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ON THE QUESTION OF A REASONABILITY OF CAPACITIVE STORAGES USE IN THE METRO

A. Sulym
State Enterprise “Ukrainian Car-building Institute”
vul. I. Prikhodka, 33, Kremenchuk, 39621, Ukraine. E-mail: sulim1.ua@gmail.com

Installation reasonability of capacitive storages on the output of railway substations, which supply power to lines “Khreschatik–Teatralna” and “Shulyavska–Beresteyska”, and on a metro railway rolling stock taking into account its operating conditions on Svyatoshinsko-Brovarska line of the public utility company “Kiev metro” was considered. According to results of experimental data and performed calculations, annual economic effect of capacitive storages use as well as their payback period was defined. Calculations results analysis allowed determining that from economical point of view it is more reasonable to install capacitive storages on railway substation outputs. From all analyzed cases the most effective is to install the capacitive storages on the output of the traction substation that provides energy for the running line “Khreschatyk–Teatralna”.

Key words: residual restored energy, capacitive storage.

ДО ПИТАННЯ ДОЦІЛЬНОСТІ ВИКОРИСТАННЯ ЄМНІСНИХ НАКОПИЧУВАЧІВ ЕЛЕКТРОЕНЕРГІЇ В МЕТРОПОЛІТЕНІ

А. О. Сулим
Державне підприємство «Український науково-дослідний інститут вагонобудування»
вул. І. Приходька, 33, м. Кременчук, 39621, Україна. E-mail: sulim1.ua@gmail.com

Розглянуто доцільність установлення ємнісних накопичувачів електроенергії на виході тягових підстанцій, що забезпечують живленням перегони «Хрещатик–Театральна» та «Шулявська–Берестейська», а також на рухомому складі метрополітену з урахуванням його умов експлуатації на Святошинсько-Броварській лінії комунального підприємства «Київський метрополітен». За результатами експериментальних даних та виконаних розрахунків визначено річний економічний ефект від застосування ємнісних накопичувачів електроенергії та їх термін окупності. Аналіз результатів розрахунку дозволив установити, що з економічної точки зору більш раціональним є встановлення ємнісних накопичувачів електроенергії на виході тягових підстанцій. Із розглянутих варіантів найбільш ефективним є встановлення ємнісних накопичувачів електроенергії на виході тягової підстанції, що забезпечує живленням перегін «Хрещатик–Театральна».

Ключові слова: надлишкова електроенергія рекуперації, ємнісний накопичувач електроенергії.

PROBLEM STATEMENT. One of the important links in the modern transport infrastructure of megacities is underground, which has the largest transportability capabilities in comparison with other forms of public transport. However, the subways are powerful energy consumers. The energy-saving problem of subway becomes more urgent with the continuous increase in the cost of energy resources. Today priority is to save electricity that is consumed with subway rolling stock, as its part is about 70 % of total energy consumption in the subway [1].

Analysis of the increasing energy efficiency problems of the subway showed the possibility of their solutions through the use of regenerative braking power [1–5]. It is known that the use of regenerative braking can save a significant portion of electricity [1–11]. Thus, efficiency of the regenerative power will depend on the following factors: availability of power consumers in the area of traction substation, the motion mode of other consumers, grading of track on the area [1, 5]. Consequently use of regenerative energy has probable character in the existing infrastructure on the Ukrainian subways [5].

One of the promising ways to use the regenerative energy in full is to use capacitive storages [2, 9–18]. The use of regenerative braking with a capacitive storage can save a considerable part of the electricity through the use of the remaining regenerative energy in the absence of consumers in the contact network.

From the electrical circuits analysis of the traction power system found that capacitive storages can be installed in front of the traction substation on the AC side, on the output of traction substation and directly on the subway rolling stock As known from the works [16–20], the most rational is the establishment of the capacitive storages on the output of a traction substation and directly on the subway rolling stock, so later in the article, we consider these installation options. The feasibility for the use of capacitive storage including the cost of installation and possible energy savings at their expense is relevant and important issue.

The purpose of the work is the technical and economic advisability of using capacitive storages by their installation on the output of a traction substation and directly on the subway rolling stock.

EXPERIMENTAL PART AND RESULTS OBTAINED. This article examines the feasibility of capacitive storage installation on the output of traction substations that provide the running lines “Khreschatyk–Teatralna”, “Shulyavska–Beresteyska” with the power. The feasibility of the capacitive storages installation on a subway rolling stock is considered taking into account its operation conditions on Svyatoshinsko-Brovarska line public utility company

(PUC) “Kyiv Metro”. The choice of these running lines is based on the track grading diverse and distance between stations in these areas. Grading of track on the running line “Khreschatyk–Teatralna” is relatively flat area minor length, the running line “Shulyavska–Beresteyska” has long difficult grading of considerable length on the one hand and the relatively long difficult ascent of considerable extent, on the other. As a result, there are different technical and economic effects from the use of capacitive storage on these running lines.

Modernized five-car electrical train, produced by PJSC "KVSZ" is accepted as an experimental rolling stock operated on Sviatoshinsko-Brovarska line.

The data obtained experimentally on a moving subway electrical train according to the schedule of Svyatoshinsko-Brovarska line are used to assess the possible energy savings through the use of capacitive storage. In the calculation the schedule of subway electrical trains for 2014 is taken into account.

During operation of subway trains on the running lines “Khreschatyk–Teatralna” and “Shulyavska–Beresteyska” the next time-interval of their movement at different times of day is given for calculation:

– on working days (5 days per week): from 5:30 to 6:30 time-interval of movement consists of 10 pairs of trains/hour with minimal loading; from 6:30 to 8:00 time-interval of movement is 16 pairs of trains/hour with nominal loading; from 8:00 to 11:00 it consist of 36 pairs of trains /hour in summer time and 40 pairs trains/hour in winter time with maximum loading; from 11:00 to 17:00 – 16 pairs of trains/hour in summer time and 20 pairs of trains/hour in winter time with nominal loading; from 17:00 to 20:00 it consist of 34 pairs of trains/hour in summer time and 38 pairs of trains/hour in winter with maximum loading; from 20:00 to 0:00 – 15 pairs of trains/hour in summer and 38 pairs trains/hour in winter with maximum loading;

– on the weekend (two days of the week): from 5:30 to 8:00 time-interval of movement consists of 10 pairs of trains/hour with minimal loading; from 8:00 to 20:00 these are 20 pairs/hour with nominal loading; from 20:00 to 0:00 these are 15 pairs of trains/hour with maximum loading.

On the basis of experimental data the quantity of consumed and regenerative energy from the network to the capacitive storages at different loading of the subway trains on the above said running lines was found. The quantity of consumed and regenerative energy is obtained from expressions:

$$A_{tyagy} = \frac{I_{sr.tyagy}\, U_{sr.tyagy}\, t_{tyagy}}{3600 \cdot 1000}; \qquad (1)$$

$$A_{rek} = \frac{I_{sr.rek}\, U_{sr.rek}\, t_{rek}}{3600 \cdot 1000}, \qquad (2)$$

where $I_{sr.tyagy}$ – average value of current in traction condition; $U_{sr.tyagy}$ – average value of voltage in traction condition; t_{tyagy} – endurance of traction mode; $I_{sr.rek}$ – average value of current in regenerative breaking mode; $U_{sr.rek}$ – average value of voltage in regenerative breaking mode; t_{rek} – endurance of regenerative breaking mode.

These experimental data, calculated by the expressions (1) and (2) for a trip of an electrical train given in the table 1, for pair of trains in both directions – in the table 2.

Table 1 – The quantity of consumed and regenerative energy before capacitive storages

Running line	The quantity of consumed and regenerative energy, kWh		
	minimal loading	minimal loading	minimal loading
Khreschatyk–Teatralna	4,85/2,01	9,55/4,8	10,49/5,67
Teatralna–Khreschatyk	5,49/1,64	10,82/3,55	10,28/3,5
Shulyavska–Beresteyska	52,25/3,48	79,2	82,32/4,61
Beresteyska–Shulyavska	4,23/23,43	5,12/43,5	4,23/45,37

Table 2 – The quantity of consumed and regenerative energy before capacitive storages

Running line	The quantity of consumed and regenerative energy, kWh		
	minimal loading	minimal loading	minimal loading
Khreschatyk–Teatralna–Khreschatyk	10,34/3,65	20,37/8,35	20,77/9,17
Shulyavska–Beresteyska–Shulyavska	56,48/26,91	84,32/47,64	86,55/49,98

Taking into consideration abovesaid time-schedule of trains, the quantity of consumed and regenerative energy on the running lines Khreschatyk–Teatralna–Khreschatyk and Shulyavska–Beresteyska–Shulyavska is calculated for different periods of time (a period of twenty four hours, a month, a year).

The quantity of consumed and regenerated energy per twenty-four hours is obtained from expressions:

$$\begin{aligned} Q_{tyagy} &= A_{min} n_1 m_1 + A_{nom} n_2 m_2 + \\ &+ A_{max} n_3 m_3, \end{aligned} \qquad (3)$$

$$Q_{rek} = A_{min(rek)} n_1 m_1 + A_{nom(rek)} n_2 m_2 + \\ + A_{max(rek)} n_3 m_3, \quad (4)$$

where A_{min}, A_{nom}, A_{max} is the quantity of consumed energy according to minimal, nominal and maximal loading of an electrical train; n_1, n_2, n_3 is the quantity of working hours per twenty-four hours according to minimal, nominal and maximal loading of electrical train; $\mathrm{m}_1, \mathrm{m}_2, \mathrm{m}_3$ is the quantity of train pairs per hour according to minimal, nominal and maximal loading of an electrical train; $A_{min(rek)}$, $A_{nom(rek)}$, $A_{max(rek)}$ is the quantity of regenerated energy according to minimal, nominal and maximal loading of an electrical train.

The quantity of consumed and regenerated energy per month is obtained from expressions:

$$Q_{tyagy(month)} = Q_{tyagy(work)} n_4 + Q_{tyagy(wend)} n_5; \quad (5)$$

$$Q_{rek(month)} = Q_{rek(work)} n_4 + Q_{rek(wend)} n_5, \quad (6)$$

where $Q_{tyagy(work)}$, $Q_{tyagy(wend)}$ – the quantity of consumed energy per working day and weekend respectively; n_4, n_5 is the quantity of working days and weekends respectively; $Q_{rek(work)}$, $Q_{rek(wend)}$ is the quantity of regenerated energy per working day and weekend respectively.

The quantity of consumed and regenerated energy per month is obtained from expressions:

$$Q_{tyagy(year)} = Q_{tyagy(sum)} n_6 + Q_{tyagy(wint)} n_7; \quad (7)$$

$$Q_{rek(year)} = Q_{rek(sum)} n_6 + Q_{rek(wint)} n_7, \quad (8)$$

where $Q_{tyagy(sum)}$, $Q_{tyagy(wint)}$ is the quantity of consumed energy per month in summer and winter time respectively; n_6, n_7 is the quantity of summer and winter months per a year; $Q_{rek(sum)}$, $Q_{rek(wint)}$ is the quantity of regenerated energy in summer and winter time respectively.

The calculation data, obtained by the expressions (3)–(8) are given in the tables 3, 4.

Table 3 – The calculation results of the energy quantity on the running line Khreschatyk–Teatralna

Period	The quantity of consumed / regenerated energy, kWh	
	Summer time	Winter time
Working day	7581,6/3201,5	8538,4/3609,2
Weekend	6393,5/2645,5	
Month	217943,2/91597	238992,8/100566,4
Year	2741616/1152980,4	

Table 4 – The calculation results of the energy quantity on the running line Shulyavska–Beresteyska

Period	The quantity of consumed / regenerated energy, kWh	
	Summer time	Winter time
Working day	32529,9/18230,9	36504,3/20502,3
Weekend	26841,8/15105,2	
Month	930392,2/521921,4	1017829/571892,2
Year	11689327,2/6562881,6	

During the operation of subway electrical train on Sviatoshinsko-Brovarska line, the following motion mode for twenty four hours is taking for calculation:

– on weekdays, two full turns with minimal loading, five full turns with nominal loading, three full turns with maximal loading;

– on weekends: one full turn with minimal loading, seven full turns with nominal loading, two full turns with maximal loading.

On the basis of experimental data the quantity of consumed and regenerative energy from the network to the capacitive storages during the motion of the subway electrical trains at different loading in the schedule between terminals are obtained from the expressions (1) and (2).

The experimental data for one subway round trip with different loading on the Sviatoshinsko-Brovarska line are given in the table 5.

Table 5 – The quantity of consumed and regenerative energy before capacitive storages

Running line	The quantity of consumed and regenerative energy, kWh		
	minimal loading	minimal loading	minimal loading
Lisova–Akademmistechko	172,36/49,49	261,15/74,98	328,57/133,95
Akademmistechko–Lisova	154,55/78,57	234,16/109,13	271,86/152,93
Lisova–Akademmistechko–Lisova	326,91/128,06	495,31/184,11	600,43/286,88

Taking into consideration abovesaid time-schedule of trains, the quantity of consumed and regenerative energy on the Sviatoshinsko-Brovarska running line is calculated for different periods of time (a period of twenty four hours, a month, a year).

The quantity of consumed and regenerated energy per twenty-four hours is obtained from expressions:

$$W_{tyagy} = W_{min}k_1 + W_{nom}k_2 + W_{max}k_3; \qquad (9)$$

$$W_{rek} = W_{min(rek)}k_1 + W_{nom(rek)}k_2 + \\ +W_{max(rek)}k_3, \qquad (10)$$

where W_{min}, W_{nom}, W_{max} is the quantity of the consumed energy in time of one round trip according to minimal, nominal and maximal loading of an electrical train; k_1, k_2, k_3 is the quantity of round trips per twenty-four hours according to minimal, nominal and maximal loading of an electrical train; $W_{min(rek)}$, $W_{nom(rek)}$, $W_{max(rek)}$ – the quantity of regenerated energy in time of one round trip according to minimal, nominal and maximal loading of an electrical train.

The quantity of consumed and regenerated energy per month is obtained from expressions:

$$W_{tyagy(month)} = W_{tyagy(work)}k_4 + W_{tyagy(wend)}k_5; \qquad (11)$$

$$W_{rek(month)} = W_{rek(work)}k_4 + W_{rek(wend)}k_5, \qquad (12)$$

where $W_{tyagy(work)}$, $W_{tyagy(wend)}$ is the quantity of consumed energy per working day and weekend respectively; k_4, k_5 is the quantity of working days and weekends respectively; $W_{rek(work)}$, $W_{rek(wend)}$ is the quantity of regenerated energy per working day and weekend respectively.

The quantity of consumed and regenerated energy per year is obtained from expressions:

$$W_{tyagy(year)} = 12W_{tyagy(month)}; \qquad (13)$$

$$W_{rek(year)} = 12W_{rek(month)}, \qquad (14)$$

де $W_{tyagy(year)}$, $W_{rek(month)}$ is the quantity of consumed and regenerated energy per year.

The calculation results, obtained by the expressions (9)–(14) are given in the table 6.

Table 6 – The calculation results of the energy quantity on the Sviatoshinsko-Brovarska running line

Period	The quantity of consumed/ regenerated energy, kWh
Working day	4931,71/2037,31
Weekend	4994,94/1990,59
Month	148457,1/60745,5
Year	1781485/728946

The reduced annual costs minimum criterion is accepted during the study of the using capacitive storages feasibility [21]. The reduced costs, in turn, depend on investment in capacitive storages and operating costs.

Reduced cost minimum criterion:

$$C_r = K_i E_n + OC_i, \qquad (15)$$

where K_i – are the investments on i-variant; E_n is the normative economic coefficient (for industry and transport infrastructure E_n=0,16 [21]); OC_i – are the operating costs (costs price) on i-variant.

The investments are calculated on the coefficient method:

$$K_i = P_w + IS + SR, \qquad (16)$$

where P_w is wholesaling price for equipment; IS=P_W0,06 are storage and retrieval costs; SR= $P_W \cdot 0,06$ are installation costs.

Operating costs:

$$OC_i = AD + WP + C_{WP} + C_{RS} + C_E + E_O, \qquad (17)$$

where AD are amortization deductions; WP are operating personnel wages; C_{WP} is charge on payroll; C_{RS} are repair and service costs; C_E is the cost of consumed energy per year; E_O are others expenses.

$$AD = \frac{K_i a_y}{100}, \qquad (18)$$

where a_y is the yearly mean amortization deductions.

$$WP = \sum_{i=1}^{n} ET_i H_{ci} C_{ec} C_{cp} \qquad (19)$$

where ET_i is worker time expenditure per year; H_{ci} is hourly cost rates; C_{ec} is the extra charge coefficient; C_{cp} is the charge on payroll coefficient.

$$C_{RS} = K_i \frac{z_P}{100}, \qquad (20)$$

where z_P is the repairing charge;

$$C_E = Q_E T_E, \qquad (21)$$

where Q_E is the consumed energy; T_E is the energy charge.

$$Q_E = W_{tyagy(year)} \eta_i, \qquad (22)$$

where $W_{tyagy(year)}$ is yearly consumed energy; $\eta_н$ is the equipment efficiency factor:

$$E_O = 0,01K_з. \qquad (23)$$

Further calculations of baseline case and design case are made. In this case, the baseline case means existing infrastructure of the subway traction power system without capacitive storages; design case means the existing infrastructure of the subway traction power system with capacitive storages installation on the output of traction substation or an electric train.

The baseline and design cases simplifications are made in the equations (15)–(23). The simplification is made in case of costs equality for the baseline and design cases. Allowing for the simplification the formulas are given to determine the minimum criteria for residual costs, operating costs, and the quantity of consumed energy for baseline and design cases.

For baseline case

– the minimum criteria for residual costs:

$$C_r(b)=OC_i\,; \tag{24}$$

– the operating costs:

$$OC_i = C_E\,; \tag{25}$$

– the quantity of consumed energy:

$$Q_E = W_{tyagy(year)}\eta_н\,. \tag{26}$$

Equations (24)–(26) show that the investments are not calculated for the basic case and operating costs depend on the amount of consumed electricity.

For the design case:

– the minimum criteria for residual costs are calculated by the expression (15);

– the investments are calculated by the expression (16);

– the operating costs:

$$OC_i(d) = AD + C_E + C_{RS} + E_O\,; \tag{27}$$

– the quantity of consumed energy:

$$Q_E = (W_{tyagy(year)} - W_{rek(year)}\eta_н\,), \tag{28}$$

where $W_{rek(year)}$ is the quantity of regenerated energy in the capacitive storage per year installed on the output of a traction substation $\eta_H = 0{,}85$; by the installation capacitive storage in the electrical train $\eta_H = 0{,}9$ [18, 22].

In operating costs for design case the service personnel wages, charges on payroll, the cost of equipment maintenance are not considered. The above costs are not taken into account because capacitive storages do not require additional personnel for their service.

Based on the results of experimental studies it is accepted: the capacitive storage energy installed on the output of the traction substations, providing the running lines "Khreschatyk–Teatralna" and "Shuliavska–Beresteyska" was respectively 5.7 kWh and 45.5 kWh; the capacitive storage energy installed on the subway electrical train is 10 kWh. Based on the adopted conditions, wholesale price of the capacitive storages is 1 million UAH, 10 million UAH, 2 million UAH [16].

The annual costs calculations are made by the expressions (24)–(26) for the baseline case. The results are given in the table 7.

The annual costs calculations are made by the expressions (15), (16), (27), (28) for the design case. The results are given in the table 8.

Table 7 – The annual costs for baseline case

Studied area	C_E, UAH	C_E, UAH	$C_r = OC_i(b)$, UAH
Khreschatyk–Teatralna	0,3084	845514	845514
Shuliavska–Beresteyska		3604988,5	3604988,5
Sviatoshinsko–Brovarska		549410	549410

Table 8 – The annual costs for design case

Studied area	K_i, UAH	T_E, UAH	C_E, UAH	$OC_i(d)$, UAH	C_r, UAH
Хрещатик–Театральна	1120000	0,3084	543272,1	554472,1	778472,1
Шулявська–Берестейська	11200000		1884595	1996595	4236595
Святошинсько-Броварська лінія	2240000		347083,7	369483,7	817483,7

The annual economic effect:

$$E_y = OC_i(b) - OC_i(d)\,. \tag{29}$$

The equipment payback period:

$$P_{ep} = \frac{K_i}{E_y}\,. \tag{30}$$

The annual economic effect and payback period for the equipment on the studied areas are calculated by the expressions (29)–(30) on the results of the annual cost for the baseline and design cases. The results are given in table 9.

Table 9 – The annual economic effect and the equipment payback period

Studied area	$OC_i(b)$, UAH	$OC_i(d)$, UAH	E_y, UAH	$P_{ep,}$ years
Khreschatyk-Teatralna	845514	554472,1	296641,9	3,8
Shuliavska-Beresteyska	3604988,5	1996595	1669994	6,7
Sviatoshinsko-Brovarska	549410	369483,7	194486,3	11,5

Note. In the calculations (table. 7, 9) the value capacitive storage data and electricity tariffs are used as of October 2014.

Analysis of calculation results of the feasibility to use capacitive storages on the studied areas estimated the following:

– annual energy savings by installing capacitive storages on the output of traction substations that provide energy for the running lines "Khreschatyk–Teatralna" and "Shuliavska–Bresteyska" is about 0.3 million UAH and 1.7 million UAH respectively; on subway rolling stock it consists about 0.2 million UAH (table 9);

– the payback period of capacitive storages at its installation on the output of traction substations that provide power for the running lines "Khreschatyk–Teatralna" and "Shuliavska–Bresteyska" is about 3.8 years and 6.7 years respectively; on subway rolling stock it consists about 11.5 years (table 9);

– there is economic feasibility of using capacitive storages in the subway, in particular on the output of the traction substations that supply power to the running line "Khreschatyk–Teatralna" because the payback period of the equipment meets the normative economic factor requirements (it is less than 6.25 years);

– from an economic point of view it is more reasonable to establish capacitive storages on the output of traction substations.

CONCLUSIONS. According to the results of calculations it is estimated that the use of capacitive storage in the subway will provide technical and economic benefit by saving electricity. It should be noted that this calculation is made for the case of upgrading existing infrastructure without considering reducing power transformers and transformer equipment, as well as the increase in the cost of electricity tariffs. If taking into account the above factors the reduced costs significantly decrease by reducing capital and the saved electricity cost. As a result, the annual economic effect will increase and the equipment payback period will decrease.

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К ВОПРОСУ ЦЕЛЕСООБРАЗНОСТИ ИСПОЛЬЗОВАНИЯ ЕМКОСТНЫХ НАКОПИТЕЛЕЙ ЭЛЕКТРОЭНЕРГИИ В МЕТРОПОЛИТЕНЕ

А. А. Сулим

Государственное предприятие «Украинский научно-исследовательский институт вагоностроения»

ул. И. Приходько, 33, г. Кременчуг, 39621, Украина. E-mail: sulim1.ua@gmail.com

Рассмотрена целесообразность установки емкостных накопителей электроэнергии на выходе тяговых подстанций, которые обеспечивают питанием перегоны «Крещатик–Театральная» и «Шулявская–Берестейская», а также на подвижном составе метрополитена с учетом условий его эксплуатации на Святошинско-Броварской линии коммунального предприятия «Киевский метрополитен». По результатам экспериментальных данных и выполненных расчетов определен годовой экономический эффект от использования емкостных накопителей электроэнергии и их срок окупаемости. Анализ результатов расчетов позволил установить, что с экономической точки зрения более рациональным является установка емкостных накопителей электроэнергии на выходе тяговых подстанций. Из рассмотренных вариантов наиболее эффективным является установка емкостных накопителей энергии на выходе тяговой подстанции, которая обеспечивает питанием перегон «Крещатик–Театральная».

Ключевые слова: избыточная электроэнергия рекуперации, емкостной накопитель электроэнергии.

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