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DEVELOPMENT OF A COMPREHENSIVE APPROACH TO DETERMINING THE RATIONAL PARAMETERS OF AN ONBOARD CAPACITIVE ENERGY ACCUMULATOR FOR A SUBWAY TRAIN

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Одним з ключових і недостатньо вивчених питань за умови впровадження бортових ємнісних накопичувачів енергії в метрополітені є визначення їх раціональних параметрів (потужності та енергоємності). Проаналізовано існуючи методи та підходи щодо вибору параметрів бортових ємнісних накопичувачів енергії. Визначено недоліки для кожного методу та підходу. Обгрунтовано необхідність розробки підходу, який би дозволив в повній мірі врахувати фактори впливу реальних умов експлуатації поїзда метрополітену. Існуючи методи та підходи щодо вибору раціональних параметрів мають недоліки та не враховують в повній мірі фактори реальних умов експлуатації поїзда метрополітену. В цій роботі запропоновано комплексний підхід, який враховує зазначені фактори впливу і дозволяє здійснювати вибір раціональних параметрів бортового ємнісного накопичувача енергії за двома показниками: масою та вартістю системи накопичення. Визначено раціональні параметри бортового ємнісного накопичувача енергії для заданих умов експлуатації поїзда метрополітену з використанням комплексного підходу. Розраховано кількість заощадженої електроенергії за рахунок впроваджень бортового накопичувача з раціональними параметрами. Результати досліджень можуть бути використані під час проектування, створення та впровадження рухомого складу метрополітену з бортовим ємнісним накопичувачем енергії, а також під час експертної оцінки кількості заощадженої електроенергії

Ключові слова: бортовий ємнісний накопичувач енергії, поїзд метрополітену, рекуперативне гальмування, система накопичення

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1. Introduction

Subway is a safe, reliable, environmentally friendly, and economical means of transportation, which accounts for a significant volume of passenger traffic in large cities. The volumes of passenger transportation by subway are constantly growing and outperform municipal transport. Therefore, further development of subways has remained an important task in terms of its practical implementation.

However, there are still numerous unresolved issues related to subway. First of all, these are the problems of developing and renovating subway cars, enhancing energy efficiency, improving resource saving at rolling stock. Thus, the issue of renewal and introduction of modern energy-efficient subway rolling stock is a relevant task that requires timely solution.

2. Literature review and problem statement

The results from a series of theoretical and practical studies [1–5] have proven that the use of capacitive energy accumulators (CEA) at a subway train with the regenerative systems makes it possible to reduce electricity consumption and improve its quality in the network. In addition, the application of CEA could reduce the installed power of power units within an energy supply system (transformers, converters, junction substations, etc.). In this case, the need to implement the onboard CEA in subway has been substantiated in numerous papers both by domestic and foreign researchers [2, 3, 6–8]. Analysis of above studies has made it possible to establish that one of the essential, yet insufficiently investigated, issues related to the implementation of onboard CEA in the subway has been the choice of their rational parameters, first of all, power and energy intensity.

The simplest technical solution in this regard is the arrangement of an onboard CEA of significant power and energy capacity, capable of storing and reusing the full volume of electricity from a train's regenerative braking during its operation [9, 10]. The main factors hindering the implementation of a given technical solution are the cost and size indicators of an onboard CEA. Thus, given the current possibilities and realities of industrial production of CEA, a leading role belongs to technical solutions for the introduction of onboard CEA of low power and energy capacity.

Available studies [3, 12] suggest defining an onboard CEA's parameters based on the estimate of a train's kinetic energy. A given approach implies choosing the parameters for an onboard CEA based on the dependence of the amount of energy from regenerative braking of a train on the speed of braking onset. Such an estimate is quite rough and does not take into consideration a series of factors, specifically the actual conditions of subway train operation (track profile, loading, running schedule, braking force, the existence of electropneumatic braking, etc.).

Papers [13, 14] proposed determining an onboard CEA's parameters under conditions of limiting the current consumption by a traction network. An approach in study [13] implies determining parameters based on the characteristics of operation of a traction induction drive of electric rolling stock. In this case, a given technique involves the application of basic provisions from the theory of electric traction and numerical methods of integration. The disadvantages of this estimation technique are a failure to take into consideration a track profile, running schedule, the presence of electropneumatic braking; in addition, there are restrictions in the field of application. The technique implies determining energy capacity of an onboard CEA only for traction units with an induction electric drive. Work [14] stated a procedure of calculating the required energy capacity of onboard CEA for a specific load schedule. The procedure implies determining the rated power and the required energy consumption of an onboard CEA by numerical integration methods based on the dynamics of electricity consumption. The disadvantage of this technique is that only a single standard cyclic motion mode is taken into consideration, but a specific schedule involves consideration of real operating conditions (track profile, congestion, braking force, etc.).

In studies [15, 16], an onboard CEA's parameters were determined using basic provisions from a probability theory. The main idea of the proposed approach is to determine the parameters according to analysis of the characteristics of power distribution density and the amount of electricity at regenerative braking. This assessment involves the construction of histograms, taking into consideration all the typical operating conditions of a train over a certain period. The disadvantage of this approach is that the choice of parameters is based on the proposed criteria, which do not make it possible to justify determining the rational parameters for an onboard CEA.

Papers [17, 18] suggest determining an onboard CEA's settings by using the theoretical basics of electrical engineering, subject to the conditions, the main of which is that there should be an aperiodic or boundary CEA discharge mode. A major drawback of this approach is the limited scope of application. A given approach implies determining energy capacity of an onboard CEA for traction units with a direct current electric drive of series excitation. Other disadvantages include the impossibility of accounting for real operating conditions and various driving modes of train.

Available studies [19, 20] propose choosing an onboard CE's parameters based on the minimum payback period of accumulation systems. The system of accumulation implies an onboard CEA, a reversible static transducer, and a control system of power exchange processes between the onboard CEA and a traction electric drive. The essence of this approach is to determine the parameters according to the analysis of characteristics (diagrams) of a payback period for the selected accumulation systems depending on their maximum power and energy intensity. The advantage of using this approach is to determine the rational parameters for an onboard CEA. This takes into consideration the real operating conditions of a subway train with regenerative systems. The disadvantage of a given approach is in determining the rational parameters for an onboard CEA based on a single criterion – the payback period.

As mentioned above, the main indicators influencing the choice of rational parameters for an onboard CEA for a subway train are the indicators of cost and weight. However, the specified techniques and approaches do not allow this to be done. Therefore, it is proposed to substantiate the choice of rational parameters using a comprehensive approach that would simultaneously take into consideration the mass and cost characteristics of the accumulation system.

3. The aim and objectives of the study

The aim of this study is to substantiate the choice of rational parameters for an onboard CEA for the predefined operating conditions of a subway train with recuperation systems by using a comprehensive approach that would make it possible to attain an energy saving effect under condition of the practical implementation of an onboard CEA and to estimate the amount of energy saved.

To accomplish the aim, the following tasks have been set:

– to develop a comprehensive approach for determining the rational parameters for an onboard CEA that would make it possible to take into consideration the mass and cost indicators of an accumulation system;

– to define rational parameters for an onboard CEA for the predefined conditions of subway train operation using a comprehensive approach;

– to determine the amount of energy saved for the predefined driving train modes by introducing a system of accumulation with rational parameters.

4. Materials and methods of research in determining the rational parameters of a capacitive energy accumulator for a subway train

4. 1. Methods, materials, and equipment used in research

The following estimation and experimental research methods were used to solve the set tasks:

– theoretical base of electric traction when performing traction calculations;

– experimental study into energy processes under standard operating conditions for a subway train with regenerative systems;

– methods of mathematical statistics to process data from experimental studies;

– methods of technical-economic analysis to estimate the cost of accumulation systems;

– analytic research methods to determine the amount of savings under conditions of implementing the accumulation systems;

– benchmarking methods to define the system of accumulation with rational parameters based on the dependence of a payback period on magnitudes of power and energy intensity.

We studied energy exchange processes at the Svyatoshinsko-Brovarska line of Kp "Kyyivs'kyy Metropoliten" (Ukraine) under standard operating conditions of rolling stock with recuperation systems over 24 hours. The examined rolling stock is a five-car train with an induction traction drive and recuperation systems, in which main cars are motor-free while intermediate ones are driven by motors.

Experimental study into energy processes under standard operating conditions was carried out using an experimental set-up, which includes the above-mentioned rolling stock and a measuring system mounted aboard. The measuring system was designed by specialists from a research group for electric and traction-energy equipment at DP "UkrNDIV" (Ukraine) in order to study energy processes between a contact network and a train under actual conditions of its operation. The measuring system includes: a personal computer, an analog-to-digital transducer, a switching unit, an alignment unit, and measuring sensors. The measuring system implies obtaining, displaying and storing data acquired from the measuring sensors, which are mounted on the examined train.

4. 2. Procedure for determining rational parameters for a capacitive energy accumulator using a comprehensive approach

The proposed comprehensive approach consists of the following stages:

– selection of an operating section and a model of a subway train with recuperation systems;

– implementation of traction calculations in order to determine a possibility to increase the traction effort of a subway train under conditions for ensuring the normalized values of acceleration and deceleration (determining mass limits for an accumulation system based on the analysis of performed traction calculations);

– determining a region of possible power and energy intensity values, taking into consideration the limitations for mass based on the results from analysis of constructed mass-power $m=f(P)$ and mass-energy intensity $m=f(A)$ dependences;

– defining standard regular conditions for driving a train along the assigned track section;

– experimental study into energy processes under typical conditions for driving a subway train according to schedule;

– processing of the obtained data sets and determining the range of change in the power and amount of electricity at regenerative braking;

– choosing onboard CEAs of the predefined level of power and energy intensity, which are in the range of change in power and amount of electricity at a train's regenerative braking taking into consideration the limitations for mass;

– determining the cost of the selected accumulation systems, taking into consideration the operating costs for their service;

– study into the amount of energy saved from the introduction of the selected accumulation systems to a train;

– construction of the characteristic for a payback period of accumulation systems depending on the operating power and energy intensity of onboard CEAs;

– determining the rational power and energy capacity of CEA based on analysis of the above characteristic.

Thus, the essence of a given comprehensive approach is to determine the rational parameters for an onboard CEA, according to the two indicators of the accumulation system – mass and cost. Next, by following this approach, we consider determining the rational power and energy capacity of an onboard CEA for specific operating conditions of rolling stock.

First stage. We have chosen, as an experimental section, the section between terminal stations along the Svyatoshinsko-Brovarska line at KP "Kyyivs'kyy Metropoliten".

Second stage. Traction calculations are based on the principles for selecting a traction power (slowing down), taking into consideration constraints for the maximum engine torque, for wheel clutch with rails, and for traction motors providing for the predefined dynamics of train motion. An algorithm of traction calculations to determine the limitations for mass is shown in Fig. 1.

One calculates the maximally permissible force of traction (deceleration) in terms of torque overload on the motor shaft under the following condition:

$$F_{\max} \leq \frac{2 \cdot M \cdot \mu \cdot \eta_{gear} \cdot N_{TM}}{D}, \quad (1)$$

where M is the maximum torque on the shaft of a traction motor, N·m; μ is the gear ratio; η_{gear} is the gearbox efficiency ratio; D is the wheel's diameter, m; N_{TM} is the number of traction motors, pcs.

Calculation of the maximally permissible traction force (deceleration) in terms of grip between wheels and rails is performed under the following condition:

$$F_{\max} \leq 1000 \cdot G_{grip} \cdot \psi, \quad (2)$$

where G_{grip} is the gravity force (coupling weight), on the train's motored axles, kN; ψ is the estimated value of grip coefficient under normal conditions.

Note. The estimated value for a grip coefficient between a wheel and a rail for a subway train with an induction traction drive under normal conditions is selected at the level of 0.22 according to [21, 22].

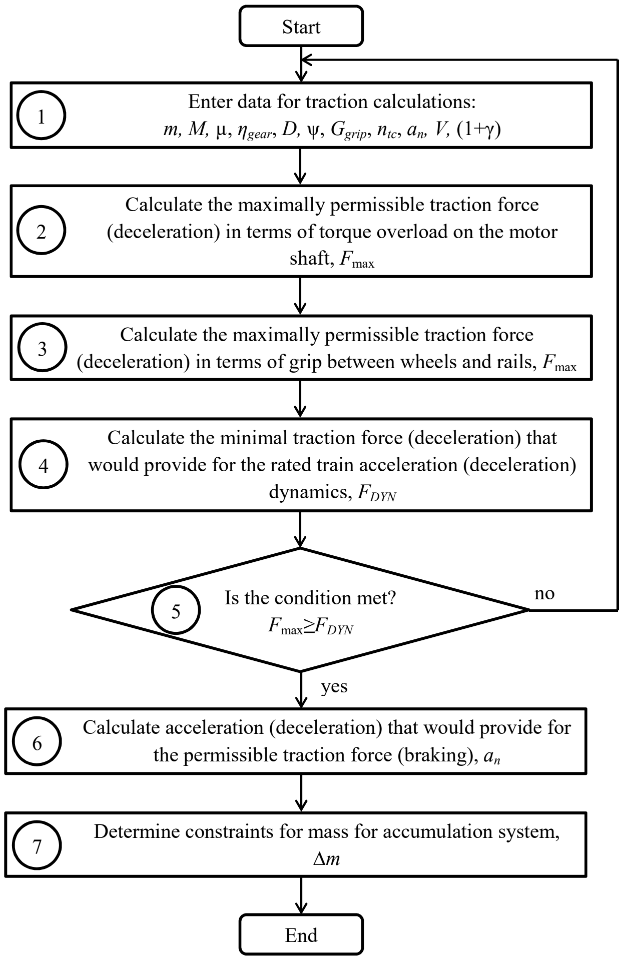

Fig. 1. Traction calculation algorithm

Calculation of the required traction force (deceleration), based on the requirements from normative documentation for intermediate acceleration values (deceleration), is performed under condition [21, 22]:

$$F_{DYN} \geq m \cdot (1+\gamma) \cdot a + W, \quad (3)$$

where M is the mass of a train, kN; $(1+\gamma)$ is the coefficient of inertia of a train's rotating masses; a is the normalized value of acceleration, m/s^2; W is the main resistance to train motion, kN.

Calculation of the main resistance to train motion is performed in line with formula [21]:

$$W = \left(1.1 + \frac{(0.09 + 0.022 \cdot n_{tc}) \cdot V^2}{m}\right) \cdot G, \quad (4)$$

where n_{tc} is the number of train cars, pcs; V is the value of train motion velocity, km/h.

Calculation of the maximum permissible traction force (deceleration) is performed taking into consideration conditions (1) to (3). In case the maximum permissible traction force (deceleration) does not meet any of the above conditions, the arrangement of CEA aboard a train is impossible. In this case, it is necessary to increase the number of motor axles of a subway train, to choose traction engines with other parameters, etc. Otherwise, one calculates the acceleration value (deceleration) that would provide for the permissible traction force in line with formula:

$$a_n = \frac{F_{max} - W}{m \cdot (1+\gamma)}. \quad (5)$$

In this case, calculation involves a less value of the permissible traction force ($F_{max} \rightarrow \min$), based on the specified conditions (1) and (2).

One determines the limitations for mass from formula:

$$\Delta m \leq \frac{F_{max} - F_{DYN}}{a \cdot (1+\gamma)}. \quad (6)$$

Third stage. One constructs the dependences of mass on power $m=f(P)$ and mass on energy capacity $m=f(A)$ taking into consideration the defined constraints for the system of accumulation in terms of mass. One constructs a family of characteristics and determines the maximum possible values of power and energy capacity depending on the types of the selected capacitor modules. In this case, under conditions of constructing a family of curves, one accepts minimum values for, accordingly, energy capacity and power for the accumulation system. Taking into consideration the constraints for mass, one determines the region of possible power and energy intensity values.

Fourth stage. We adopted the following typical operating conditions for a subway train:

– on workdays (5 days per week), three and two full circles in line with a "non-peak" schedule under nominal and maximum loading, respectively. One and two full circles in line with a "peak" schedule under nominal and maximum loading, respectively. One full circle in line with a "non-peak" schedule under minimal loading;

– on weekends (2 days per week), two, seven, and one full circle in line with a "non-peak" schedule under minimum, nominal, and maximum loading, respectively.

Standard operating conditions for a subway train were obtained based on the schedule of trains at KP "Kyyivs'kyy Metropoliten" over the period of 2017–2018; in this case, summer and winter timetables of trains were taken into consideration.

It is accepted that over the year a train operates 315 days, of which 225 are workdays and 90 weekends.

The fifth stage, which implies experimental study into energy processes under standard operating conditions, is executed by using the above-specified experimental set-up.

The sixth stage implies processing data arrays. Data are processed on a personal computer that is equipped with certified software.

Based on the results of processing the data arrays obtained under standard operational conditions of rolling stock with regenerative systems, the following indicators are determined:

– the mean value of contact network voltage under traction and regenerative braking modes (U_{mvtrac}, U_{mvreg});

– the mean value of current under a train's traction modes (I_{mvtrac});

– the mean value of current generated by a train to the contact network during regenerative braking (I_{mvreg});

– the mean value of voltage on braking resistors (U_{mvbr});

– the mean value of current dissipated as heat on braking resistors under the mode of regenerative braking (I_{mvbr});

– the motion time under traction and regenerative braking modes (t_{trac}, t_{reg});

– the mean operating speed along a section ($V_{mvopspd}$).

Based on the values of magnitudes determined in the process of data arrays processing, the following energy indicators are calculated:

– the amount of electricity spent under traction modes (A_{trac});

– the amount of electricity generated by a train at regenerative braking (A_{reg});

– maximum power under regenerative braking modes (P_{max}).

The amount of electricity consumed under traction modes is calculated from formula [21, 22]:

$$A_{trac}=\frac{U_{mvtrac}\cdot I_{mvtrac}\cdot t_{trac}}{3600\cdot 1000}. \quad (7)$$

The amount of electricity generated by a train during regenerative braking is calculated from formula [15, 21]:

$$A_{reg}=\frac{U_{mvreg}\cdot I_{mvreg}\cdot t_{reg}}{3600\cdot 1000}+\frac{U_{mvbr}\cdot I_{mvbr}\cdot t_{reg}}{3600\cdot 1000}. \quad (8)$$

The train's instantaneous capacity for regenerative braking modes is determined from expression [15]:

$$p(t)=u(t)\cdot i(t). \quad (9)$$

Maximum power of regenerative braking is determined based on the maximum recorded value of instantaneous power during the regenerative braking of the train:

$$\begin{bmatrix} p_1 \\ p_2 \\ \dots \\ p_n \end{bmatrix}\rightarrow P_{\max}. \quad (10)$$

At the *seventh stage*, onboard CEAs are selected with the specified level of power and energy intensity according to the analysis of results from processing the acquired data sets during experimental study.

At the *eighth stage*, one estimates the cost of accumulation systems based on the results from analysis of the cost of selected on-board CEAs, reverse converters, and other equipment from the manufacturers of these products.

The ninth stage is to estimate the amount of energy saved as a result of the implementation of the selected accumulation systems. Study is performed for each type of the selected system. First, for each standard operating condition and selected accumulation system, one checks constraints for capacity, the results of which, if necessary, could be the base for recalculating the amount of electricity recuperated to the accumulator. Next, one estimates the amount of energy saved, taking into consideration the constraints for energy intensity by using the subprogram "Energy Recovery". The algorithm of the above sub-program is described in detail in paper [23]. The simplified algorithm for performing these studies is shown in Fig. 2.

In our study into the estimation of the amount of electricity saved, the following assumptions were accepted:

– the device is completely discharged before the calculations;

– efficiency of the accumulator is 0.98 (η_{CEA}=0.98);

– efficiency of the reversible converter is 0.96 (η_{REVC}=0.96);

– efficiency of the traction motor is 0.94 (η_{TM}=0.94);

– gearbox efficiency is 0.98 (η_{GEAR}=0.98).

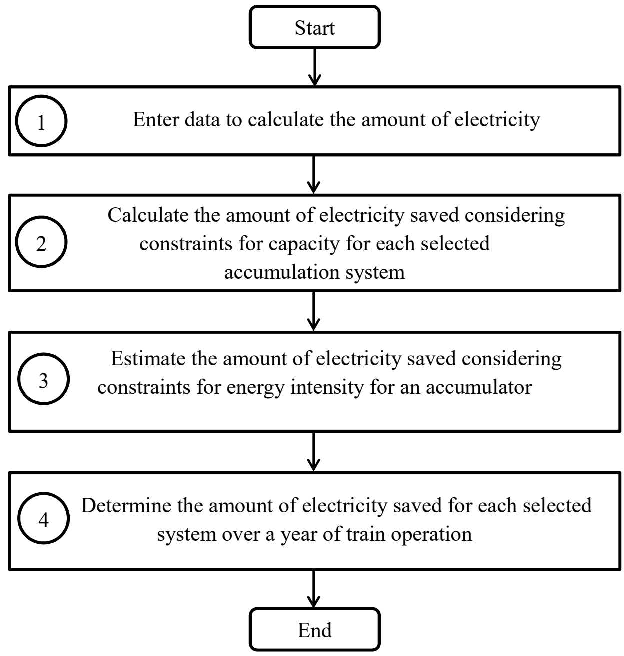

Fig. 2. Algorithm to study the estimation of the amount of electricity saved

The following indicators were determined in the course of research:

– the amount of electricity saved over a cycle of energy saving (regenerative braking and its accumulation at train acceleration);

– the amount of electricity saved for each standard operating condition;

– the amount of electricity saved in one day and over a year.

The amount of energy saved over the cycle regenerative braking-train acceleration is determined from formula [23]:

$$E=A_{reg}\cdot\eta_{trac}, \quad (11)$$

where $\eta_{trac}=\eta_{CEA}\cdot\eta^2_{REVC}\cdot\eta_{TM}\cdot\eta_{GEAR}$ are the efficiency of energy exchange processes over the cycle of saving and accumulation of recovery electricity.

The amount of energy saved for each standard operating condition is determined from formula [23]:

$$E_k=E_1+E_2+\dots+E_N, \quad (12)$$

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

The amount of energy saved in one day is determined from formula [23]:

$$E_d=m_1\cdot E_{k1}+m_2\cdot E_{k2}+\dots+m_n\cdot E_{kn}, \quad (13)$$

where m is the number of circles per day for a standard condition of train operation; n is the number of standard operating conditions of the train.

The amount of energy saved over a year is determined from formula [23]:

$$E_r=l_1\cdot E_{d1}+l_2\cdot E_{d2}, \quad (14)$$

where l_1, l_2 is the number of working and weekend days; E_{d1}, E_{d2} is the amount of energy saved on a workday and on a day-off, respectively.

The tenth stage implies the construction of a characteristic (diagrams) of the payback period of accumulation systems, depending on the operating power and power consumption by onboard CEAs. The magnitude for a payback period is determined from the ratio of cost from the introduction of a system of accumulation to the cost of electricity saved by this system over a year

$$T_{ок} = \frac{Q}{T_e \cdot E_r}, \quad (15)$$

where Q is the cost of an accumulation system; T_e is the tariff for electricity (T_e=0.0788 USD/kWh).

Eleventh stage. According to the results from an analysis of charts for a payback period of the selected accumulation systems, one determines a system with rational parameters.

In order to implement an accumulation system with rational parameters, we calculated the amount of saved electricity in line with formula [21]:

$$\alpha = \frac{E_r}{A_{trac(year)}} \cdot 100, \quad (16)$$

where $A_{trac(year)}$ is the amount of electricity consumed per year, kWh.

5. Results of research into determining the rational parameters for an onboard capacitive accumulator

Acting regulatory document [24] sets the requirements to the dynamics of acceleration (braking) of a subway train. According to this document, the acceleration of a train to a speed of 33 km/h must provide for the mean acceleration of not less than 1.2 m/s^2. At train braking from the speed of 90 km/h, the mean deceleration not less than 1.15 m/s^2 under condition of its rated loading. Given that the examined subway train is equipped with a combined braking (a combination of electric and pneumatic), it is important to ensure the normalized acceleration. Thus, traction calculations were performed to check the condition for ensuring the acceleration of the train.

There are the following parameters of traction induction motors (TIM), installed on a modernized subway train: P_n=150 kW; U_n=610 V; I_n=185 A; n_n=1,900 rpm; f_n=65 Hz; M=2.21 kN·m. Parameters for traction transmission and a subway train: D=0.825 m; η_{GEAR}=0.975; μ=6.95; m=238.7 t (rated loading); G_{grip}=1.44 kN; (1+γ)=1.06; a=1.2 m/s^2.

Results of traction calculations in line with formulae (1) to (6) are given in Table 1.

Table 1

Results of traction calculations

Parameter	Value
F_{max} from formula (1), kN	≤436
F_{max} from formula (2), kN	≤317
F_{DYN}, kN	≥307
W, kN	2.9
a_n, m/s^2	1.24
Δm, t	7.86

The region of possible values of power and energy intensity is determined under conditions of using the accumulation systems, assembled on the basis of capacitor modules made by ZAT ELTON (Russia). Specifications of capacitor modules the type of EK303, EK404, EK406, EK503 are given in Table 2.

Table 2

Technical characteristics of capacitor modules

Indicator title	Capacitor module type			
	EK303	EK404	EK406	EK503
Working voltage, V	1.5–0.75	1.5–0.75	1.5–0.75	1.5–0.75
Capacitance, F	45,000	12,000	8,800	7,200
Total (maximum) amount of energy an accumulator can store, kJ	50.6	12.6	9.3	7.6
Energy stored in the operating voltage range, kJ	38.0	10.1	7.4	6.1
Internal resistance, mOhm	2.0	0.4	0.4	0.4
Mass, kg	3.4	0.9	1.0	1.0
Dimensions, mm	51×18×250	84×32×210	84×32×210	84×32×148
Maximum power, kW	2.8	1.4	1.4	1.4
Working temperature, °C	–50...+70	–50...+60	–50...+65	–50...+70

We constructed the families of characteristics taking into consideration the accepted conditions (at construction of dependence $m=f(P)$ the minimum value of energy intensity was accepted as 1 kWh; at construction of dependence $m=f(A)$ the minimum power value was 500 kW). Based on the results of determining the constraints for mass, we constructed the dependences of mass on power $m=f(P)$ and mass on energy capacity $m=f(A)$, shown in Fig. 3. In this case, the accumulation systems of required value of working voltage, power, and energy intensity, were formed by the sequential-parallel connection of these capacitor modules. The mass of an accumulation system was calculated taking into consideration the mass of capacitor modules (an accumulator), controlled transducer, a metallic structure, connecting wires (buses), the current and voltage sensors, the cooling system and control system elements, as well as other additional materials.

The results from analysis of graphs (Fig. 3) helped establish the regions of possible values for power and energy intensity, taking into consideration the constraints for mass. Specifically, for an accumulation system with a working voltage of 450–900 V, assembled from capacitor modules the type of EK303, the maximum permissible value for power and energy intensity should not exceed 3.36 mW and 12.67 kWh. For that from modules the type of EK 404, it should not exceed 6.8 mW and 12.9 kWh. For that from modules the type of EK406, it should not exceed 6.0 mW and 6.2 kWh. For that from modules the type of EK503, it should not exceed 6.0 mW and 7.1 kWh.

Using a measuring system with the frequency of 2.5 kHz, we acquired the oscillographs of a contact network voltage (on the current-collector), current, the speed of train motion under its standard operation conditions. At each experimental travel, we registered, as data arrays, the dynamic and energy indicators of the train. The data array was formed from the instantaneous values for the indicators acquired at a specific frequency of data registration using a measuring system. The instantaneous values were treated using the methods of mathematical statistics and a probability theory.

The results from processing data arrays obtained using a measuring system are given in Table 3.

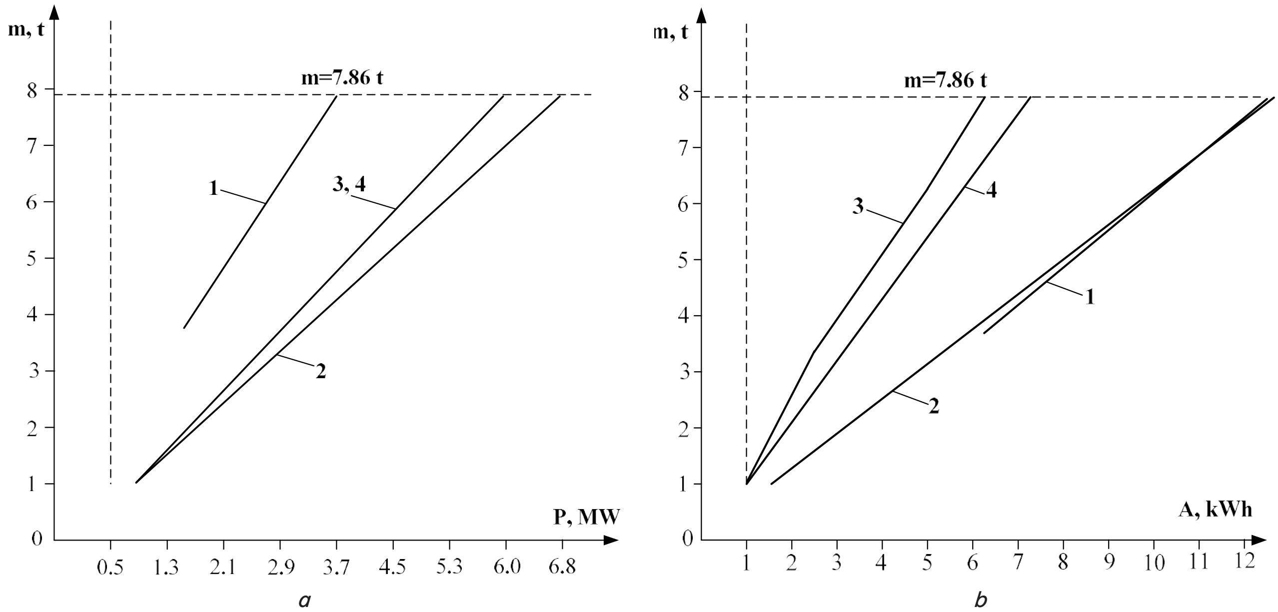

Fig. 3. Dependence of power and energy intensity taking into consideration the constraints for mass of accumulation systems, assembled from capacitor modules of the type (1 — EK303; 2 — EK404; 3 — EK406; 4 — EK503): *a* — dependence of mass on power; *b* — dependence of mass on energy intensity

Table 3

Results from processing data arrays

Examined section	«Non-peak» schedule minimum/rated/maximum train load			«Peak» schedule rated/maximum train load		
	A_{trac}, kWh	A_{reg}, kWh	P_{max}, mW	A_{trac}, kWh	A_{reg}, kWh	P_{max}, mW
1	2	3	4	5	6	7
Lisova–Chernihivs'ka	7.17/9.68/8.46	2.84/4.76/5.33	1.45/1.8/2.41	12.28/14.6	8.5/10.06	3.88/2.5
Chernihivs'ka–Darnytsya	6.45/10.48/11.11	3.5/2.7/4.1	1.12/1.24/2.12	15.34/15.92	6.27/7.67	2.43/2.09
Darnytsya–Livoberezhna	7.89/16.44/8.98	3.08/1.23/3.49	1.14/1.42/1.66	13.65/13.63	6.07/6.65	2.44/1.97
Livoberezhna–Hidropark	7.35/15.24/9.8	3.11/4.18/5.93	1.96/1.67/2.7	14.26/18.68	8.59/10.51	2.46/2.72
Hidropark–Dnipro	13.61/22.82/21.81	2.02/2.43/6.75	1.22/1.25/2.1	23.71/23.52	8.29/8.07	2.49/2.22
Dnipro–Arsenal'na	3.64/4.63/3.48	5.88/9.68/8.97	2.06/3.03/3.36	3.38/2.28	8.45/8.22	2.37/2.36
Arsenal'na–Khreshchatyk	8.76/12.03/12.77	2.35/4.49/4.89	0.99/1.56/2.31	13.92/13.94	4.59/6.87	3.05/2.21
Khreshchatyk–Teatral'na	4.87/8.18/8.25	2.02/4.17/4.11	0.83/1.33/1.74	11.06/14.18	5.29/7.69	1.87/2.53
Teatral'na–Universytet	5.91/8.14/9.2	2.25/3.21/4.14	0.87/1.18/2.023	11.3/13.55	3.64/5.42	1.18/2.73
Universytet–Vokzal'na	6.22/8.47/9.85	1.84/3.02/3.89	0.74/1.15/1.74	9.3/14.45	3.15/6.54	1.04/3.06
Vokzal'na–KPI	10.84/16.19/16.75	3.33/4.76/4.74	1.02/1.79/2.31	14.4/20.53	2.98/6.48	1.13/2.19
KPI–Shulyavs'ka	8.68/11.67/13.05	2.66/3.41/4.75	0.95/1.45/2.06	15.78/18.37	4.44/7.31	1.26/2.66
Shulyavs'ka–Beresteys'ka	52.39/78.21/81.31	3.48/4.08/4.29	1.18/1.38/1.68	79.27/84.09	3.51/5.52	1.18/1.9
Beresteys'ka–Nyvky	8.81/11.96/17.68	3.19/7.16/9.04	1.76/2.51/3.07	15.78/21.82	7.36/11.64	2.15/3.71
Nyvky–Svyatoshyn	9.07/13.61/13.69	2.44/3.64/3.76	0.83/1.07/1.78	13.15/9.66	3.36/3.26	1.07/2.48
Svyatoshyn–Zhytomyrs'ka	5.34/7.83/6.25	6.16/9.75/8.69	1.7/2.8/2.85	6.04/11.95	8.55/12.26	2.18/3.44
Zhytomyrs'ka–Akademmistechko	1.65/2.63/2.88	1.82/2.44/3.1	0.58/0.91/1.1	4.98/4.15	4.34/3.67	1.77/1.3
Akademmistechko–Zhytomyrs'ka	15.17/22.04/19.03	3.61/5.54/3.78	1.14/2.02/1.68	24.22/25.22	6.75/7.35	3.05/2.67
Zhytomyrs'ka–Svyatoshyn	14.45/24.63/24.56	2.87/3.94/3.47	0.93/1.26/1.73	24.14/25.92	7.05/4.02	1.24/1.84
Svyatoshyn–Nyvky	6.31/10.48/8.47	4.31/8.04/6.46	2.03/3.11/3.04	14.15/12.05	10.18/7.68	2.84/2.57
Nyvky–Beresteys'ka	11.07/11.43/13.39	5.22/5.44/6.35	2.1/1.72/2.94	15.5/17.85	7.01/8.67	2.35/2.9
Beresteys'ka–Shulyavs'ka	4.94/5.14/5.11	25.3/44.26/45.93	2.68/2.76/3.34	4.69/5.72	44.35/45.36	2.14/3.84
Shulyavs'ka–KPI	7.53/14.01/11.78	2.28/8.2/6.6	1.54/2.46/2.93	9.28/17.83	5.19/9.86	1.72/3.38
KPI–Vokzal'na	11.07/14.76/15.21	1.76/5.39/5.0	0.7/1.29/1.31	14.85/16.2	5.01/6.35	1.27/1.29

Continuation of Table 3

1	2	3	4	5	6	7
Vokzal'na–Universytet	6.86/8.04/8.15	1.9/2.33/2.53	0.64/0.78/0.91	8.08/10.44	2.15/3.89	0.72/1.82
Universytet–Teatral'na	5.81/8.67/7.94	2.57/3.21/2.7	0.6/0.99/0.81	8.18/10.39	2.35/3.97	0.76/1.44
Teatral'na–Khreshchatyk	6.01/6.7/8.14	1.06/0.95/2.13	0.74/0.55/0.65	11.44/12.93	4.14/5.49	1.44/1.89
Khreshchatyk–Arsenal'na	11.05/12.76/13.83	2.99/3.38/5.0	0.93/1.9/1.82	12.58/13.88	3.34/4.83	0.78/1.57
Arsenal'na–Dnipro	15.76/22.94/23.13	2.6/4.57/4.5	1.31/2.21/2.48	22.42/22.32	4.35/3.78	1.4/1.63
Dnipro–Hidropark	9.87/13.61/10.49	6.27/11.93/9.86	1.85/2.17/2.76	13.1/15.91	11.21/13.69	2.76/3.11
Hidropark–Livoberezhna	8.71/12.6/15.07	2.55/2.78/4.66	0.88/1.3/1.99	13.1/17.75	3.12/5.64	0.95/1.96
Livoberezhna–Darnytsya	7.32/10.44/9.96	3.69/5.69/5.42	0.94/1.39/2.4	12.45/12.83	7.21/7.1	1.82/1.87
Darnytsya–Chernihivs'ka	9.91/12.68/11.52	4.6/2.08/6.13	1.51/1.11/2.22	11.34/11.0	5.91/5.19	2.02/2.59
Chernihivs'ka–Lisova	8.36/14.99/11.83	1.77/2.72/3.4	1.09/1.38/0.98	16.28/15.4	6.3/6.0	1.51/3.02

The results from processing data on each regenerative braking (Table 3) demonstrate that the value of maximum electricity power varies from 0.47 mW to 3.88 mW, the amount of electricity – in the range from 0.58 kWh to 45.93 kWh. Based on the obtained range of change in data, and taking into consideration the constraints for mass, we have selected for further calculations, depending on the type of capacitor modules, the onboard CEAs with the level of power and working energy capacity shown in Table 4.

Table 4

Selected parameters for onboard CEAs

Capacitor module type	Power, mW	Energy intensity, kWh
EK303	2; 3	7; 8; 9; 10; 11; 12
EK404	1; 2; 3; 4	1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 11; 12
EK406	1; 2; 3; 4	1; 2; 3; 4; 5; 6
EK503	1; 2; 3; 4	1; 2; 3; 4; 5; 6; 7

Thus, the total number of the selected onboard CEAs with varying levels of power and energy intensity in this case for the systems of accumulation assembled from capacitor modules the type of EK303 is 12; the type of EK404 – 48; the type of EK406 – 24; the type of EK503 – 28.

The cost of the selected accumulation systems based on the cost analysis of the selected onboard CEAs, reverse converters, and other equipment, is given in Table 5. Our analysis has made it possible to establish that the cost of an accumulation system mainly depends on the price of onboard CEA and a reverse converter while other completing equipment has a much lower price. In general, the difference in the cost of capacitor modules of various types made by ZAT "ELTON" is insignificant. Specific cost of the selected accumulation systems depending on their power and the type of capacitor modules applied is at the level of 25.6–108 thousand USD per 1 kWh.

By using the above algorithm (Fig. 2) and applying formulae (5) to (8), we determined the amount of electricity saved as a result of implementing the selected accumulation systems. Results from estimating the amount of energy saved per year for each selected accumulation system are given in Table 6.

Results from the payback period calculation for the selected accumulation systems are depicted in the form of diagrams in Fig. 4.

Table 5

Cost of the selected accumulation systems

Power, kW	Cost considering different working energy intensity of onboard CEAs [kWh], thousand USD											
	1	2	3	4	5	6	7	8	9	10	11	12
EK303												
2,000	–	–	–	–	–	–	180	208	236	272	304	340
3,000	–	–	–	–	–	–	216	248	280	312	348	388
EK404												
1,000	40	72	100	124	148	172	196	220	240	260	284	312
2,000	60	92	120	144	168	196	220	244	268	288	312	340
3,000	80	112	140	164	188	220	244	268	296	316	340	368
4,000	100	132	160	184	208	244	268	292	324	344	368	396
EK406												
1,000	44	76	104	128	152	172	–	–	–	–	–	–
2,000	64	100	128	148	172	200	–	–	–	–	–	–
3,000	84	120	148	168	192	220	–	–	–	–	–	–
4,000	104	140	168	188	212	248	–	–	–	–	–	–
EK503												
1,000	52	80	108	132	156	180	208	–	–	–	–	–
2,000	68	108	136	152	176	204	236	–	–	–	–	–
3,000	88	128	156	172	196	224	256	–	–	–	–	–
4,000	108	148	176	192	216	252	280	–	–	–	–	–

Table 6

Amount of electricity saved over a year

Power, kW	Amount of saved electricity taking into consideration different working energy intensity of onboard CEAs [kWh], million kWh											
	1	2	3	4	5	6	7	8	9	10	11	12
1,000	0.08	0.16	0.23	0.27	0.29	0.3	0.3	0.31	0.31	0.31	0.32	0.32
2,000	0.08	0.16	0.23	0.28	0.32	0.35	0.36	0.38	0.38	0.39	0.4	0.4
3,000	0.08	0.16	0.23	0.28	0.32	0.35	0.37	0.38	0.39	0.4	0.41	0.41
4,000	0.08	0.16	0.24	0.28	0.32	0.35	0.37	0.38	0.39	0.4	0.41	0.41

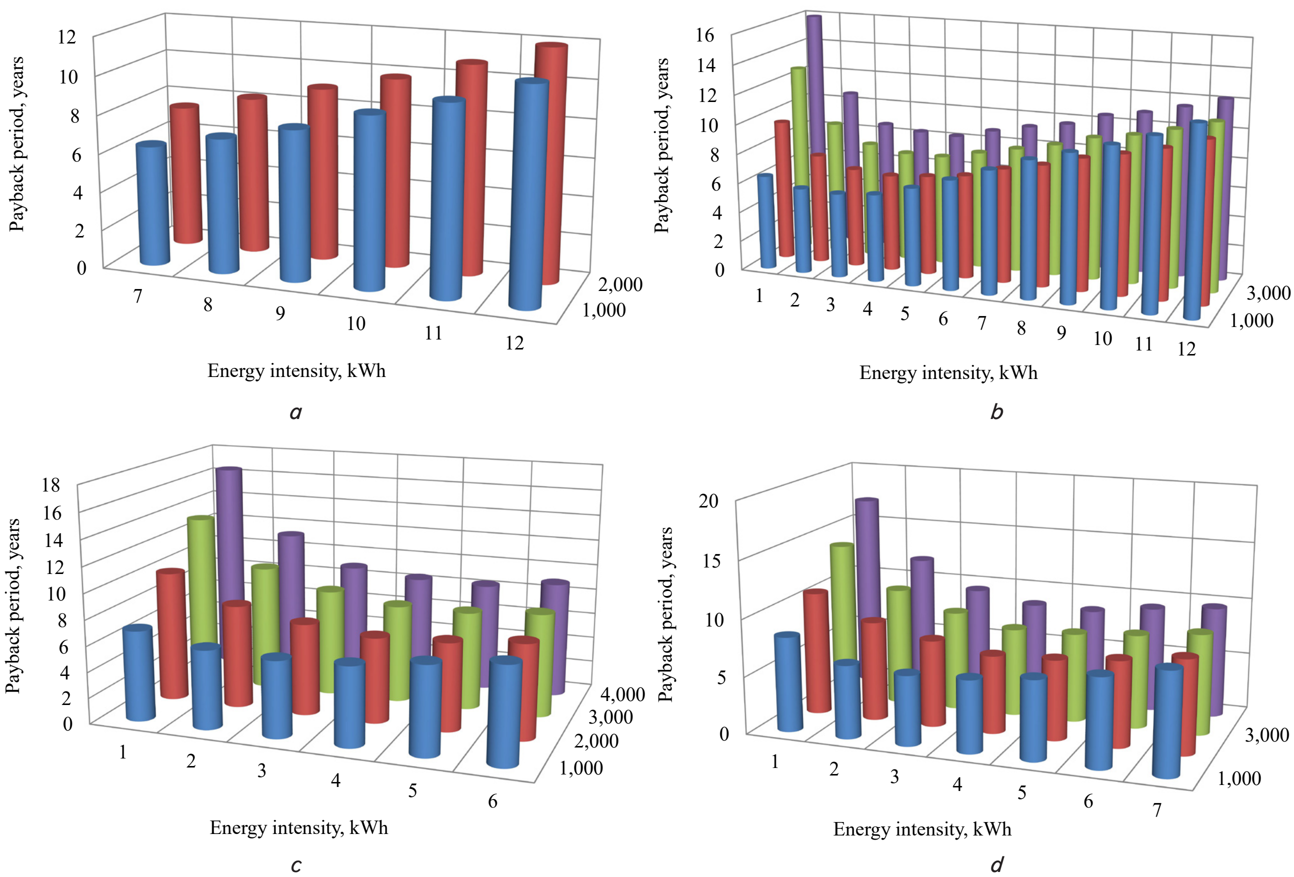

Fig. 4. Payback period diagrams for the selected accumulation systems, assembled from capacitor modules the type of: *a* – EK303; *b* – EK404; *c* – EK406; *d* – EK503

By applying formula (10) it was determined that for the assigned operating conditions the implementation of an accumulation system with rational parameters of the onboard CEA would make it possible to save 16.1 % of the volume of electricity consumed for traction.

6. Discussion of results from studying the rational parameters for an onboard CEA

Cost analysis of the selected accumulation systems (Table 5) has made it possible to establish that its main component is the price of an onboard CEA and a reverse converter. The difference in the cost of capacitor modules of various types made by ZAT ELTON is insignificant.

It should be noted that the proposed approach implies the research into determining rational parameters for onboard systems of accumulation with various technical characteristics, including a possibility to analyze the systems assembled from onboard CEAs made by different manufacturers.

Further study should address determining a payback period of the accumulation systems assembled from capacitor modules produced by other manufacturers (Maxwell, Epcos, Nesscap, YUNASKO, etc.). In this case, it is necessary to carry out a comparative analysis of cost indicators for an accumulation system assembled from capacitor modules by different manufacturers.

Results from analysis of diagrams (Fig. 4) established the following:

– among the selected accumulation systems under the assigned operating conditions for a subway train, the most rational system is the system whose magnitude of working energy intensity is 3 kWh and whose maximum power is 1 mW, assembled from capacitor modules such as EK404.

The payback period of this system is minimal and is 5.7 years; its mass is about 1.5 tons;

– the maximum payback period is demonstrated by the system whose magnitude of working energy intensity for an onboard CEA is 1 kWh and whose maximum power is 4 mW, assembled from capacitor modules such as EK503. The payback period of this system is about 17 years;

– the dynamics of change in the payback period of accumulation systems is quadratic in character under conditions of an increase in the magnitude of energy intensity and at the constant value of maximum permissible power. The payback period of most systems increases linearly under conditions of an increase in maximum power at the steady values of energy intensity.

In a given case, the total number of the selected accumulation systems with different levels of power and energy intensity of onboard CEAs was 112. Among them, the accumulation systems assembled of capacitor modules the type of EK304 – 12; EK404 – 48; EK406 – 24; EC503 – 28. This is enough for us to determine for the assigned operating conditions a system with rational parameters. For a more accurate determination of the rational parameters, it is necessary during calculations to choose a greater number of onboard CEAs with different levels of power and energy intensity. And this in turn would increase the volume and execution time of such studies.

Further research must focus on the construction of mathematical models, which would make it possible to determine the traffic parameters for a subway train under the predefined conditions to drive it. In this case, a compulsory component is to verify these models by comparing results from studies obtained when using the developed mathematical models and in the process of experimental research (correlation of data). A transition from experimental to theoretical determination of the parameters for train motion using mathematical models could greatly reduce the cost and improve the functionality of undertaking such a research. Specifically, it would become possible to take into consideration the loading and unloading of passengers at each station (such a possibility is ruled out during experimental research).

7. Conclusions

1. A comprehensive approach has been proposed to determine the rational parameters for an onboard CEA in a subway train, which makes it possible to take into consideration the mass and cost indicators of an accumulation system. Based on the suggested approach, we have determined the rational parameters for an onboard CEA (maximum power and working energy intensity) for the predefined conditions of subway train operation with recuperation systems.

2. The results of our study have established that for the assigned modes of train drive it is rational to use an accumulation system with an onboard CEA, whose working energy intensity is 3 kWh and whose maximum power is 1 mW. It was determined that the payback period of this system is 5.7 years; its mass is 1.5 tons.

3. The implementation of an accumulation system with rational parameters for the assigned operating conditions could save 16.1 % of the volume of electricity consumed for traction.

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