}^{6/10/35n}=W_{reg}^{input\,27,5n}\bullet\gamma_{rec}^{6/10/35n}. \quad (16)$$

The value of recovery of regenerative energy through the input of the highest voltage of each traction substation of the section, kW•h is:

$$W_{reg}^{VNn}=W_{reg}^{input\,27,5n}(1-\delta^{PT})-W_{reg}^{6/10/35n}. \quad (17)$$

The components of the efficient use of regenerative energy in the AC sections, determined by the method, can be illustrated in the form of a block diagram (Pic. 2).

6. The absolute value of beneficial use of regenerative energy within the considered section for the calculated period $W_{reg.eff}^{ERS}$ is defined as the sum of the components of the effective use of regenerative energy, presented respectively in Pic. 1 and 2 for DC and AC sections. In this case, the relative value of beneficial use of regenerative energy generated by ERS, % can be calculated as:

$$\delta_{reg.eff}^{ERS\,section}=\frac{W_{reg.eff}^{ERS}}{W_{reg}^{ERS}}\bullet 100\ \%, \quad (18)$$

where W_{reg}^{ERS} is the amount of energy, determined by the formula:

$$W_{reg}^{ERS}=W_{reg}^{CN}+W_{reg}^{ERS\,o.n.}, \quad (19)$$

where W_{reg}^{CN} – the amount of regenerative energy transferred by ERS in the contact network in the considered section for the calculated period; $W_{reg}^{ERS\,o.n.}$ – the amount of regenerative energy consumed by the regenerating ERS for own needs.

Absolute and relative values of beneficial use of regenerative energy, calculated for the railway test section, can be used to assess the economic efficiency of the application of regenerative braking and the use of regenerative energy [10].

Conclusions. *The performed researches and the developed techniques described in the article allow to estimate a measure of efficiency of the use of regenerative energy on separate sections of railways and a test section as a whole.*

The proposed methodology is based in obtaining the values of five coefficients that determine the efficiency of use of regenerative energy and emphasize the uniqueness of the author's methodology.

The methodology helps to assess the impact on the energy efficiency of the use of regenerative energy of the operation modes of TPPS, organization of train traffic, the activities of locomotive facilities corporate units with the aim of intensifying the use of regenerative braking, while avoiding costs of equipping the sections with additional measuring equipment.

REFERENCES

1. Gonzalez, I., Pilo, E. Regenerative braking and the different traction systems, Energy Recovery Workshop. [Electronic resource]: http://uic.org/forms/IMG/pdf/regenerative_braking_traction_systems.pdf. Last accessed 18.09.2017.
2. Frilli, A., Meli, E., Nocciolini, D., Pugi, L., Rindi, A. Energetic optimization of regenerative braking for high speed railway systems. Energy Conversion and Management, 2016, Vol. 129, pp. 200–215. DOI: 10.1016/j.enconman.2016.10.011.
3. Ashida, Nozomu. Energy storage systems. Way-side System for Optimizing Regenerative Brakes, Energy Recovery Workshop. [Electronic resource]: http://uic.org/forms/IMG/pdf/recovery_system_jr_east.pdf. Last accessed 18.09.2017.
4. Cheremisin, V. T., Nikiforov, M. M. Increase of energy efficiency of traction power supply system and electric rolling stock [*Povyshenie energeticheskoj effektivnosti sistemy tjagovogo elektrosnabzhenija i elektropodvizhnogo sostava*]. Innovative projects and new technologies in education, industry and transport: Proceedings of scientific-practical conference / Omsk State Transport University. Omsk, 2012, pp. 9–15.
5. Nikiforov, M. M., Kashtanov, A. L., Kandaev, V. A. Methodology for assessing the energy efficiency potential of the application of regenerative braking [*Metodika ocenki potenciala energoeffektivnosti primenenija rekuperativnogo tormozhenija*]. *Izvestija Transsiba*, 2012, Iss. 1, pp. 72–78.
6. Cheremisin, V. T., Nikiforov, M. M., Wilhelm, A. S. The main provisions of the methodology for assessing the efficiency of the use of regenerative energy [*Osnovnye polozhenija metodiki ocenki effektivnosti ispol'zovanija energii rekuperacii*]. *Vestnik Rostovskogo gosudarstvennogo universiteta putej soobshhenija,* 2017, Iss. 1, pp. 114–120.
7. Cheremisin, V. T., Nikiforov, M. M., Kashtanov, A. L., Wilhelm, A. S. Increase in the energy efficiency of regenerative braking on the test section of direct current: Monograph [*Povyshenie energeticheskoj effektivnosti rekuperativnogo tormozhenija na poligone postojannogo toka: Monografija*]. Omsk, OSTU publ., 2016, 176 p.
8. Nikiforov, M. M., Wilhelm, A. S., Gutnikov, V. I. Influence of parameters and operating modes of the traction power supply system on the efficiency of use of generative energy [*Vlijanie parametrov i rezhimov raboty sistemy tjagovogo elektrosnabzhenija na effektivnost' ispol'zovanija energii rekuperacii*]. *Izvestija Transsiba*, 2017, Iss. 1, pp. 74–90.
9. Nikiforov, M. M., Wilhelm, A. S. Influence of regenerative energy on the level of losses in the traction power supply system [*Vlijanie energii rekuperacii na uroven' poter' v sisteme tjagovogo elektrosnabzhenija*]. *Transport Urala,* 2017, Iss. 2, pp. 55–60.
10. Cheremisin, V. T., Nikiforov, M. M., Wilhelm, A. S. Method of calculating the economic efficiency of the application of regenerative braking and the use of regenerative energy recovery [*Metodika raschjota ekonomicheskoj effektivnosti primenenija rekuperativnogo tormozhenija i ispol'zovanija energii rekuperacii*]. *Transport Urala*, 2016, Iss. 3, pp. 95–99.

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