UDC 621.314 **doi: 10.20998/2074-272X.2019.5.04**

G.G. Zhemerov, D.S. Krylov, A.V. Mashura

ENERGY EFFICIENCY OF THE SUBWAY ELECTRICAL SUPPLY SYSTEM WITH ELECTRICAL ENERGY RECOVERY AT BRAKING

Purpose. The purpose of the paper is to assess the efficiency of the subway power supply system, which uses a four-quadrant DC drive with energy recovery in the supply network in the braking mode. Methodology. We have applied the theory of electrical circuits and mathematical simulation in Matlab package. Results. The theoretical dependence of the efficiency of the electrical supply system with a bidirectional flow of energy on the coefficient of resistive short circuit at the load terminals has been obtained. The theoretical result is verified by modeling. Originality. The equivalent circuit of the subway power supply system with a four-quadrant DC drive and the possibility of energy recovery to the supply network in braking mode is developed, its parameters are determined, and the schedule of the electric train movement was set. Practical value. The use of the obtained dependencies and simulation results will allow to determine the direction of the future development of the subway power supply system and optimize its energy efficiency. References 8, tables 1, figures 5.
Key words: **power supply system, energy, energy return coefficient, efficiency, energy recovery.**

Мета. Метою статті є оцінка ККД системи електропостачання метрополітену, в якій використовується чотирьохквадрантний привід постійного струму з рекуперацією енергії в мережу живлення в режимі гальмування. Методика. Для проведення досліджень використовувалася теорія електричних кіл, математичне моделювання в пакеті Matlab. Результати. Отримана теоретична залежність ККД СЕ з двонаправленим потоком енергії від коефіцієнта резистивного короткого замикання на клемах навантаження. Теоретичний результат перевірений моделюванням. Наукова новизна. Розроблена еквівалентна схема системи електропостачання метрополітену з чотирьохквадрантним приводом постійного струму і можливістю рекуперації енергії в мережу живлення в режимі гальмування, визначені її параметри, заданий графік руху електропоїзда. Практичне значення. Використання отриманих залежностей і результатів моделювання дозволить визначити напрямок перспективного розвитку системи електропостачання метрополітену, оптимізувати її енергоефективність. Бібл. 8, табл. 1, рис. 5.
Ключові слова: **система електропостачання, енергія, коефіцієнт повернення енергії, коефіцієнт корисної дії, рекуперація енергії.**

Цель. Целью статьи является оценка КПД системы электроснабжения метрополитена, в которой используется четырёхквадрантный привод постоянного тока с рекуперацией энергии в питающую сеть в режиме торможения. Методика. Для проведения исследований использовалась теория электрических цепей, математическое моделирование в пакете Matlab. Результаты. Получена теоретическая зависимость КПД СЭ с двунаправленным потоком энергии от коэффициента резистивного короткого замыкания на клеммах нагрузки. Теоретический результат проверен моделированием. Научная новизна. Разработана эквивалентная схема системы электроснабжения метрополитена с четырёхквадрантным приводом постоянного тока и возможностью рекуперации энергии в питающую сеть в режиме торможения, определены её параметры, задан график движения электропоезда. Практическое значение. Использование полученных зависимостей и результатов моделирования позволит определить направление перспективного развития системы электроснабжения метрополитена, оптимизировать её энергоэффективность. Библ. 8, табл. 1, рис. 5.
Ключевые слова: **система электроснабжения, энергия, коэффициент возврата энергии, коэффициент полезного действия, рекуперация энергии.**

Introduction. The functioning of the transport system of a modern large city is impossible without the use of the subway, which provides a significant part of passenger traffic. Its high reliability is combined with not the highest energy efficiency, which is due to the use of a DC collector electric drive of sequential excitation without the possibility of returning energy to the supply network. Many scientific works have been devoted to improving the efficiency of the subway power supply system [1-3]. One of the solutions to the problem of energy conservation is the use of a four-quadrant DC electric drive, which makes it possible to organize a bi-directional flow of electrical energy between the source and the load. This will allow the energy stored in the moving train to be return to the industrial network of three-phase alternating current, which, in turn, should increase the efficiency of the entire supply power supply system. However, as shown in [3], the effect of energy saving from the use of regenerative braking is not always obvious. It depends on the configuration of the used power supply system and the operating modes of the electric drive. Under certain conditions, the effect of reducing the total efficiency of the system due to the occurrence of additional losses during the return of energy to the network is possible.

The goal of the work is the assessment of the efficiency of the subway power supply system, which uses a four-quadrant DC drive with energy recovery to the supply network in the braking mode.

Traction substation structure. A traditional traction substation uses uncontrolled diode rectifiers to convert AC voltage to DC, which does not allow the return of energy to the supply network. To implement a possible increase in the efficiency of the circuit, instead of diode bridges, it is necessary to use a four-quadrant thyristor rectifier, shown in Fig. 1.

The network 6(10) *kV* is represented by a three-phase symmetric system of sinusoidal voltages u_{SA}, u_{SB}, u_{SC}. The network parameters are taken into account by the active resistance R_0. The parameters of the line connecting the traction substation and the three-phase converter transformer 6(10) kV / 0.71 kV are determined by the active resistance R_1. The network windings of the transformer T_1 are connected to the network 6(10) kV, and the valve windings are connected to the six-pulse four-quadrant bridge rectifier $VS1$ – $VS12$. Losses in the thyristor bridge are represented by an equivalent source of counter-EMF of level of 1 V in the forward and reverse directions and transferred to the DC circuit. Line parameters from transformer T_1 to rectifier bridges correspond to the active resistance R_2. The load is represented by a DC motor with independent excitation. The line parameters from the controlled rectifier (CR) to the DC motor are taken into account by the resistance of the contact rail R_{KR}. The inductances in the power line, which are present there in fact, do not participate in the formation of losses during energy transfer, therefore they are transferred to the load and they are not shown in the equivalent circuit.

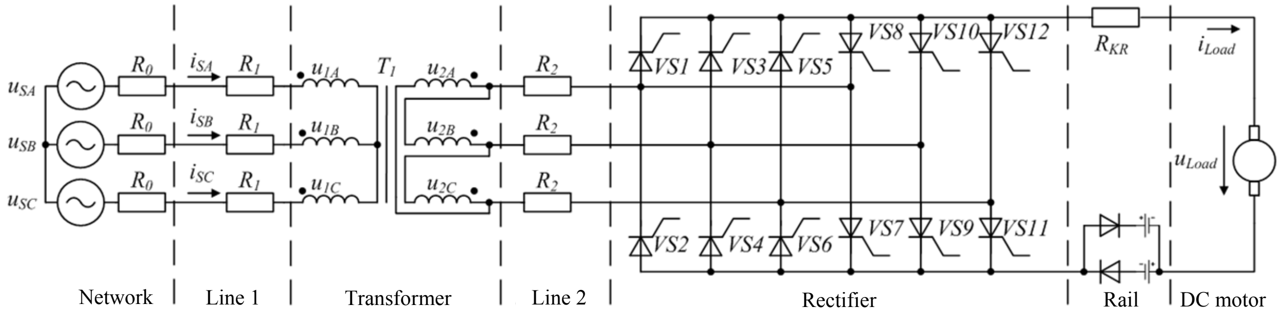

Fig. 1. Equivalent circuit of SPSS with four-quadrant CR

To adequately assess the energy efficiency of the subway power supply system (SPSS), it is necessary to know the train schedule, which, according to [1-3], contains the following intervals: the acceleration interval from zero to nominal speed (time t_{ac}) averages 20-30 s; braking time from nominal to zero speed (t_{br}) is on average 40-50 s; the train stop interval (time t_{st}) is usually 25 s; the interval of movement with nominal speed (t_{mov}) is 110-130 s. Taking into account that the time of movement of rolling stock between two stations is on average three minutes [1], in accordance with [3] we accept the following values of traffic intervals: t_{ac} = 25 s, t_{mov} = 115 s, t_{br} =45 s, t_{st} = 25 s.

The graph of changes in current, voltage, and load power for the indicated intervals of movement of the train in the considered SPSS can be of the form shown in Fig. 2.

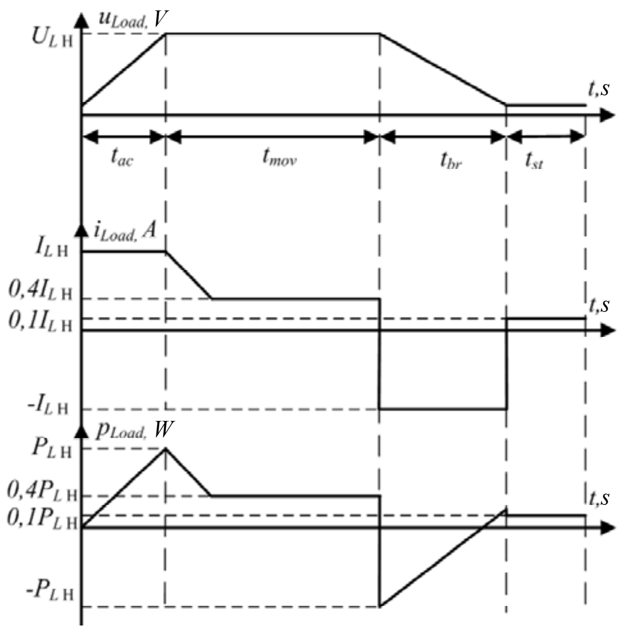

Fig. 2. Schedule of trains between stations

In the interval of the train acceleration t_{ac}, the automatic control system linearly changes the speed of the train from zero to nominal, which, with independent excitation of the DC machine, corresponds to a linear increase in the load voltage from zero to nominal. The load current is limited at the nominal level. The power developed at this stage also linearly rises to the nominal value. In the interval of movement t_{mov} at nominal speed, the nominal voltage will be applied to the load, and the train will overcome the drag and friction, developing up to 30-50 % of the nominal power. The current consumed by the load will be at the same level. In braking mode, the automatic control system provides a smooth linear decrease in speed to zero level during t_{br}. The load voltage will also decrease linearly to zero. In order to ensure the return of kinetic energy stored by the train to the supply network, it is necessary to change the polarity of the load current with its limitation at a level not exceeding the nominal value. With the beginning of recovery, the load current passes to the reversible valve group and is maintained negative until the energies returned and consumed by the train are equal at the braking stage. After that, the linearly changing load power becomes positive again, and the load current transfers to the positive valve group as a result of switching the rectifier bridges. In the stop interval t_{st} the electric drive of the train does not consume energy. At all stages of movement, the train consumes energy of its own needs, which is spent on heating, lighting and ventilation of cars, its value can reach 10 % of the nominal one. This is taken into account in the graphs presented in Fig. 2.

The power developed at the stages of movement depends on the physical parameters of the train, on its speed and mass. The mass of rolling stock is determined by the number of cars and the number of passengers in each car. According to [4], the train consists of five cars with a mass of 33 t each. The car accommodates from 200 to 300 passengers with an average weight of 60-70 kg.

Thus, we can assume that the mass of the train is 200-250 *t*. The nominal speed is 25 *m/s* or 90 *km/h*. According to [4], trains operating on the subway lines are equipped with an electric drive with nominal power of up to 2 *MW*. In an equivalent circuit for further calculations and modeling, an *NP800KS* motor with a nominal power of 2.013 *MW* and a nominal current of 3053 *A* was chosen. Moments of resistance and inertia of the train are reduced to its rotor.

To calculate the energy of losses in a bidirectional flow, it is necessary to set the parameters of the SPSS circuit shown in Fig. 1. The characteristics of the supply network are determined by the parameters of the three-phase transformer of the supply substation type ТМН 4000/35/6 [1], for which the phase resistance $R_0 = 0.1\ \Omega$ [1]. The parameters of line 1 (see Fig. 1) are determined by the distance between the traction substation and the converter transformer, which, on average, is from 1 to 3 *km* [1]. The aluminum three-wire cable used in line 1 has a phase resistance value R_1 of 0.3 Ω/km, and its cross section is selected according to the current that the considered drive can consume, and is equal to 95 mm^2 [1]. The ТСЗП-2500/10У3 6(10)/0.71 *kV* series converter transformer has a nominal power of 2.509 *MW* and short circuit losses of 20 *kW*. The total equivalent resistance of his phase R_{TV} will be 2 $m\Omega$. The parameters of line 2 are determined by the distance between the converter transformer T_1 and the rectifier, which is assumed to be 50 *m*. In this case, the cross section of the copper cable will be equal to 1000 mm^2, the value of the phase resistance R_2 is 0.9 $m\Omega$. The R_{KR} steel contact rail has a standard cross-section of 6600 mm^2 and a resistance of 9 $m\Omega/km$. Its length can vary from 1 to 3 *km*, depending on the location of the train on the run between stations. The active resistance of the previously selected DC machine is 8 $m\Omega$.

Efficiency of SPSS with bidirectional energy flow. Let us evaluate the efficiency of the power supply system shown in Fig. 1. According to [3], the maximum possible efficiency of SPSS with a bi-directional energy flow is determined by the formula:

$$\eta_{\max\leftrightarrow} = \frac{\eta_{\max\rightarrow}(2-\eta_{\max\leftarrow}^{-1}) - k_E}{1-k_E}, \tag{1}$$

where $\eta_{\max\rightarrow}$ and $\eta_{\max\leftarrow}$ are the maximum possible values of the efficiency of three-phase SPSS in the forward and reverse energy flows, respectively; k_E is the coefficient of energy return from the load to the source, determined by the expression from [3]:

$$0 \le k_E = \frac{P_{S\leftarrow}}{P_{S\rightarrow}} \le 1, \tag{2}$$

where $P_{S\leftarrow}$ and $P_{S\rightarrow}$ are the source powers in forward and reverse energy flows, respectively.

The value of the maximum possible efficiency of the SPSS in a direct energy flow $\eta_{\max\rightarrow}$ is determined by the expression [3]:

$$\eta_{\max\rightarrow} = \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{1}{k_{SC}}}, \tag{3}$$

where k_{SC} is the short circuit coefficient, determined by the ratio of the short circuit power at the load terminals to the net active load power:

$$k_{SC} = \frac{P_{SC}}{P_{usf}}, \tag{4}$$

where P_{SC} is the power of the resistive short circuit of SPSS with the load off; P_{usf} is the average value of the effective active load power in the repeatability interval of the train schedule according to Fig. 2.

The values of P_{usf} and k_E depend on the train schedule, task intervals, acceleration and braking speeds of the train. The power of the resistive short circuit P_{SC} depends on the configuration of SPSS and can be determined from the relation:

$$P_{SC} = \frac{3U_{sm}^2}{2R_\Sigma}, \tag{5}$$

where U_{sm} is the amplitude of the sinusoidal phase voltage of the power source; R_Σ is the equivalent active resistance of SPSS shown in Fig. 1.

The value of the active equivalent resistance of the power supply system, according to Fig. 1 includes the following components:

$$R_\Sigma = R_0^{'} + R_1^{'} + R_{TV} + R_2 + R_{RF} + R_{KR} + R_J, \tag{6}$$

where $R_0^{'}$ is the phase resistance of the AC voltage source 6(10) *kV*, reduced to the secondary winding of the converter transformer (CT); $R_1^{'}$ is the resistance of the section phase of line 1, reduced to the secondary winding of the CT; R_{TV} is the total resistance of the CT phase; R_2 is the resistance of the section phase of line 2 from the transformer to the rectifier; R_{RF} is the resistance of the controlled rectifier; R_{KR} is the resistance of the contact rail; R_J is the resistance of the armature circuit of the DC motor.

The value of the maximum possible efficiency of the SPSS in the reverse energy flow $\eta_{\max\leftarrow}$ can be determined by the following expression [3]:

$$\eta_{\max\leftarrow} = \frac{1}{1+k_E^2 k_{SC}^{-1}}. \tag{7}$$

We find the value of the maximum possible efficiency of SPSS with a bi-directional energy flow and determine the possible range of its changes using the above expressions.

To determine the coefficient of energy return from the load to the source k_E, according to (2), it is necessary to know $P_{S\leftarrow}$ and $P_{S\rightarrow}$. Their values can be determined from the train schedule shown in Fig. 2. Having calculated the area under the curve of the graph of power changes for the forward and reverse energy flows, we obtain the values $P_{S\rightarrow}$ = 50.3 *MW*, $P_{S\leftarrow}$ = 108.7 *MW* and, in accordance with (2), k_E = 0.5.

We find the average value of the effective load active power by integrating the instantaneous power graph in the interval of train repeatability. The value P_{usf} = 1.44 *MW* was obtained.

To find the power of the resistive short circuit P_{SC}, we determine the components of the equivalent active resistance of the power supply system R_{Σ} and the possible range of their changes.

According to the above data, the reduced phase resistance of the source phase $R_0^{'}$ can be calculated by the expression:

$$R_0^{'} = kR_0, \quad (8)$$

where $k = 1/k_{tr}^2$ is the coefficient of reduction of the parameters of the elements of the primary winding of the converter transformer to the secondary, equal to 0.014. The resistance $R_0^{'}$ value is 1.4 $m\Omega$.

Similarly, the reduced phase resistance of line 1 $R_1^{'}$ is calculated:

$$R_1^{'} = kR_1. \quad (9)$$

The remaining components of expression (6) and the possible range of their changes were determined above, the parameter values are summarized in Table 1, according to which the resistance $R_1^{'}$ lies in the range from 4.2 $m\Omega$ to 12.6 $m\Omega$. Active equivalent resistance of SPSS R_{Σ}, shown in Fig. 1 will have values ranging from 27 $m\Omega$ to 44 $m\Omega$.

Table 1

Resistances of the SPSS circuit and the range of their changes

Parameter		Value
$R_0^{'}$, $m\Omega$		1.4
$R_1^{'}$, $m\Omega$	1000 *m*	4.2
	2000 *m*	8.4
	3000 *m*	12.6
R_{TV}, $m\Omega$		3
R_2, $m\Omega$		1
R_{RF}, $m\Omega$		1
R_{KR}, $m\Omega$	1000 *m*	9
	2000 *m*	13.5
	3000 *m*	18
R_J, $m\Omega$		8

The short-circuit power P_{SC} calculated according to (5), depending on the circuit parameters, has a value from 34 to 56 *MW*. The short circuit coefficient calculated according to (4), depending on the active equivalent resistance, lies in the range from 25 to 40.

In a real power supply system, additional losses of electricity may be present, which can be taken into account in theoretical calculations by introducing the coefficient of additional losses k_{add}. In this case, the efficiency of the SPSS can be calculated from [3] by the expression:

$$\eta_{real\leftrightarrow} = \frac{\dfrac{1 - k_E^2 k_{SC}^{-1} k_{add\leftarrow}}{1 + \left(\left(0.5 + \sqrt{0.25 - k_{SC}^{-1}}\right)^{-1} - 1\right) k_{add\rightarrow}} - k_E}{1 - k_E}. \quad (10)$$

A graph of the real efficiency of SPSS with a bi-directional energy flow on the short-circuit coefficient at the load terminals k_{sc} is shown in Fig. 3 by dashed line.

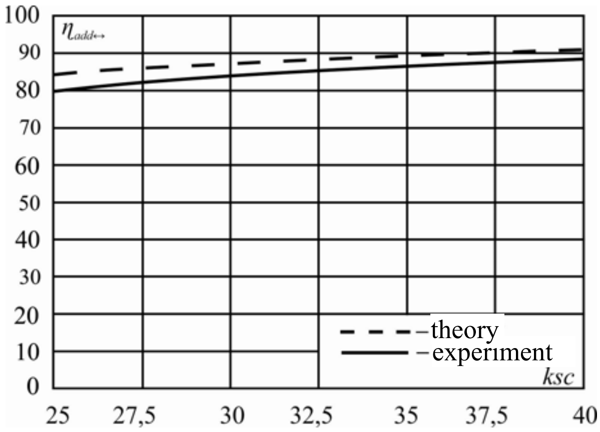

Fig. 3. Efficiency of SPSS

Modeling of SPSS with bidirectional energy flow. For experimental verification of theoretical results, the *MatLab* model of SPSS with a four-quadrant controlled rectifier, simulating the circuit shown in Fig. 1 was developed. *MatLab* model is shown in Fig. 4. It consists of the following blocks:

- power circuit – blocks 1, 3, 4, 5, 7, 8, 10;
- thyristor CR control system – block 6;
- torque, current and speed controllers – blocks 9, 13;
- current and voltage sensor – block 2;
- calculator – block 11;
- multipath oscilloscope – block 12.

Purpose of power circuit blocks: 1 – industrial network; 3 – cables connecting the traction substation and the three-phase conversion transformer 6(10) *kV* / 0.71 *kV*, which is indicated by block 4; 5 – cables coming from the transformer 4 to the rectifier bridges 7; 8 – steel contact rail connecting the CR with a DC motor 10.

The parameters of the power circuit elements in the model were set in strict accordance with SPSS data given above. Data of the DC motor model correspond to those for a *NP800KS* type machine. The mechanical part of the electric drive was reduced to the rotor of a DC machine, and the kinetic energy stored by the train during movement was reduced to the energy of an equivalent flywheel. The DC machine load specified in block 9 takes into account both the losses of own needs and the friction and drag of the air to the moving train.

The rectifier control system is built on a vertical principle and has an arccosinusoidal characteristic of a phase-shifting device. The bridge switching logic monitors the reference signal from the controller output and the instantaneous value of the load current, making a decision to transfer pulses depending on their superposition.

The autoregulation system is made in a closed manner using a dual-circuit slave current-speed controller tuned to a technical optimum. This ensured the qualitative maintenance of the set speed in accordance with the train schedule.

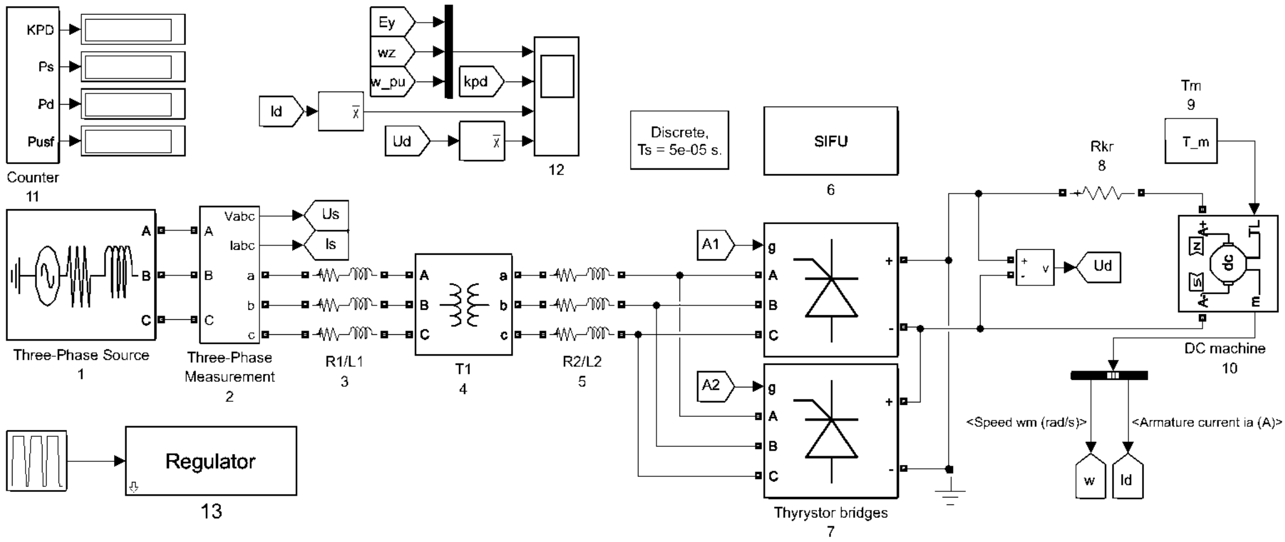

Fig. 4. MatLab model of SPSS

As a result of the simulation, the following were obtained: oscillograms of changes in current, voltage, and energy flow rate for the train motion intervals in the considered SPSS, shown in Fig. 5. A graph of the real efficiency of SPSS with a bi-directional energy flow versus short-circuit coefficient at the load terminals is built, which, for clarity, is shown in Fig. 3, together with a theoretical graph.

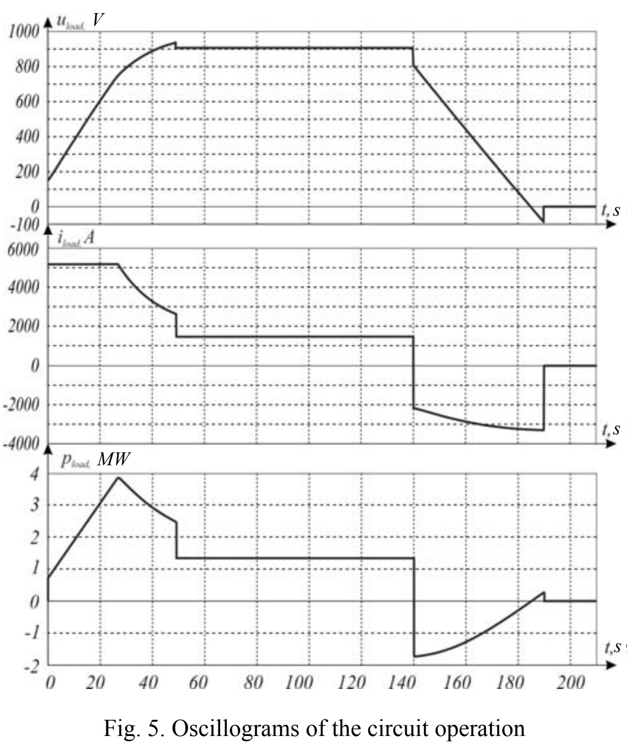

Fig. 5. Oscillograms of the circuit operation

Conclusions.

1. An equivalent circuit of the subway power supply system with a four-quadrant DC drive and the ability to recover energy to the supply network in the braking mode is developed, its parameters are determined, and the train schedule is set.

2. Using well-known formulas for the developed power supply system, a theoretical dependence of the efficiency of SPSS with a bi-directional energy flow on the coefficient of resistive short circuit at the load terminals is obtained.

3. A *MatLab* model of SPSS with a four-quadrant DC electric drive based on the base of a six-pulse controlled bridge rectifier with the possibility of realizing a bi-directional flow of electrical energy between the source and load is built.

4. Using the *MatLab* model, the real dependence of the efficiency of SPSS with a bi-directional energy flow on the short-circuit coefficient at the load terminals, which repeats the dynamics of the theoretical curve, is taken. Some discrepancy between the theoretical curve and the data of the obtained model can be explained by taking into account additional energy losses in the model, such as friction, air resistance, switching losses, etc.

REFERENCES

1. Zhemerov G.G., Ilyina N.A., Tugay D.V., Kholod O.I. Subway power systems with modern semiconductor converters and energy storage devices. *Electrical engineering & electromechanics*, 2013, no.1, pp. 41-49. (Rus) **doi: 10.20998/2074-272X.2013.1.10.**

2. Zhemerov G.G., Tugay D.V., Kholod O.I. Energy efficiency of power supple systems for a subway. *Technical electrodynamics*, 2014, no.1, pp. 67-74. (Rus).

3. Zhemerov G.G., Ilina N.A., Mashura A.V., Tugay D.V. Efficiency of regenerative braking in energy supply systems with electric regulated drives. *Technical electrodynamics*, 2018, no.8, pp. 73-76. (Ukr). **doi: 10.15407/techned2018.06.073.**

4. *Electric carriage types 81-718/719, 81-718.0/719.0 and 81-718.2/719.2*. Available at: http://vagon.metro.ru/passenger/81-718.html (Accessed 12 May 2016). (Rus).

5. Kostin N.A., Nikitenko A.V. Autonomy of recuperative braking – the basis of reliable energy-efficient recovery on the electromotive force constant current. *Railway Transport of Ukraine*, 2014, no.3, pp. 15-23. (Rus).

6. Shcherbak Ya.V., Nerubatsky V.P. Analysis of the use of recuperative inhibition on the railways of Ukraine. *Railway Transport of Ukraine*, 2011, no.2, pp. 30-34. (Ukr).
7. Sablin O.I. Analysis of the quality of the recovered electricity in the electric transport system. *Bulletin of NTU «KhPI»*, 2013, no.38, pp. 187-190. (Rus).
8. Posokhov I.M. Research of the car-building market of Ukraine and competitiveness of the industrial enterprises of railway transport in the world market and CIS markets. *Bulletin of NTU «KhPI»*, 2015, no.60, pp. 115-118. (Ukr).

Received 05.06.2019

G.G. Zhemerov[1], *Doctor of Technical Science, Professor,*
D.S. Krylov[1], *Candidate of Technical Science, Associate Professor,*
A.V. Mashura[1], *Postgraduate Student,*
[1] National Technical University «Kharkiv Polytechnic Institute»,
2, Kyrpychova Str., Kharkiv, 61002, Ukraine,
phone +380 577076312,
e-mail: zhemerov@gmail.com

How to cite this article:
Zhemerov G.G., Krylov D.S., Mashura A.V. Energy efficiency of the subway electrical supply system with electrical energy recovery at braking. *Electrical engineering & electromechanics*, 2019, no.5, pp. 25-30. **doi: 10.20998/2074-272X.2019.5.04**.