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## ANALYSIS OF TECHNICAL SOLUTIONS FOR THE IMPLEMENTATION OF ON-BOARD ENERGY STORAGE ON THE ELECTRIC STOCK

**Purpose.** Analysis of existing technical solutions for management of energy exchange processes on traction electric stock with on-board energy storage devices and search for the rational one among them. Research on energy exchange processes and estimation of the amount of saved electricity during the application of various technical solutions.

**Methodology.** The work provides a comparative analysis of existing technical solutions for control of energy exchange processes on traction electric stock with on-board energy storage devices. The advantages and disadvantages of each of the existing technical solutions are formulated. The nature of the flow of energy exchange processes is determined and the amount of electricity is estimated by directly connecting the on-board energy storage to the traction motors and through a static reversible converter of controlled type for the specified operating conditions of the electric stock and accepted assumptions.

**Findings.** It is determined that a static reversible converter of controlled type with inductive or capacitive power dispensers is the most rational and energy efficient device for controlling the charge and discharge processes of an on-board energy storage unit on electric stock.

**Originality.** The theory of the use of energy storage devices on electric stock, which, unlike the existing ones, allowed determining the amount of saved electricity for the cycle of “regenerative braking – acceleration of the train” depending on the type of connection of the on-board energy storage and its energy intensity.

**Practical value.** It is found that the control of energy exchange processes in the energy storage system by applying a static converter of controlled type is more rational. It is determined that for control of energy exchange processes on traction electric stock with on-board energy storage devices, the most rational and energy efficient one is the use of current-reversed pulse-width converter with inductive or capacitive power metering unit. The obtained research results can be used by industrial enterprises in the design and creation of innovative electric stock in order to increase its operational characteristics.

**Keywords:** *on-board energy storage, electricity dispenser, energy exchange processes, electric stock, static reversing converter*

**Introduction.** At present time the problem of reducing electricity consumption is becoming a strategic direction for the development of many branches of industries and sectors of the Ukrainian economy, including rail transport. It is known that one of the promising measures that will greatly save electricity in rail transport is the implementation of regenerative braking systems on its traction electric stock (ES) [1].

**Literature review.** From the source [2] it is known that among the traction ES rail transport the largest reserves of energy saving due to the implementation of recovery systems are in the subway due to the peculiarities of operation of its electric rolling stock (frequent acceleration and braking, a small distance between stations, and others). The energy savings from the use of regenerative braking power in the subway make 50 % of the electricity consumed per traction [2]. However, under the existing infrastructure of the subway energy supply system, the use of recuperation electricity is probable and does

not exceed 10 % [1]. Consequently, much of this electricity is excess and dissipates in the form of heat on the braking resistors of the rolling stock or the bus of the overhead lines. Thus, there is currently a problem of inefficient use of regenerative braking electricity.

One of the most promising ways of solving this problem is the use of on-board capacitive energy storages (CES) [1, 3]. The main advantages of the onboard installation of capacitive energy storages compared to affixed ones is the maximum efficiency of energy exchange, stabilization of the voltage of the overhead line, ensuring the autonomous operation of the electric rolling stock. It is known that the introduction of CES in the subway will greatly increase the efficiency of the use of electricity by regenerative braking and additionally save the electricity consumed by the traction of the rolling stock of about 10–20 % [4]. At the same time, the search for a rational technical solution for the effective reception and return of regenerative braking electricity remains one of the important and urgent questions, provided that it is installed on the electric rolling stock.

**Purpose.** Analysis of the existing technical solutions for controlling the energy exchange processes on the traction ES with on-board CES and finding the rational one among them under conditions of implementation in the subway; research on energy exchange processes and estimation of the amount of saved electricity during the application of various technical solutions.

**Results.** Existing technical solutions for the control of energy exchange processes on traction ES with on-board CES have been analyzed through a series of studies. During this analysis, the technical solutions applicable to both the rolling stock of the subway and other traction ES of the direct current (suburban electric trains, electric locomotives, trams, and so on) were considered. In work [5], a direct connection of the capacitive energy storage to the traction drive is considered, as well as through a nonadjustable converter and a bi-directional converter. In works [6–10], technical solutions are proposed in which the control of energy exchange processes is carried out by means of controlled static converters.

In work [6], it is proposed to control the energy-exchange processes with a reversing converter installed in the circuit of the on-board energy storage, which is a converter capable to provide an up-down conversion factor (Fig. 1, *b*). In work [7], it is proposed to use a DC-DC converter for these purposes, the scheme of which is shown in Fig. 1, *a*. In work [8], it is also proposed to use down, up or up-down voltage converter of DC-DC type, which provides a two-zone speed control of the traction motor (Figs. 1, *a*, *c*) to control the operation of the on-board capacitive energy storage and electric traction drive. In work [9], a scheme of voltage converter due to impulse control, which works in the mode of up-down converter (Fig. 1, *a*), is proposed. Technical solution for control of energy exchange processes on the traction rolling stock with on-board capacitive energy storage presented in work [10] is shown in Fig. 1, *c*. Thus, in many works, it is proposed to use a reversible up-down DC-DC transducer of a converter type as a converter.

Based on the analysis of the abovementioned works, it is found that the control of energy exchange processes between the on-board CES and the traction actuator can be nonadjustable and adjustable. In the case of nonadjustable control, it is possible to connect the BNE directly to the electric traction drive, as well as through nonadjustable devices (current-forming active resistors, inductors or capacitors, nonadjustable converters with unchanged algorithm of operation in charge and discharge modes of CES). With regulated control, the CES connection to the electric traction drive is made through a converter of adjustable type. In order to determine the advantages and disadvantages of applying the appropriate technical solution in energy storage systems (ESS) for the implementation of the control of energy exchange processes, a comparative analysis of the following factors was performed: the efficiency coefficient of the energy exchange processes, the value of the “dead” volume of CES, the coefficient of energy use of the device, cost and weight. The results of their comparative analysis are given in Table 1.

Costs and weight-and-dimensions characteristics are given for the ESS as a whole, taking into account the cost and dimensions of the device itself (if any) and CES.

Direct connection of the CES to the electric traction drive results in a low percentage of the on-board CES’s working volume (the dead volume is about 75–90 %), resulting in a CES of considerable total energy consumption [5] is necessary. The charge and discharge processes are unstable and depend on many factors, above all the value of the voltage in the overhead line. Therefore, there is a clear dependence of the stability of the flow of energy exchange processes between the traction drive and the on-board CES on the energy processes in the overhead line. However, under conditions of stable energy exchange process, its efficiency coefficient will be quite high (about 90–98 %). There is no need for use of additional devices and control systems, a considerable resource of work CES.

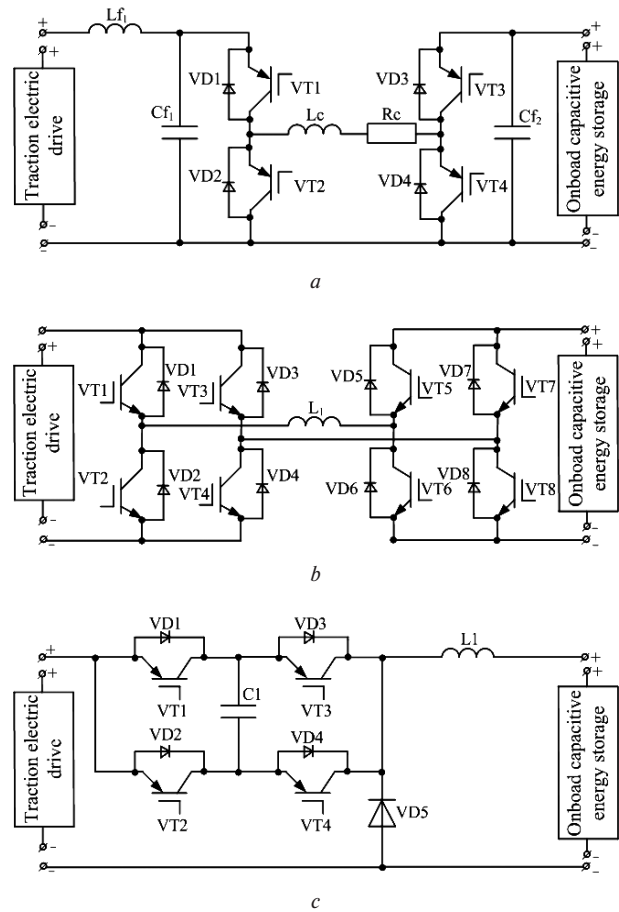


Fig. 1. Power type schemes of static converters of the adjustable type:

*a* – up-down voltage converter; *b* – four-quadrant converter with intermediate inductive insert; *c* – down voltage converter; VT1–VT8 – IGBT – transistors; VD1–VD8 – diodes; L1, C1 – inductance and capacity of the energy metering device in the converter circuit;  $L_{f1}$ ,  $C_{f1}$ ,  $C_{f2}$  – inductance and capacity of the filter;  $R_c$ ,  $L_c$  – resistance and inductance of the converter

Thus, the advantages of the direct CES connection scheme are the high efficiency of energy exchange processes, absence of additional devices and control systems (simple and reliable technical solution), a considerable resource of the on-board CES operation; disadvantages include the need to use on-board CES of significant energy consumption, significant mass and cost values of CES, instability of the flow of energy exchange processes, significant impulse current loads that reduce the operational life of traction motors.

The main function of current-forming elements (resistors, inductors, capacitors) is to limit currents during the charge and discharge processes of the on-board CES [4]. The most simple and reliable connection is CES through the resistor; however, the efficiency of charge and discharge processes does not exceed 50 %, which significantly limits its scope. Under the condition of a series connection of inductance or parallel connection of the capacity of the efficiency coefficient of energy exchange processes it increases and makes 50–90 %, however the weight and cost of ESS increase. Therefore, in general, the use of current-forming elements in the control of energy-exchange processes is not widely used (especially in the case of ESS with powerful on-board CES) due to the following disadvantages: low efficiency of charge and discharge processes, significant mass and cost of ESS. The advantage of using current-forming elements over the direct connection of the CES is to reduce the amount of “dead” volume and to increase the stability of the flow of energy exchange processes.

Comparative analysis of different CES connection schemes

Type of the on-board CES connection to the electric traction drive	Efficiency coefficient, %	Amount of the “dead” volume of CES, %	Cost of ESS*	Weight of the ESS*	Operating factor of the device
<b>Nonadjustable type of charge and discharge mode control CES</b>					
Direct connection	90–98	62–90	–	1.5–2 times less	–
Resistor	30–50	40–65	1.5–2.5 times less	2–3 times less	0.5–0.6
Inductivity, capacity	50–90	35–60	1.5–1.8 times less	–	0.6–0.7
Nonadjustable converter	40–60	15–40	2.5–4 times less	2.5–5 times less	0.8–1.0
<b>Adjustable type of charge and discharge mode control CES</b>					
Transistor converter of the direct current to direct	90–94	5–20	2–3 times less	3.5–7 times less	0.8–1.0
Adjustable devices at charging with direct current - amplitude-impulse control; - frequency-pulse control;	87–92	10–40	1.5–3 times less	2.5–5.5 times less	0.5–0.7
Adjustable devices which support mode of constant power	82–90	10–40	1.5–3 times less	3–5 times less	0.6–0.7

\* Note. The “–” mark indicates the device implementation of which shows the highest cost and mass dimensions of the ESS. For other devices, these values are calculated by reference to the highest values

While controlling the charge and discharge modes of the CES through a nonadjustable static converter, there is a low efficiency coefficient of energy exchange processes (of about 40–60 %), a considerable percentage of the working volume of the CES (the “dead” volume is about 15–35 %). The charge and discharge processes are relatively stable.

*Advantages* of CES connection scheme for traction electric drive through nonadjustable converter are a small amount of “dead” on-board CES volume, stability of energy exchange processes and maximum operation factor of the device, among *disadvantages* there is low efficiency coefficient of charge and discharge processes, significant values of weight and cost of the ESS.

When using devices (static converters) of adjustable type, there are following *advantages*: high efficiency of charge and discharge processes, a small amount of “dead” CES volume, stability of flow of energy exchange processes and maximum operation factor of the device, ability to work in a wide range of operating voltages. The *disadvantages* of these circuit solutions are the need to use sensors and control systems for the efficient and stable flow of energy exchange processes between the energy storage and the electric traction drive of the electric rolling stock.

According to the results of the comparative analysis (Table 1) it is noticeable that the advantage of using devices of adjustable type is obvious. This advantage is achieved, first of all, by reducing the weight and cost of ESS, increasing the efficiency of charge and discharge processes of CES, and reducing the amount of “dead” CES volume. Thus, it was found that the control of energy exchange processes by applying a static converter of adjustable type is more rational.

From the source [8], it is known that in static converters the control of energy exchange processes is carried out with amplitude-pulse, pulse-width or frequency-pulse control. In the design of static converters electricity meters (inductive, capacitive, inductive-capacitive) are usually used [8].

The block diagram of the electric traction drive with the capacitive energy storage, in which the control of energy exchange processes is carried out through a converter of adjustable type, is shown in Fig. 2.

The analysis of works [5, 9, 10] has made it possible to determine that among the pulse converters, the use of the current-reversed pulse-width converter with inductive or capacitive metering device is the most rational and energy efficient

for controlling the energy exchange processes in the traction electric stock with CES. In this case, this converter must provide a decreasing and increasing conversion factor of several units.

For the given conditions of operation of the electric rolling stock the estimation of the indicative parameters of the ESS and the character of the energy flow exchange processes between CES and the electric traction drive. The assessment was made under the conditions of direct connection of the CES to the traction drive and through a static converter of the adjustable type (pulse-width converter with inductive power metering device). The research was carried out using current oscillograms, the voltage of the overhead line (on the current collector), running speed, which are shown in Fig. 3. The given oscillograms were obtained experimentally under the real standard operating conditions of the electric rolling stock with the systems of recovery between several stations. The block diagram of the test complex, which includes the subway rolling stock and the measuring system, is described in detail in work [11].

The estimation of the approximate parameters of the ESS and the nature of the of energy exchange processes running between the CES and the electric traction drive were carried out according to the following input data and assumptions: the rolling stock is fed with the traction substation, the voltage of nonworking stroke of the traction substation ( $U_{ocvic} = 825$  V), weight of the rolling stock at maximum load ( $m = 264$  t), CES is considered to be previously charged, the capacitive energy storage is charged during regenerative braking of the train and feeds (discharges) traction motors in the mode of its accelera-

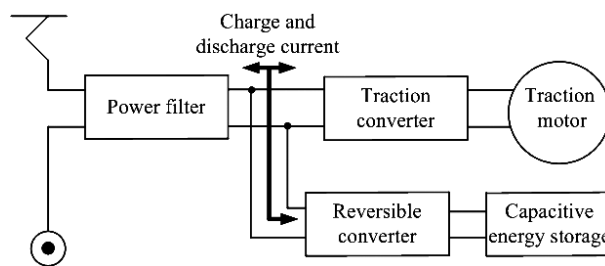


Fig. 2. Block diagram of the electric traction drive with the capacitive energy storage

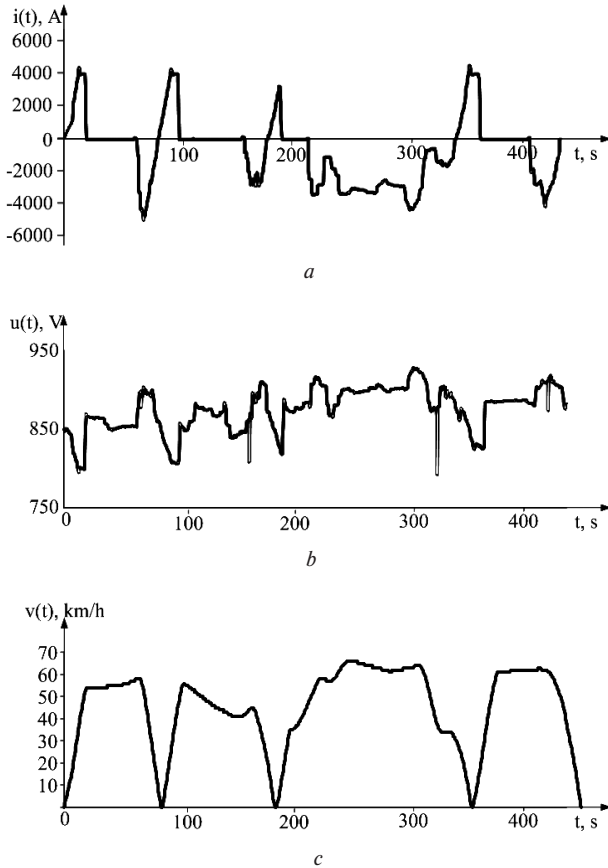


Fig. 3. Oscillograms during the operation of rolling stock between stations:

a – rolling stock current in modes of traction and regenerative braking  $i(t)$ ; b – voltage at the current collector  $u(t)$ ; c – the running speed  $v(t)$

tion, the efficiency coefficient of the CES ( $\eta_{CES} = 0.98$ ), the inertia coefficient of the circulating train weight  $(1 + \gamma) = 1.06$ , current consumption in the neutral position ( $I_{np} = 0$  A) [11]. The research was performed under the condition of alternate use of two CESs with different technical parameters. The energy consumption (A) of the first is  $5 \text{ kW} \cdot \text{h}$ , of the other –  $25 \text{ kW} \cdot \text{h}$ .

Under the conditions of direct connection of the CES to the electric traction drive, the following assumptions are made: the processes of charge and discharge depend on the level of voltage in the overhead line and the current of consumption (recovery), the efficiency coefficient in the mode of charge and discharge of the CES ( $\eta_{CD} = 0.99$ ), the value of the “dead” volume of the CES ( $C_0 = 80\%$ ). For traction mode: the CES discharge process is constant, i.e. 100% of the energy is transmitted to the electric traction drive. For regenerative braking mode: subject to the voltage of the contact network  $u(t) \geq 900$  V and the recuperation current  $i(t) \geq 3000$  A, the CES charge process is constant, i.e. 100% of the energy is transmitted to the capacitive energy storage; provided  $u(t) = 850\text{--}900$  V and  $i(t) = 1000\text{--}3000$  A, the CES charge process is not constant, i.e. 50% of the energy is transferred to the capacitive energy storage; provided  $u(t) \leq 850$  V and  $i(t) \leq 1000$  A, the capacitive energy storage is not charging [5]. The diagram of the voltage change of the capacitive energy storage depending on the amount of stored energy is shown in Fig. 4.

Under conditions of connection of the CES to the electric traction drive through a static converter of adjustable type, the following assumptions are made: the processes of charge and discharge are constant and do not depend on the voltage level in the overhead line (100% of the energy is transmitted to the capacitive energy storage and electric traction drive), the effi-

ciency coefficient in the mode of charge and discharge of the CES ( $\eta_{CD} = 0.9$ ), the value of the “dead” volume of the CES ( $C_0 = 20\%$ ) [5]. The diagram of the voltage change of the capacitive energy storage depending on the amount of stored energy is shown in Fig. 5.

The amount of electricity consumed in the traction mode and generated by the train in regenerative braking mode in simplified form can be determined analytically by the formula [12]

$$A = \int_{V_1}^{V_2} \frac{V^2(1+\gamma) \cdot m \cdot V}{3600} dV = \frac{(1+\gamma) \cdot m \cdot (V_2^2 - V_1^2)}{2 \cdot 3600}, \quad (1)$$

where  $V_1, V_2$  are initial and final speed of the rolling stock.

In real operating conditions, the amount of electricity is significantly influenced by the track profile, the voltage of the overhead line and others. Therefore, under real operating conditions, formula (1) does not allow taking into account these factors. Estimation of the amount of electricity according to the oscillogram obtained experimentally during the operation of the train is carried out according to the formula [12]:

a) for the traction mode

$$A_{tr} = \frac{I_{av.tr} \cdot U_{km.tr} \cdot t_{tr}}{3600 \cdot 1000}, \quad (2)$$

where  $I_{av.tr}$  is the average value of current in the traction mode;  $U_{km.tr}$  is the average value of the voltage in the traction mode;  $t_{tr}$  is duration of the traction mode;

b) for regenerative braking mode

$$A_{rec} = \frac{I_{av.rec} \cdot U_{km.rec} \cdot t_{rec}}{3600 \cdot 1000}, \quad (3)$$

where  $I_{av.rec}$  is the average current value in regenerative braking mode;  $U_{km.rec}$  is the average voltage of the overhead line in the mode of regenerative braking;  $t_{rec}$  is duration of the regenerative braking mode.

The amount of regenerative braking electricity that can be used to accelerate a train is estimated by the formula

$$A_{useful} = A_{rec} \cdot \eta_{CD}^2 \cdot \eta_{CES}. \quad (4)$$

The amount of saved electricity for the cycle of regenerative braking-acceleration of the train is determined depending on the value of the working energy intensity of CES:

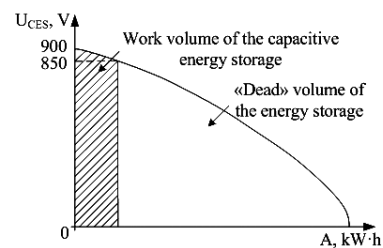


Fig. 4. Diagram of the voltage change on the capacitive energy storage at its direct connection to the traction electric drive

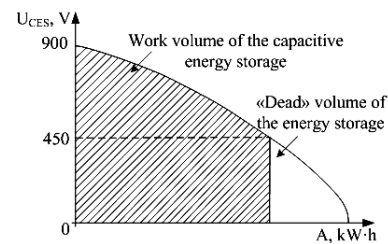


Fig. 5. Diagram of the voltage change on the capacitive energy storage when connected to the traction drive through a static converter of adjustable type

a)  $(A_{rec} \cdot \eta_{CD} \cdot k_{st}) \geq A_{work}$ ,  
so

$$A_{sav} = A_{work} \cdot \eta_{CD} \cdot \eta_{CES}, \quad (5)$$

where  $k_{st}$  is the coefficient that takes into account the stability of the energy exchange processes (when directly connected  $k_{st}$  is determined by the results of the processing of currents and voltages of the overhead line; when connected through a static converter of adjustable type –  $k_{st} = 1$ );  $A_{work}$  is working energy intensity of CES.

$$A_{work} = A - \frac{A \cdot C_0}{100}, \quad (6)$$

b)  $(A_{rec} \cdot \eta_{CD} \cdot k_{st}) < A_{work}$ ,  
so

$$A_{sav} = A_{rec} \cdot \eta_{CD}^2 \cdot k_{st} \cdot \eta_{CES}. \quad (7)$$

The efficiency of CES application of a given energy intensity is determined by the formula

$$\alpha = \frac{A_{sav}}{A_{tr}} \cdot 100. \quad (8)$$

The total amount of consumed, recovered and save electricity is determined by the formulas

$$A_{tr\Sigma} = \sum_{n=1}^N A_{trn}; \quad (9)$$

$$A_{rec\Sigma} = \sum_{n=1}^N A_{recn}; \quad (10)$$

$$A_{sav\Sigma} = \sum_{n=1}^N A_{savn}, \quad (11)$$

where  $n$  is the number of the test section;  $N$  is the total number of test sections.

The overall efficiency of CES application of a given energy intensity is determined by the formula

$$\alpha = \frac{A_{sav\Sigma}}{A_{tr\Sigma}} \cdot 100. \quad (12)$$

The results of the calculations made by formulas (2–12) are given in Tables 2, 3.

The obtained character of the energy exchange processes, taking into account the received data and assumptions is shown in Fig. 6.

According to the results of the performed research, for the given equal conditions of operation of the electric rolling stock (Tables 2, 3, and Fig. 6), it is established that:

- the energy exchange between the capacitive energy storage and the electric traction drive greatly depends on the type of CES connection and its energy intensity;
- stability of energy exchange under conditions of direct connection of CES to the traction electric drive is in the range of 0.44–0.6;
- the total amount of saved electricity for the cycle of regenerative braking-acceleration of a train depends on the type of CES connection and its energy intensity, and is in the range of 3.88–34.94 kW·h; the overall efficiency of the CES application of the specified energy intensity is in the range of 9.4–84.9 %;
- in case of CES using the same energy intensity, it is more efficient to connect it through a static converter of adjustable type (efficiency is higher by 2.3–3.6 times) due to the stability of the energy exchange processes and increase in CES working volume;
- to maintain the full volume of regenerative braking electricity, it is necessary to use CES with a working energy of at least 44.36 kW·h.

Table 2

The results of the calculations of the on-board CES directly connected to the electric traction drive

Test section	$I_{av, tr}, A$	$U_{km, tr}, B$	$t_{tr}, s$	$I_{av, rec}, A$	$U_{km, rec}, B$	$t_{rec}, s$	$A_{tr}, kW \cdot h$	$A_{rec}, kW \cdot h$	$k_{st}$	$A_{useful}, kW \cdot h$	$A_{work}, kW \cdot h$		$\alpha, \%$	$A_{sav}, kW \cdot h$		$\alpha, \%$
											$A = 5 kW \cdot h$			$A = 25 kW \cdot h$		
Section No. 1	2475	824	18.5	1914	890	16.5	10.48	8.04	0.6	7.72	1	0.97	9.3	5	4.63	44.2
Section No. 2	2772	825	18.0	1227	886	18.0	11.43	5.44	0.44	5.22	1	0.97	8.5	5	2.3	20.1
Section No. 3	1065	855	20.5	1503	901	118.0	5.19	44.36	0.46	42.61	1	0.97	18.7	5	4.85	93.6
Section No. 4	2772	846	21.5	1304	905	25.0	14.01	8.2	0.44	7.87	1	0.97	6.9	5	3.47	24.7
$\Sigma$	–	–	–	–	–	–	41.15	65.49	–	–	–	3.88	9.4	–	15.25	37.1

Table 3

The results of calculations of the on-board CES connected through an adjustable type converter

Test section	$I_{av, tr}, A$	$U_{km, tr}, B$	$t_{tr}, s$	$I_{av, rec}, A$	$U_{km, rec}, B$	$t_{rec}, s$	$A_{tr}, kW \cdot h$	$A_{rec}, kW \cdot h$	$k_{st}$	$A_{useful}, kW \cdot h$	$A_{work}, kW \cdot h$		$\alpha, \%$	$A_{sav}, kW \cdot h$		$\alpha, \%$
											$A = 5 kW \cdot h$			$A = 25 kW \cdot h$		
Section No. 1	2475	824	18.5	1327	890	16.5	10.48	8.04	1.0	6.38	4	3.53	33.7	20	6.38	60.9
Section No. 2	2772	825	18.0	871	886	18.0	11.43	5.44	1.0	4.32	4	3.53	30.9	20	4.32	38.6
Section No. 3	1065	855	20.5	1503	901	118.0	5.19	44.36	1.0	35.07	4	3.53	68.0	20	17.64	339.9
Section No. 4	2772	846	21.5	1304	905	25.0	14.01	8.2	1.0	6.51	4	3.53	25.2	20	6.51	46.5
$\Sigma$	–	–	–	–	–	–	41.15	65.49	–	–	–	14.12	34.3	–	34.94	84.9

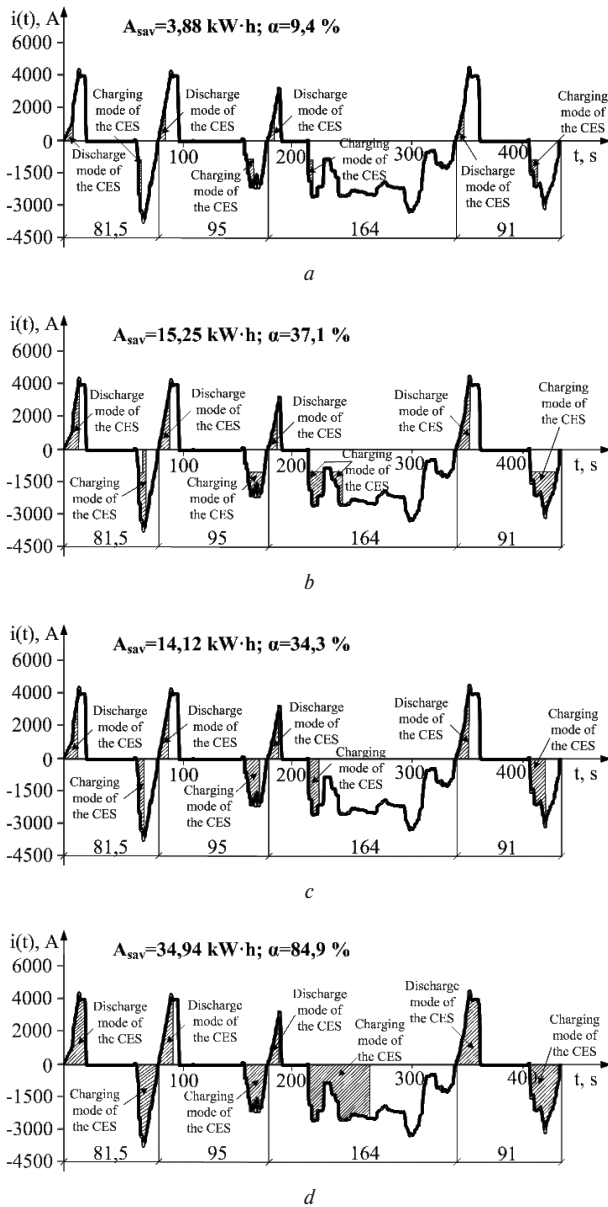


Fig. 6. The behavior of the energy exchange processes under the following conditions:

- a – direct connection of CES with energy intensity of 5 kW · h; b – direct connection of CES with energy intensity of 25 kW · h; c – connection of CES with energy intensity of 5 kW through a static converter of adjustable type; d – connection of CES with energy intensity of 25 kW through a static converter of adjustable type

The analysis of existing research studies [5, 11] allowed us to establish the estimated mass-dimensional parameters of the CES for the above mentioned energy capacities (5 kW · h and 25 kW · h), provided they are directly connected to the electric traction drive and through a static converter of adjustable type. According to the results of this analysis, it is established that the mass-dimensional CES parameters when directly connected are greater by 3.8–4.5 times as compared to the connection through a static converter of adjustable type. In this case, the dimensions of the ESS are smaller by 2.4–3.3 times when the CES is connected through a static converter of adjustable type.

According to the results of the research analysis [11, 12] and our own research studies performed (Tables 3, 4, and Fig. 6) it is established that one of the important and urgent issues is the determination of the necessary parameters of CES, first of all power and energy intensity. The simplest technical solution in this regard is the placement of on-board CES

of considerable power and energy capacity, capable of storing and reusing the full amount of electricity of the regenerative braking of the train during its operation. However, an analysis of existing research indicates that the application of this technical solution is inappropriate in most cases. The main factors stopping and limiting the implementation of CES of significant capacity and energy intensity are the following: sophisticated CES production technology for large voltage values, cost and mass-dimensional parameters. Therefore, taking into account the above mentioned factors, the most reasonable is the implementation of technical solutions, which use systems for the accumulation of low energy and capacity. So, in view of the above, a rather urgent issue is to determine the rational parameters of the energy storage system, first of all CES and the reversible converter of the adjustable type.

Establishment of an energy saving system with rational parameters will allow receiving a minimum payback period from implementation on the electromotive structure of this system.

**Conclusions.** According to the results of a generalized analysis of a considerable amount of existing research in this area of work, as well as the research performed in the work, the following is established:

1. The most rational and energy-saving device for controlling the charge and discharge processes of the CES on the electric rolling stock is a static reversible converter of adjustable type, produced on the basis of power IGBT transistors, with inductive or capacitive power metering devices. Its application will allow obtaining the charge and discharge processes efficiency of 85–94%, to set the value of the dead volume of 5–25% and to reduce the CES mass dimensions by 2.5–4 times compared to the direct connection.

2. For the given conditions of operation of the electric rolling stock the indicative mass-dimensional parameters of the CEN and the efficiency of energy exchange processes were determined under the conditions of direct connection of the CES to the traction motors and through a static reversible converter of adjustable type with the same values of the CES energy intensity. It is established that under conditions of connecting CES to the traction drive through a static reversible converter of adjustable type, the efficiency of energy exchange processes between the CES and the electric traction drive increases by 2.3–3.6 times, and the mass dimensions of the CES in the same working capacity is reduced by 3.8–4.5 times.

3. The problems of using on-board capacitive energy storage devices on the electric rolling stock, which solution will allow increasing its energy efficiency and obtaining the maximum technical and economic effect on this type of transport, are indicated.

4. In the actual operating conditions of a subway train, it is not always appropriate to use CES of considerable power and energy to conserve, store and accumulate the full amount of regenerative braking energy. The main factors stopping and limiting the implementation of on-board CESs of considerable power and energy intensity are production technology, cost and size parameters. Therefore, taking into account these factors, the implementation of technical solutions that use systems of low energy intensity and capacity accumulation is currently the most promising one.

Further research should focus on determining the values of the rational power and energy intensity of the on-board capacitive energy storage devices, taking into account the actual operating conditions of the electric rolling stock with recovery systems.

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### **Аналіз технічних рішень при впровадженні бортових накопичувачів енергії на електрорухомому складі**

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**Мета.** Аналіз існуючих технічних рішень для здійснення керування енергообмінними процесами на тяговому електрорухомому складі з бортовими накопичувачами енергії та пошук оптимального серед них. Дослідження енергообмінних процесів та оцінка кількості заощадженої електроенергії під час застосування різних технічних рішень.

**Методика.** У роботі виконано порівняльний аналіз існуючих технічних рішень із керування енергообмінними процесами на тяговому електрорухомому складі з борто-

вими накопичувачами енергії. Сформульовані переваги й недоліки кожного з існуючих технічних рішень. Визначено характер протікання енергообмінних процесів і здійснена оцінка кількості електроенергії за безпосереднього підключення бортового накопичувача енергії до тягових двигунів і через статичний реверсивний перетворювач регульованого типу для заданих умов експлуатації електрорухомого складу та прийнятих припущень.

**Результати.** Визначено, що найбільш раціональним та енергоефективним пристроєм для керування процесами заряду й розряду бортового накопичувача енергії на електрорухомому складі є статичний реверсивний перетворювач регульованого типу з індуктивними або ємнісними дозаторами електроенергії.

**Наукова новизна.** Набула подальшого розвитку теорія застосування накопичувачів енергії на електрорухомому складі, що, на відміну від існуючих, дозволила визначити кількість заощадженої електроенергії за цикл «рекупераційне гальмування – розгін поїзда» залежно від типу підключення бортового накопичувача енергії та його енергоємності.

**Практична значимість.** Встановлено, що керування енергообмінними процесами в системі накопичення енергії шляхом застосування статичного перетворювача регульованого типу є більш раціональним. Визначено, що, для керування енергообмінними процесами на тяговому електрорухомому складі з бортовими накопичувачами енергії, найбільш раціональним та енергоефективним є використання реверсивного за струмом широтно-імпульсного перетворювача з індуктивним або ємнісним дозатором електроенергії. Отримані результати досліджень можуть бути використані промисловими підприємствами під час проектування та створення інноваційного електрорухомого складу з метою підвищення його експлуатаційних характеристик.

**Ключові слова:** бортовий накопичувач енергії, дозатор електроенергії, енергообмінні процеси, електрорухомий склад, статичний реверсивний перетворювач

### **Анализ технических решений при внедрении бортовых накопителей энергии на электроподвижном составе**

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**Цель.** Анализ существующих технических решений для реализации управления энергообменными процессами на тяговом электроподвижном составе с бортовыми накопителями энергии и поиск оптимального среди них. Исследование энергообменных процессов и оценка количества сбереженной электроэнергии при применении различных технических решений.

**Методика.** В работе выполнен сравнительный анализ существующих технических решений относительно управления энергообменными процессами на тяговом электроподвижном составе с бортовыми накопителями энергии. Сформулированы преимущества и недостатки каждого из существующих технических решений. Определен характер протекания энергообменных процессов и выполнена оценка количества электроэнергии при непосредственном подключении бортового накопителя энергии к тяговому двигателю и через статический реверсив-

ный преобразователь регулируемого типа для заданных условий эксплуатации электроподвижного состава и принятых допущений.

**Результаты.** Определено, что наиболее рациональным и энергоэффективным устройством для управления процессами заряда и разряда бортового накопителя энергии на электроподвижном составе является статический реверсивный преобразователь регулируемого типа с индуктивными или емкостными дозаторами электроэнергии.

**Научная новизна.** Получила дальнейшее развитие теория применения накопителей энергии на электроподвижном составе, которая, в отличие от существующих, позволила определить количество сэкономленной электроэнергии за цикл «рекуперативное торможение – разгон поезда» в зависимости от типа подключения бортового накопителя энергии и его энергоемкости.

**Практическая значимость.** Установлено, что управление энергообменными процессами в системе накопле-

ния энергии путем применения статического преобразователя регулируемого типа является наиболее рациональным. Определено, что, для управления энергообменными процессами на тяговом электроподвижном составе с бортовыми накопителями энергии, наиболее рациональным и энергоэффективным является использование реверсивного по току широтно-импульсного преобразователя с индуктивным или емкостным дозатором электроэнергии. Полученные результаты исследований могут быть использованы промышленными предприятиями при проектировании и создании инновационного электроподвижного состава с целью повышения его эксплуатационных характеристик.

**Ключевые слова:** бортовой накопитель энергии, дозатор электроэнергии, энергообменные процессы, электроподвижной состав, статический реверсивный преобразователь

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