*Запропоновано підхід для визначення раціональних параметрів ємнісного накопичувача енергії (ЄНЕ) для рухомого складу метрополітену, суть якого полягає у визначенні максимальної потужності та енергоємності бортового ЄНЕ за аналізом терміну окупності систем накопичення. Встановлено, що для заданих умов експлуатації рухомого складу метрополітену раціональним є впровадження ЄНЕ, максимальна потужність якого складає 1000 кВт, а робоча енергоємність – 3 кВт·год*

*Ключові слова: транспортна механіка, енергозбереження, енергоефективність, ємнісний накопичувач енергії, рухомий склад метрополітену*

*Предложен подход для определения рациональных параметров емкостного накопителя энергии (ЕНЭ) для подвижного состава метрополитена, суть которого заключается в определении максимальной мощности и энергоемкости бортового ЕНЭ по анализу срока окупаемости систем накопления. Установлено, что для заданных условий эксплуатации подвижного состава метрополитена рациональным является внедрение накопителя, максимальная мощность которого составляет 1000 кВт, а рабочая энергоемкость – 3 кВт·час*

*Ключевые слова: транспортная механика, энергосбережение, энергоэффективность, емкостной накопитель энергии, подвижной состав метрополитена*

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# DETERMINING RATIONAL PARAMETERS OF THE CAPACITIVE ENERGY STORAGE SYSTEM FOR THE UNDERGROUND RAILWAY ROLLING STOCK

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## 1. Introduction

One of the key requirements to modernization of an existing or creation of a new rolling stock at present is the introduction of power-efficient and energy-saving systems [1]. This particularly concerns underground railways. This is explained by the nature of their rolling stock operation. The necessity and urgency of introduction of energy saving systems are also dictated by the constant rise in the cost of energy resources over recent years.

Over the last years, modernized and new rolling stock has been gradually put into operation by Ukrainian underground railways in order to reduce the cost of traction electric energy for trains. The main features of this rolling stock include the use of asynchronous electric drives, microprocessor control systems as well as introduction of other energy-saving equipment and technologies, primarily recuperation systems. According to the studies [2], upgrading of the existing rolling stock can reduce consumption of traction electric energy by 35–40 % for a five-car train. At present, Ukrainian underground railways take measures for saving energy and improving power efficiency of the rolling stock.

At the same time, issues of determining rational parameters of capacitive energy storage systems (CESS) become of special relevance for the underground railway rolling stock (see block diagram of connection of the on-board CESS to the traction electric drive (Fig. 1, *a*) and the emergence of on-board CESS (Fig. 1, *b*).

The above is explained by the necessity of determining an economic optimum between the cost of the energy storage systems and subsequent energy return from them. Urgency of energy saving in transport through introduction of energy storage systems is also confirmed by the world trends in implementation of appropriate means.

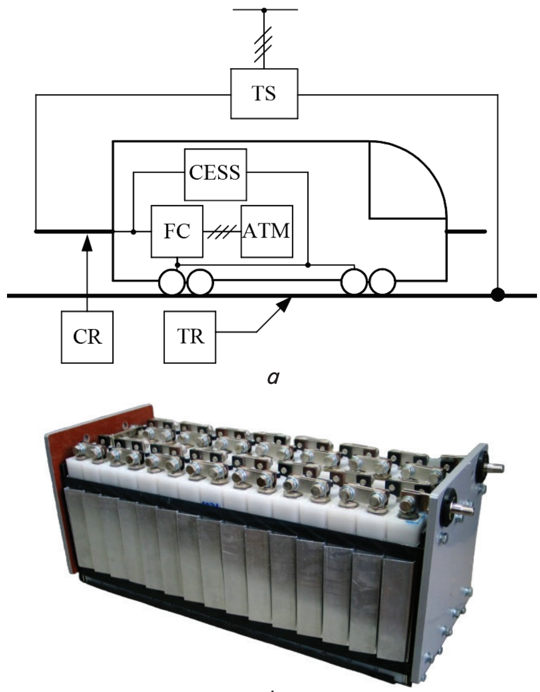


Fig. 1. Block diagram of CESS connection to the traction electric drive (*a*) and appearance of the on-board CESS (*b*)

## 2. Literature review and problem statement

To date, numerous scientific works are devoted to resource saving in railway transport through improvement of rolling stock. For example, the results of study of reducing tractive resistance by improving the wheel rolling surface are presented in [3]. General ways of improvement of technical and economic parameters of rolling stock through improving structures of load carrying systems are given in [4]. Authors of work [5] implemented the proposed way of improving dynamic characteristics of trains. However, one of the main ways of improving energy efficiency of the underground railway rolling stock is an efficient use of recuperation energy. Therefore, issues of this nature are of particular importance for the underground railway rolling stock.

From the results of existing studies, it is known that electric energy of recuperative braking is not fully realized [6]. Much of this electric power is excessive and dissipated in a form of heat in the brake resistors of the rolling stock [7]. In the existing energy supply systems of Ukrainian underground railways, the quantity of electric energy used for recuperative braking is only 5–10 % of the amount of electricity consumed for traction [8]. However, it is known that there are reserves of additional energy savings at a level of 20–30 % [9, 10].

Thus, at present, there is a problem of raising efficiency of use of electric energy of recuperative breaking of the underground railway rolling stock.

One of the promising ways of solving this problem is introduction of on-board CESS in the underground railway rolling stock [11–13]. At the same time, one of the key and insufficiently studied issues in conditions of introduction of on-board CESS is still a proper choice of their rational parameters, first of all, power and energy intensity [14].

In studies [15, 16], it is suggested to determine parameters of on-board CESS according to the estimate of the quantity of kinetic energy of the rolling stock. Essence of this approach consists in choosing parameters of the on-board CESS based on dependence of the amount of recuperative braking energy of the rolling stock on the breaking start speed. Such an assessment is rather rough and does not take into account a number of factors, in particular, real conditions of operation of the underground railway rolling stock. The main of them include the track profile, load of passengers, train schedule, braking force, and availability of an electro-pneumatic braking system.

In [17], parameters of on-board CESS are proposed to be determined in conditions of limited traction power consumption. This approach is based on determining parameters according to the working characteristics of the asynchronous traction drive of the rolling stock. This method involves the use of basic provisions of the theory of electric traction and numerical integration methods [18]. Disadvantages of this assessment method consist in that the track profile, train schedule and availability of electro-pneumatic breaking system are not taken into account.

An algorithm for calculating required energy intensity of the on-board CESS is formulated in [19] for a concrete loading schedule. This algorithm essence is determination of nominal power and required energy intensity of the CESS by numerical integration methods based on the dynamics of power consumption. This method disadvantage is that only one regular cyclic motion mode is taken into account [19]. However, this method takes into consideration actual operating conditions for a concrete loading (loading of the track profile, load of passengers, etc. [20]).

Parameters of the on-board CESS are determined in [20, 21] using basic provisions of the probability theory.

The main idea of the proposed approach is determining parameters by analyzing characteristics of the power distribution density and the amount of recuperative braking energy. The above assessment involves construction of histograms taking into account all typical conditions of train operation during a certain period of time. Disadvantage of this approach is that the choice of parameters is made based on the proposed criteria which do not ensure substantiation of definition of rational parameters of the on-board CESS.

To conclude, the general disadvantage of the considered methods and approaches is that none of them enables determination of rational parameters of the on-board CESS. Therefore, the choice of rational parameters by the criterion of minimum storage system payback period may be promising. It is implied that the storage system consists of an on-board CESS, a reversible static converter and a system for controlling the processes of energy exchange between the CESS and the traction electric drive.

## 3. The aim and objectives of the study

This work objective was to determine rational energy intensity and power of the on-board capacitive energy storage system by the criterion of minimum payback period of this system.

To achieve this goal, the following tasks were solved:

– to develop an approach to determining rational parameters of an on-board CESS by the criterion of its minimum payback period;

– to determine rational parameters of an on-board CESS for given conditions of operation of the underground railway rolling stock according to the developed approach;

– to determine the quantity of energy saved in specified modes of the rolling stock operation through introduction of an energy storage system with rational parameters.

## 4. The examined materials and methods used for determining rational parameters of the capacitive energy storage system

**4. 1. Methods, materials, and equipment used in the study**

The calculation and experimental study methods used to solve the set tasks:

– experimental study of energy processes in regular conditions of operation of the underground railway rolling stock with recuperation systems;

– methods of mathematical statistics for processing experimental data;

– methods of technical and economic analysis to assess the cost of storage systems;

– analytical study methods for determining savings under the conditions of implementation of the storage systems;

– methods of comparative analysis for defining the storage system with rational parameters by the dependence of the payback period on the values of energy intensity and power.

The study of energy-exchange processes was performed at the Svyatoshino-Brovary line of Kyiv Metropoliten Public Utility Enterprise, Ukraine. These studies were carried out under conditions of operation of the rolling stock with recuperation systems in a one-day period. The experimental rolling stock was a five-car train with an asynchronous traction drive and recuperation systems. In this case, the lead train cars were motorless and the intermediate ones were driving cars.

Experimental study of the energy processes taking place in typical operating conditions was conducted using an investigation complex which includes the above-mentioned rolling stock and the measuring system installed on its board. The measuring system was designed to study the energy processes between the contact network and the train in real conditions of its operation. The measuring system consisted of a personal computer, an analog-digital converter, a switching unit, a coordination unit and measuring sensors. The measuring system involved collecting, displaying, and storing data taken from the measuring sensors installed on the experimental train.

**4. 2. Procedure for determining rational parameters of the capacitive energy storage system by the criterion of a minimum payback period**

The proposed approach consisted of the following steps:

– choice of the operation area and the model of the underground railway rolling stock with recuperation systems;

– definition of typical standard conditions of the rolling stock operation at the experimental track section;

– experimental study of the energy processes taking place in typical conditions of running the underground railway rolling stock according to the train schedule;

– processing of the obtained data bodies and determining the range of changes of power and quantity of recuperative braking energy;

– choice of on-board CES which have a given level of power and energy intensity in the range of changes of power and quantity of electric energy of recuperative braking of the rolling stock;

– determining cost of the storage systems taking into account operating costs for their maintenance;

– study of the quantity of saved electric energy resulting from introduction of the chosen storage systems in the rolling stock;

– construction of characteristics of the payback period of the storage systems depending on the working power and energy intensity of the CESS;

– definition of the rational power and energy intensity of the CESS based on analysis of above characteristics.

Thus, the essence of this approach is to determine parameters of on-board CESS according to analysis of characteristics of the payback period of the storage systems. Next, let us apply this approach and consider determination of rational power and energy intensity of the CESS for concrete specified conditions of rolling stock operation.

*Stage 1.* The section between the final stations of the Svyatoshino-Brovary line of the Kyiv Metropoliten was selected as a section to be studied.

*Stage 2.* The following typical conditions of operation of the underground train were accepted:

a) working days (5 days a week):

– three and two full circles with observance of «non-peak» traffic schedule at nominal and maximum load of passengers, respectively;

– one and two full circles with observance of the «peak» traffic schedule at nominal and maximum load of passengers, respectively;

– one full circle with observance of «non-peak» traffic schedule with minimal load of passengers;

b) on weekends (2 days a week): two, seven and one full circles with observance of «non-peak» traffic schedule, with minimum, nominal, and maximum load of passengers, respectively.

It was accepted that the train is operated for 315 days a year, of which 225 are working days, and 90 weekends.

*Stage 3.* Experimental study of energy processes was carried out in typical operating conditions using the above-mentioned experimental complex.

*Stage 4.* Processing the data bodies. Data were processed using the personal computer and certified software.

According to the results of processing data obtained in standard conditions of operation of the rolling stock with recuperation systems, the following indicators were determined:

– the average value of the contact network voltage in the modes of traction and recuperative braking ($U_{av.trac}$, $U_{av.rec.}$);

– average value of current in modes of train traction ($I_{av.trac}$);

– average value of current generated by the train and given back to the contact network during recuperative braking ($I_{av.rec.}$);

– average value of voltage on the braking resistors ($U_{av.R}$);

– average value of current dissipated in the form of heat on the brake resistors in the mode of recuperative braking ($I_{av.R}$);

– time of movement in the modes of traction and recuperative braking ($t_{trac}$, $t_{rec.}$);

– average operating speed on the line leg ($V_{av.line}$).

The following energy indicators were calculated according to the values determined in data processing:

– quantity of electric energy ($A_{trac}$) consumed in traction modes;

– quantity of electric energy ($A_{rec}$) generated by the train during recuperative braking;

– maximum power ($P_{\max}$) in recuperative braking modes.

The amount of electric energy consumed in the traction mode was calculated by formula:

$$A_{trac} = \frac{U_{av.trac} \cdot I_{av.trac} \cdot t_{trac}}{3600 \cdot 1000}. \quad (1)$$

The amount of electric energy generated by the train during recuperative braking was calculated by formula:

$$A_{rec.} = \frac{U_{av.rec.} \cdot I_{av.rec.} \cdot t_{rec.}}{3600 \cdot 1000} + \frac{U_{av.R.} \cdot I_{av.R.} \cdot t_{rec.}}{3600 \cdot 1000}. \quad (2)$$

The instantaneous train power for the modes of recuperative braking was determined by expression:

$$p(t) = u(t) \cdot i(t). \quad (3)$$

The maximum power of recuperative braking was determined by the recorded maximum instantaneous power values during recuperative braking of the train:

$$\begin{bmatrix} p_1 \\ p_2 \\ \dots \\ p_n \end{bmatrix} \rightarrow P_{\max}. \quad (4)$$

*Stage 5.* On-board CESS were chosen with a specified level of power and energy intensity according to analysis of the results obtained in processing of data bodies during experimental studies.

*Stage 6.* Estimation of storage system cost based on the results of cost analysis of the CESS and the information on reversible transducers and other component equipment obtained from their manufacturers.

*Stage 7.* Estimating the quantity of electric energy saved due to introduction of the chosen storage systems. Studies were performed for each type of the chosen system. Initially, power limit was checked for each typical operating condition and the chosen storage system. If necessary, the obtained results were used in calculation of the quantity of recuperated electric energy supplied to the storage system. Next, estimation of quantity of the saved energy was performed taking into account the energy intensity constraints with the help of the Recuperation of Energy subprogram. The algorithm of this subprogram is described in detail in [6]. Simplified algorithm for these studies is shown in Fig. 2.

The following assumptions were made in the studies to estimate quantity of the saved energy:

– the storage system is completely discharged before the calculations;

– efficiency factor of the storage system is 0.98 ($\eta_{CESS} = 0{,}98$);

– efficiency factor of the reversible transducer is 0.96 ($\eta_{RT} = 0{,}96$);

– efficiency factor of the traction motor is 0.94 ($\eta_{TM} = 0{,}94$);

– efficiency factor of the reducer is 0.98 ($\eta_{RED} = 0{,}98$).

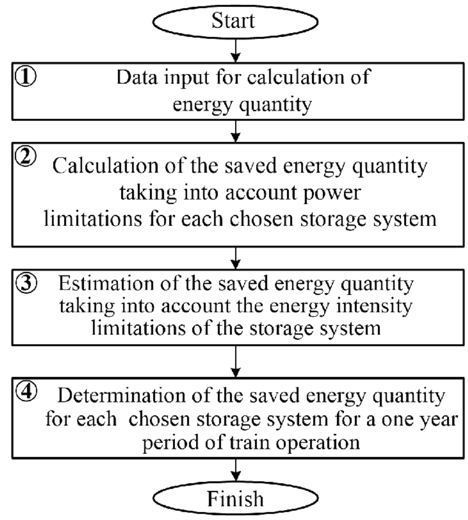


Fig. 2. Algorithm of studies to estimate quantity of the saved energy

The following indicators were determined in the studies: quantity of the energy saved in a cycle of energy storing (energy of recuperative braking and its accumulation) during train acceleration, quantity of the energy saved for each typical operating condition, quantity of the energy saved in a day and in a year.

Quantity of the energy saved in a recuperative braking – train acceleration cycle was determined by formula [6]:

$$E = A_{rec} \cdot \eta_{trac}, \quad (5)$$

where $\eta_{trac} = \eta_{CESS} \cdot \eta_{RT}^2 \cdot \eta_{TM} \cdot \eta_{RED}$ is the efficiency factor of the energy exchange processes for a cycle of recuperation energy storage and accumulation.

Quantity of the saved energy for each typical operating condition was determined by the formula:

$$E_k = E_1 + E_2 + \dots + E_N, \quad (6)$$

where $N$ is the number of cycles for a typical condition of train operation.

Quantity of the energy saved in a day was determined by the formula:

$$E_d = m_1 \cdot E_{k1} + m_2 \cdot E_{k2} + \dots + m_n \cdot E_{kn}, \quad (7)$$

where $m$ is the number of circles gone per day in a typical condition of the train operation; $n$ is the number of typical conditions of train operation.

Quantity of electric energy saved in a year is determined by the formula:

$$E_r = l_1 \cdot E_{d1} + l_2 \cdot E_{d2}, \quad (8)$$

where $l_1$, $l_2$ is the number of working and weekend days in a year; $E_{d1}$, $E_{d2}$ is quantity of the electric energy saved on working and weekend days, respectively.

*Stage 8.* Construction of characteristics (diagrams) of the payback period of the storage systems depending on the CESS working power and energy intensity. The payback period was determined by the ratio of the cost of introduction of the storage system to the cost of the energy saved by this system in a year:

$$T_{DET} = \frac{Q}{T_e \cdot E_r}, \quad (9)$$

where $Q$ is cost of the storage system; $T_e$ is the electric energy rate ($T_e$=1.97 UAH/kWh).

*Stage 9*. According to analysis of the graphs of the payback period of the chosen storage systems, a system with rational parameters was found.

To implement a storage system with rational parameters, quantity of the saved energy was calculated by formula:

$$\alpha = \frac{E_r}{A_{trac(yr)}} \cdot 100, \quad (10)$$

where $A_{trac(yr)}$ is quantity of the electric energy consumed in a year, kWh.

## 5. Results of the study conducted for determining rational parameters of the capacitive energy storage system

With the help of a 2.5 kHz measuring system (Fig. 3), oscillograms (Fig. 4, 5) of voltage in the contact network (on the current collector), current and speed of the rolling stock in its typical operating conditions were obtained.

The results of calculations according to formulas (1)–(4) are given in Table 1.

From the results of data processing for each recuperative braking (Table 1), it is evident that the value of maximum electric power varies from 473 kW to 3.879 kW and the quantity of electric energy varies from 0.58 kWh to 45.93 kWh. Based on the obtained limits of data change, the on-board CESS have been chosen with the level of power and working energy intensity shown in Table 2.

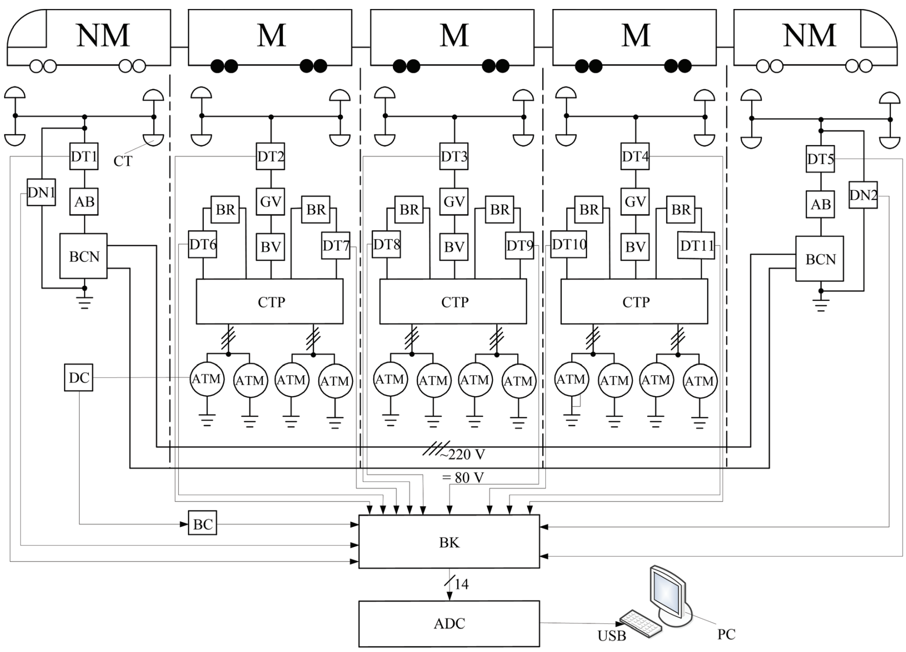


Fig. 3. Block diagram of the measuring complex

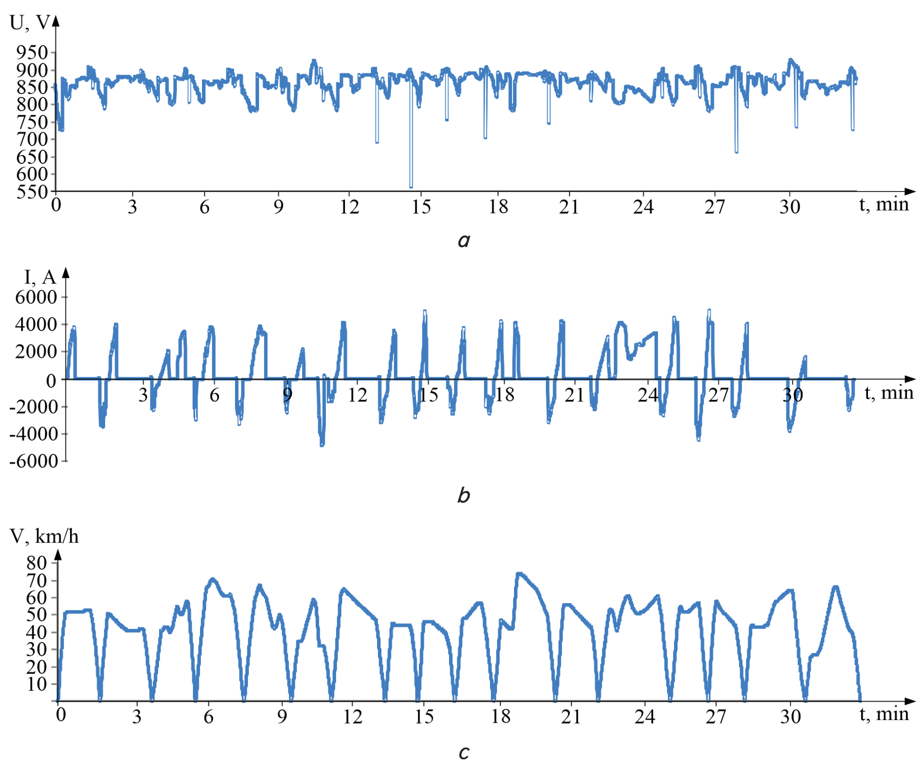


Fig. 4. Oscillograms of voltage on the current collector (*a*), the train current (*b*) and the train speed (*c*) during its operation between Lisova and Akademmistechko stations

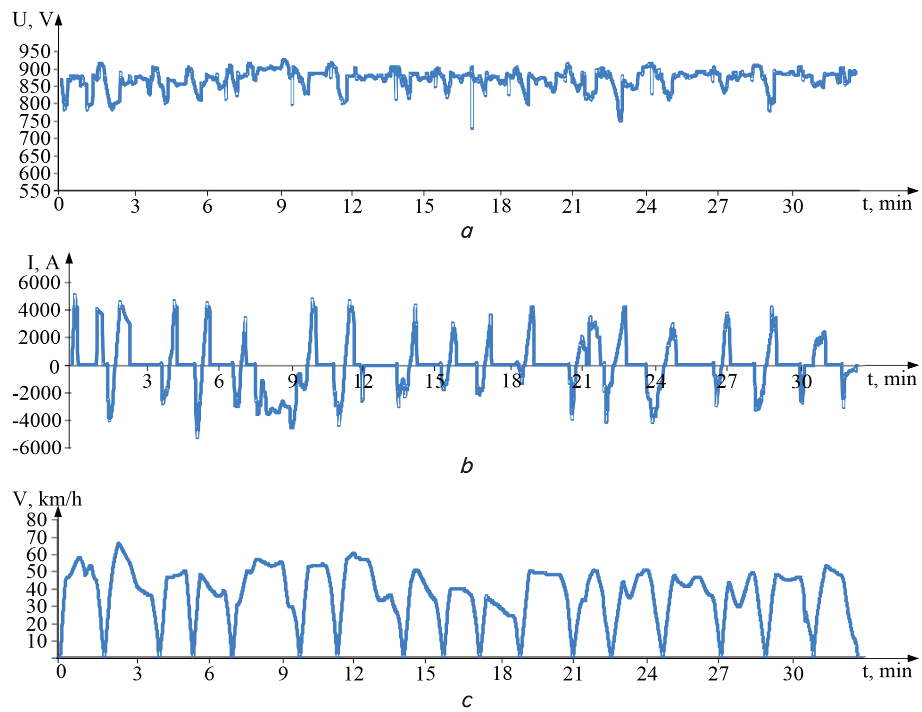


Fig. 5. Oscillograms of voltage on the current collector (*a*), the train current (*b*) and the train speed (*c*) during its operation between Akademmistechko and Lisova stations

Table 1

Results of data processing

| Study section | «Non-peak» traffic schedule: minimum/nominal/maximum load of passengers | | | «Peak» traffic schedule: nominal/maximum load of passengers | | |
|---|---|---|---|---|---|---|
| | $A_{trac}$, kWh | $A_{rec}$, kWh | $P_{max}$, kW | $A_{trac}$, kWh | $A_{rec}$, kWh | $P_{max}$, kW |
| Lisova – Chernigivska | 7.17/9.68/8.46 | 2.84/4.76/5.33 | 1445/1798/2406 | 12.28/14.6 | 8.5/10.06 | 3879/2496 |
| Chernigivska – Darnytsia | 6.45/10.48/11,11 | 3.5/2.7/4.1 | 1119/1240/2120 | 15.34/15.92 | 6.27/7.67 | 2425/2093 |
| Darnytsia – Livoberezhna | 7.89/16.44/8.98 | 3.08/1.23/3.49 | 1143/1422/1662 | 13.65/13.,63 | 6.07/6.65 | 2442/1969 |
| Livoberezhna – Gidropark | 7.35/15.24/9.8 | 3.11/4.18/5.93 | 1963/1665/2701 | 14.26/18.68 | 8.59/10.51 | 2455/2719 |
| Gidropark – Dnipro | 13.61/22.82/21.81 | 2.02/2.43/6.75 | 1216/1248/2102 | 23.71/23.52 | 8.29/8.07 | 2492/2219 |
| Dnipro – Arsenalna | 3.64/4.63/3.48 | 5.88/9.68/8.97 | 2056/3028/3364 | 3.38/2.28 | 8.45/8.22 | 2367/2364 |
| Arsenalna – Khreshchatyk | 8.76/12.03/12.77 | 2.35/4.49/4.89 | 993/1563/2313 | 13.92/13.94 | 4.59/6.87 | 3050/2208 |
| Khreshchatyk – Teatralna | 4.87/8.18/8.25 | 2.02/4.17/4.11 | 831/1333/1740 | 11.06/14.18 | 5.29/7.69 | 1874/2531 |
| Teatralna – Universytet | 5.91/8.14/9.2 | 2.25/3.21/4.14 | 867/1182/2027 | 11.3/13.55 | 3.64/5.42 | 1178/2733 |
| Universytet – Vokzalna | 6.22/8.47/9.85 | 1.84/3.02/3.89 | 736/1147/1743 | 9.3/14.45 | 3.15/6.54 | 1038/3060 |
| Vokzalna – KPI | 10.84/16.19/16.75 | 3.33/4.76/4.74 | 1022/1790/2312 | 14.4/20.53 | 2.98/6.48 | 1127/2189 |
| KPI – Shuliavska | 8.68/11.67/13.05 | 2.66/3.41/4.75 | 947/1451/2058 | 15.78/18.37 | 4.44/7.31 | 1261/2661 |
| Shuliavska – Beresteiska | 52.39/78.21/81.31 | 3.48/4.08/4.29 | 1184/1379/1675 | 79.27/84.09 | 3.51/5.52 | 1182/1904 |
| Beresteiska – Nyvky | 8.81/11.96/17.68 | 3.19/7.16/9.04 | 1763/2508/3073 | 15.78/21.82 | 7.36/11.64 | 2145/3713 |
| Nyvky – Sviatoshyn | 9.07/13.61/13.69 | 2.44/3.64/3.76 | 828/1071/1784 | 13.15/9,66 | 3.36/3.26 | 1071/2478 |
| Sviatoshyn – Zhytomyrska | 5.34/7.83/6.25 | 6.16/9.75/8.69 | 1695/2798/2849 | 6.04/11.95 | 8.55/12.26 | 2177/3437 |
| Zhytomyrska – Akademmistechko | 1.65/2.63/2.88 | 1.82/2.44/3.1 | 582/906/1097 | 4.98/4.15 | 4.34/3.67 | 1772/1299 |
| Akademmistechko – Zhytomyrska | 15.17/22.04/19.03 | 3.61/5.54/3.78 | 1144/2023/1677 | 24.22/25.22 | 6.75/7.35 | 3050/2668 |
| Zhytomyrska – Sviatoshyn | 14.45/24.63/24.56 | 2.87/3.94/3.47 | 931/1261/1729 | 24.14/25.92 | 7.05/4.02 | 1242/1843 |
| Sviatoshyn – Nyvky | 6.31/10.48/8.47 | 4.31/8.04/6.46 | 2029/3112/3041 | 14.15/12.05 | 10.18/7.68 | 2835/2565 |
| Nyvky – Beresteiska | 11.07/11.43/13.39 | 5.22/5.44/6.35 | 2096/1722/2936 | 15.5/17.85 | 7.01/8.67 | 2352/2901 |
| Beresteiska – Shuliavska | 4.94/5.14/5.11 | 25.3/44.26/45.93 | 2677/2761/3341 | 4.69/5.72 | 44.35/45.36 | 2136/3835 |
| Shuliavska – KPI | 7.53/14.01/11.78 | 2.28/8.2/6.6 | 1539/2462/2934 | 9.28/17.83 | 5.19/9.86 | 1720/3376 |
| KPI – Vokzalna | 11.07/14.76/15.21 | 1.76/5.39/5.0 | 696/1294/1306 | 14.85/16.2 | 5.01/6.35 | 1268/1285 |
| Vokzalna – Universytet | 6.86/8.04/8.15 | 1.9/2.33/2.53 | 636/782/914 | 8.08/10.44 | 2.15/3.89 | 720/1819 |
| Universytet – Teatralna | 5.81/8.67/7.94 | 2.57/3.21/2.7 | 602/986/811 | 8.18/10.39 | 2.35/3.97 | 764/1439 |
| Teatralna – Khreshchatyk | 6.01/6.7/8.14 | 1.06/0.95/2.13 | 739/545/653 | 11.44/12.93 | 4.14/5.49 | 1436/1888 |
| Khreshchatyk – Arsenalna | 11.05/12.76/13.83 | 2.99/3.38/5.0 | 934/1903/1815 | 12.58/13.88 | 3.34/4.83 | 775/1567 |
| Arsenalna – Dnipro | 15.76/22.94/23.13 | 2.6/4.57/4.5 | 1306/2208/2478 | 22.42/22.32 | 4.35/3.78 | 1400/1629 |
| Dnipro – Gidropark | 9.87/13.61/10.49 | 6.27/11.93/9.86 | 1845/2168/2763 | 13.1/15.91 | 11.21/13.69 | 2757/3106 |
| Gidropark – Livoberezhna | 8.71/12.6/15.07 | 2.55/2.78/4.66 | 876/1300/1990 | 13.1/17.75 | 3.12/5.64 | 952/1961 |
| Livoberezhna – Darnytsia | 7.32/10.44/9.96 | 3.69/5.69/5.42 | 944/1387/2396 | 12.45/12.83 | 7.21/7.1 | 1817/1868 |
| Darnytsia – Chernigivska | 9.91/12.68/11.52 | 4.6/2.08/6.13 | 1513/1114/2217 | 11.34/11.0 | 5.91/5.19 | 2024/2590 |
| Chernigivska – Lisova | 8.36/14.99/11.83 | 1.77/2.72/3.4 | 1089/1384/979 | 16.28/15.4 | 6.3/6.0 | 1512/3017 |

Table 2

Chosen parameters of on-board CESS

| Power, kW | Energy intensity, kWh |
|---|---|
| 1,000; 2,000; 3,000; 4,000 | 1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 20; 30; 45 |

Thus, the total number of chosen on-board CESS with various levels of power and energy intensity in this case was 52.

Based on the results of analysis of cost of the chosen on-board CESS, reversible transducers and other component equipment, the cost of chosen storage systems is given in Table 3. This analysis has made it possible to find that the cost of the storage system mainly depends on the cost of the on-board CESS and the reversible transducer, the cost of other component equipment being much lower.

Using the results of cost analysis based on the manufacturers' information (Table 3), graphs were constructed in the form of dependencies of cost of storage systems on their power and energy intensity (Fig. 6).

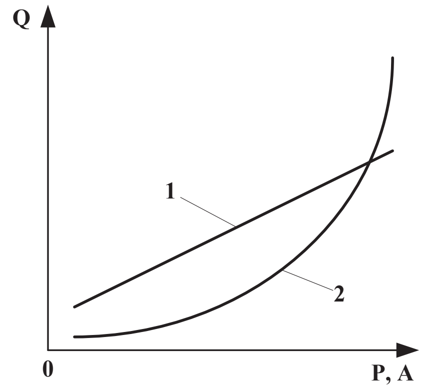


Fig. 6. Graphs of changes in the cost of storage systems depending on their power and energy intensity: dependence of $Q=f(P)$ at $A=$ const (1); dependence $Q=f(A)$ at $P=$ const (2)

Using the above-mentioned algorithm (Fig. 1) and formulas (5)–(8), quantity of the electric energy saved through introduction of the chosen storage systems was determined. The results of estimation of quantity of the energy saved per year for each of the chosen storage systems are shown in Table 4.

Table 4

Quantity of the saved electric energy per year

| Power, kW | Quantity of the saved electric energy taking into account various working energy intensities of the on-board CESS [kWh], million kW·yr | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 20 | 30 | 45 |
| 1,000 | 0.08 | 0.16 | 0.23 | 0.27 | 0.29 | 0.3 | 0.3 | 0.31 | 0.31 | 0.31 | 0.34 | 0.35 | 0.35 |
| 2,000 | 0.08 | 0.16 | 0.23 | 0.28 | 0.32 | 0.35 | 0.36 | 0.38 | 0.38 | 0.39 | 0.42 | 0.44 | 0.47 |
| 3,000 | 0.08 | 0.16 | 0.23 | 0.28 | 0.32 | 0.35 | 0.37 | 0.38 | 0.39 | 0.4 | 0.43 | 0.46 | 0.49 |
| 4,000 | 0.08 | 0.16 | 0.24 | 0.28 | 0.32 | 0.35 | 0.37 | 0.38 | 0.39 | 0.4 | 0.43 | 0.46 | 0.49 |

The results of calculating the payback period for the chosen storage systems are depicted in the form of diagrams in Fig. 7.

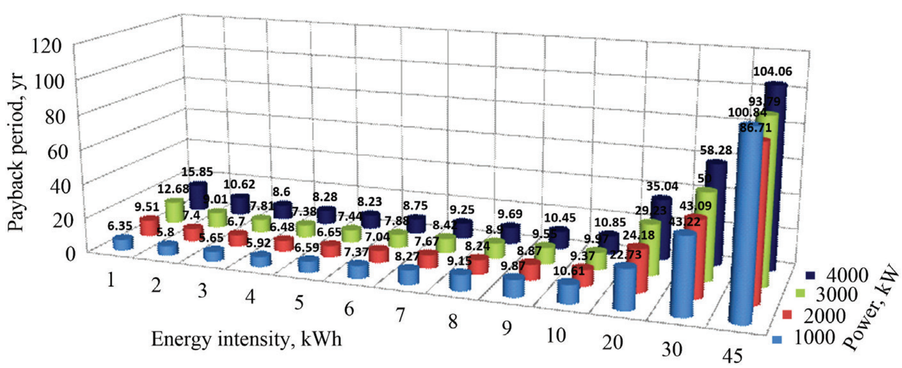


Fig. 7. Diagrams of the payback periods of the chosen storage systems

It was determined with the help of formula (10) that for the given operating conditions, introduction of a storage system with rational parameters will save 16.1 % of the electric energy consumed for train traction.

Table 3

Cost of the chosen storage systems

| Power, kW | Cost with an account of various working energy intensities of on-board CESS [kWh], USD | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 20 | 30 | 45 |
| 1,000 | 0.3 | 0.5 | 0.7 | 0.8 | 1.0 | 1.1 | 1.3 | 1.5 | 1.6 | 1.7 | 4.0 | 8.0 | 18.6 |
| 2,000 | 0.4 | 0.6 | 0.8 | 1.0 | 1.1 | 1.3 | 1.5 | 1.6 | 1.8 | 1.9 | 5.3 | 9.9 | 21.2 |
| 3,000 | 0.5 | 0.7 | 0.9 | 1.1 | 1.2 | 1.5 | 1.6 | 1.8 | 2.0 | 2.1 | 6.6 | 11.9 | 23.9 |
| 4,000 | 0.7 | 0.9 | 1.1 | 1.2 | 1.4 | 1.6 | 1.8 | 1.9 | 2.1 | 2.3 | 8.0 | 13.9 | 26.5 |

*Note: Cost estimation of on-board systems is given for the conditions of use of condenser modules produced by Elton CJSC. The value of the «dead» volume of the condenser modules was taken equal to 20 %*

## 6. Discussion of results of determining rational parameters of the capacitive energy storage system

Analysis of the graphs in Fig. 6 has allowed us to establish that with increase in power of the storage system, its cost increases linearly and with increase in energy intensity, the cost increases according to the exponential law. At the same time, the cost has a slight increase at the initial stage of increasing the energy intensity of the storage system but there is a clearly pronounced, sharp cost increase after a certain value of the energy intensity. This is explained by the fact that the current technology of manufacture of the on-board CESS in the chosen energy intensity range is at diverse stages. The storage systems with energy intensity of up to 10 kWh are manufactured in series, while above 10 kWh, the storage systems exist only as prototypes.

Analysis of diagrams in Fig. 7 has shown the following:

– of all chosen storage systems, under the specified conditions of operation of the underground railway rolling stock, the most rational was the system with a value of the working energy intensity of 3 kWh and a maximum power of 1,000 kW. The payback period of this system was minimal: 5.65 years;

– the maximum payback period had a system with a working energy intensity of the on-board CESS equal to 45 kWh and a maximum capacity of 4,000 kW. It is capable of storing and accumulating the entire quantity of recuperative braking energy. The payback period of this system is about 104 years. It should be noted that in comparison with others, this system has also the largest size indicators. As a result, it is impractical to utilize this system by the two factors: the payback period and size indicators;

– dynamics of the change in the payback period of the storage systems with the working energy intensity of the on-board CESS up to 10 kWh is insignificant while, there has a pronounced growth nature after 10 kWh.

In this study, 52 storage systems with various levels of power and energy intensity were selected. Probably, this was quite enough to determine the system with rational parameters for the given operating conditions. For more accurate determination of rational parameters, it is necessary to calculate a greater number of on-board CESS with various levels of power and energy intensity (for example, choose a 20×8 matrix instead of 13×4).

Further studies should be focused on development of a comprehensive approach that would enable determining rational parameters of the on-board CESS by two criteria. The first one is the minimum payback period of the storage system and the second one is low weight of this system.

## 7. Conclusions

1. Based on the proposed approach, studies were carried out. The studies have resulted in determination of rational parameters of on-board CESS (maximum power and working energy intensity) for the specified conditions of operation of the underground railway rolling stock with recuperation systems. With the help of a measuring system, voltage at the current collector, current and the train speed at its typical operating conditions were recorded at a sampling frequency of 2.5 kHz.

2. According to the results of the performed studies, it was found that for the given modes of the rolling stock operation, it is rational to use the storage system with an on-board CESS having working energy intensity of 3 kWh and the maximum power of 1,000 kW. It was found that the payback period of this system is 5.65 years.

3. Introduction of a storage system with rational parameters for the given operating conditions will save 16.1 % of the quantity of electric energy consumed for train traction.

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