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Determination of rational placement for energy storages in the power supply system of the underground

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Abstract
The possible placements of energy storages in the power supply system of underground were considered. The advantages and disadvantages of each placement of the energy storages according to various indicators were defined. According to the results of the general analysis of existing researches, their comparative analysis and the proposed approach using a scoring scale was established, the placement of accumulators on underground rolling stock was the most appropriate.
Keywords: ENERGY STORAGE, UNDERGROUND POWER SUPPLY SYSTEM, UNDERGROUND ROLLING STOCK

Introduction

Nowadays one of the priorities of developed countries is to solve problems of energy saving and energy efficiency. Under conditions of constant increase in the energy resources cost for many modern enterprises reducing the energy intensity and energy component of the production cost is also one of the determining factors of effective development [1-6].

In papers [7, 8], the use of energy storages was proposed to solve these problems. The application of energy storages allows solving a number of complex problems. The main ones are the following: reduction of energy consumption from the mains by maintaining and reusing of excess energy; straightening of minute and hour load diagrams; providing static and dynamic stability of the power system; reduction of the installed capacity of power plants engaged in the supply and power conversion (transformers, converters, distribution substations, etc.); reduction of current loads and power units heating temperature, respectively, which allows increasing their service life; providing the uninterrupted stable power supply in emergency modes of the main supply sources [7-11].

The rail transport with abruptly variable load, and in particular, the underground is one of the promising areas of energy storages application [6, 10-16]. The main advantage of their use in the underground is a peculiarity of its rolling stock operation: distinct impulse uneven character of load; small distance between the railway hauls, as a result, frequent starting and braking; often changing profile of the track; stable movement schedule compared with other types of rail transport (shunting locomotives, main line electric locomotives, trams) [15, 16].

From analysis of researches [6, 10-15], it is known that most of the energy costs in the underground are the traction costs (about 70%) [15, 17, 18]. In order to reduce energy consumption for traction the undergrounds of Ukraine, new cars are bought and upgrades to existing ones that exhausted their service life are performed with the possibility of electricity generating to the contact system in regenerative braking mode. From the analysis of researches [6, 13, 15, 19], it has been established that the energy efficiency of regenerative braking depends on many factors (the presence of consumers in the power area of traction substations, the operating condition of other consumers, track profile etc.). As a consequence, the use of regenerative braking power has a probabilistic nature and can save about 10% consuming on the rolling stock traction [11, 15]. However, to provide the use of regenerative braking electricity at maximum efficiency without additional hardware including energy storage units is impossible [6, 10, 11, 15, 19]. Energy efficiency of regenerative braking and the payback period of additional technical means, in turn, are largely dependent on the choice of energy storages placement in the power supply system of underground.

Work objective is to analyze the problem of rational justification of the energy storages placement in the power supply system of underground.

Materials and research results

From the analysis of the electrical schematic diagrams and existing studies [6, 15, 20-24], it is know that the energy storages can be placed in front of the traction substation, directly on the traction substation, on the section pillars, on the output of traction substation along the contact system line (on the stations at the ends of console areas of electric traction network) and on the rolling stock of the underground. The structural scheme of the underground power supply system with possible placements of energy storages is shown in Figure 1. In the structural scheme (Figure 1) the following list of symbols was adopted: TPP - Thermal Power Plant; PL - power line; RS - regional substation; SP - section pillar; ES - energy storage; TS - traction substation; RS - rolling stock; CR - contact rail; OT – open track.

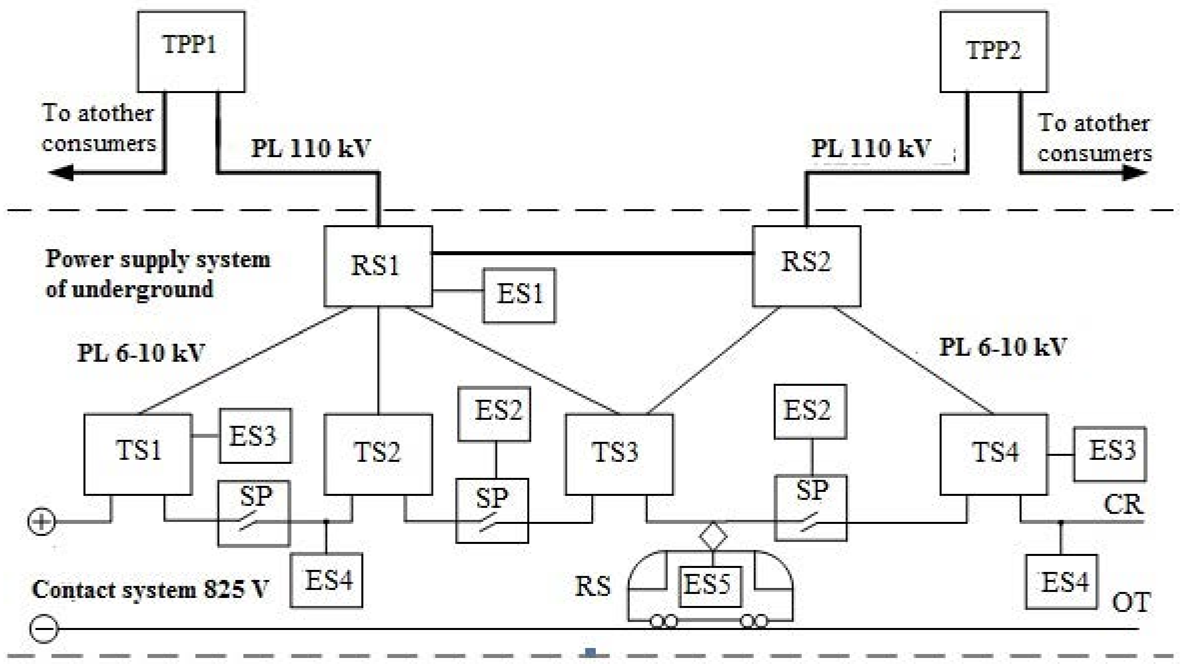

Figure 1. Structure scheme of the underground power supply system with possible placements of energy storages

When determining the rational placement a comparative analysis was proposed to carry out according to the following indicators: energy efficiency, capital investment, economic feasibility, impact on electric energy quality of the contact system, providing the increased crossing capacity of railway haul, the impact on the service life of power supply elements in the underground system, the ability to ensure the autonomous conduct of the rolling stock in case of emergency mode in the power supply underground system, the influence on acceleration and braking characteristics of the train, the implementation of energy processes control.

The results of the comparative analysis of different energy storages placement for the above indicators are shown in Table. 1.

Table 1. Comparative analysis of storage units according to their placement

Indicator name	Energy storage placement				
	ES1	**ES2**	**ES3**	**ES4**	**ES5**
Energy efficiency	Minimum	Average	Average	Average	Maximum
Capital investment	Average	Minimum	Average	Average	Maximum
Economic feasibility *	Minimum	Maximum	Average	Average	Average
Impact on electric energy quality	Maximum	Average	Average	Average	Minimum (not influence)
Providing the increased crossing capacity of railway haul	Minimum	Average	Average	Average	Maximum
Impact on the service life of power supply elements in the underground system	Maximum	Average	Average	Average	Minimum
Ability to ensure the autonomous conduct of the rolling stock in case of emergency mode in the power supply underground system	Minimum	Average	Average	Average	Maximum
Influence on acceleration and braking characteristics of the train	Not influence	Not influence	Not influence	Not influence	Influence
Energy processes control	Complex	Complex	Complex	Complex	Simple

Note: the economic feasibility indicator is calculated only on the basis of savings from increased energy efficiency in energy supply system of underground

Performed comparative analysis on these indicators (Table 1) allowed us to establish the following:

- the main advantage of placement energy storage at the district substations (ES1) is the lack of impact on the acceleration and braking characteristics of the train and the need for fewer storage units (possibly only one). However, their energy capacity should be substantial and account for more than 10 GJ [6, 23]. With this placement, it is necessary to equip the traction substations with inverters, this follows with the need of additional investments. As a result, the capital investments for this placement are average. Other indicators emphasize only the shortcomings of this placement. In particular, the energy efficiency is small and amounts to 10% of the electricity are consumed in the traction [15]. The impact on electric energy quality and service life of the power supply elements of the underground system is the largest due to the non-linearity recovery source and low TS power factor in power inverting mode, as well as the transition of additional excess voltage through a significant number of the power equipment elements (wires, tires, valves, etc.). Providing of increase capacity is the smallest due to the influence of inertia conditions of the system and electrical equipment heating. The autonomous movement of the train is the least, since at occurrence of an emergency shutdown of the main power supply at the area from RS to the current collectors mounted on the train carriages; the further movement of the latter is not possible in the traction mode. When energy processes control a significant number of factors that complicate the overall control system should be considered. The increasing complexity of the control system consists in using a large number measuring and control devices at each stage of the electricity transit and development at these stages of complex multi-level algorithms;

- the main advantages of placing energy storage at the section pillar (ES2) are the lack of influence on the acceleration and braking characteristics of the train, little capital investments and the largest saving. The total amount of storages installation on SP is insignificant, and their energy consumption should be about 100-200 MJ [6, 23, 24]. Energy efficiency indicators of the impact on power quality, providing increased traffic capacity of railway haul, the impact on the service life of elements of underground power supply system, the possibility of providing the autonomous conduct of the rolling stock when emergency operation in the power supply system of underground are mediocre. Energy efficiency is up to 25% of the electricity consumed for traction [23, 24]. The impact on electric energy quality is carried out due to the non-linearity of the recovery source. The service life of power supply system elements of the underground is reduced by decreasing resource of wires, tires due to additional excess currents flowing. The movement of the train in the traction mode is impossible in case of emergency in the area from TS to the current collectors mounted on the carriages of the train. The disadvantage of placing ES2 is the need of taking into account other modes of conducting other electricity consumers and, as a consequence, this will complicate the construction of work algorithms and the development energy processes control system;

- the main advantages of energy storage placing at traction substations (ES3) are the lack of influence on the acceleration and braking characteristics of the train. Other indicators are mediocre, except for the indicator of the energy processes control. Synthesis of control system is complex due to the need of taking into account operating conditions of other consumers. The main advantages and disadvantages, as well as the mediocre characteristics under condition of energy storage placing on TS output along the contact system line (ES4) are similar to that when ES3 placing. The difference between ES3 and ES4 placements is determined by the basic functional purpose. For ES3 placing the primary functional purpose is to take regenerative braking electricity near the source of its release, thereby reducing the contact system losses; for ES4 placing it is stabilization of the contact system voltage at the ends of cantilevered areas of electric traction network, resulting in increased traffic capacity of railway haul. The total amount of installation ES3 and ES4 storages is medium, and their energy content should be up to 100 MJ [6].

- the main advantages of energy storages (ES5) placement in rolling stock are the following: the largest energy efficiency; no impact on the electric energy quality of contact system and the service life of its elements (wires, tiers, etc.); the ability to ensure the autonomous work of the rolling stock in the case of emergency mode in the power supply system of underground and increase the railway haul traffic capacity are the highest; energy processes control in comparison with other placements is the easiest. Energy efficiency is up to 35% of the electricity consumed on traction [6, 15]. Electric energy of regenerative braking circulates on a small circle without its release in the contact system, so there is no impact on the electric energy quality of the contact system and the life of its elements. There is a possibility of autonomous rolling stock conduct in case of emergencies at any part of the underground power supply system. The traffic capacity is increased to 50% [20]. The economic indicator is average compared to other placements. The disadvantage of ES5 placing is the need of the largest capital investments and impact on the acceleration and braking characteristics of the train. The total amount of installation of ES5 storages is the highest, because each rolling stock should be equipped with such system and it requires substantial investment [6, 20, 23, 24]. Their energy consumption should be up to 30 MJ [6, 15].

According to the results of the comparative analysis to answer unequivocally, which placement of energy storage is rational, is not possible, since there are both advantages and disadvantages for each placement. The only exception is placing on the regional traction substation (ES1), which can be excluded from the search of the rational due to the availability of a significant number of shortcomings. Thus, the author proposed to determine rational energy storage placement according to grade scale. The essence of this approach is to develop evaluation criteria for each indicator which is used for comparison, which will be determined by the total number of points for each placement and direct choice of the rational placements based on the maximum number of points.

In this case, the following criteria for indicators evaluation were adopted: energy efficiency, economic feasibility, providing increased traffic capacity of railway haul, possibility of providing the autonomous conduct of the rolling stock in case of emergency modes in power supply system of underground: when minimum values - 1 point, medium - 2 points, maximum - 3 points; investment, impact on electric energy quality and durability of elements of the underground power supply system when the maximum values - 1 point, medium - 2 points, minimum - 3 points. When influencing on the acceleration and braking characteristics of the train, and complexity of the energy processes control, it takes 1 point, in other cases - 2 points.

Taking into account adopted evaluation conditions the maximum points could reach 25 points. The calculation results for considered placing of energy storages are shown in the diagram in Figure 2.

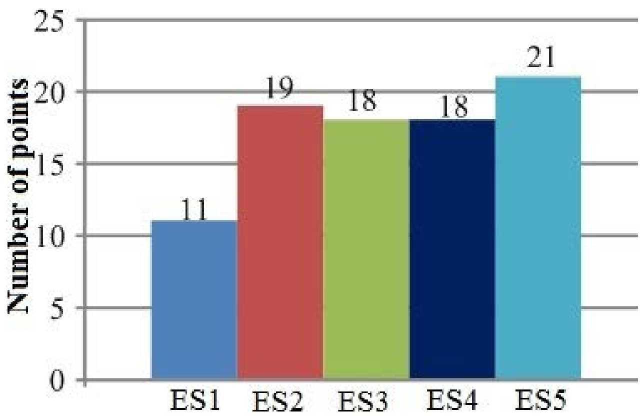

Figure 2. The results of points calculations for different energy storages placements

Thus, according to the analysis of numerous studies [6, 10, 15-17, 23] and the proposed approach, it is determined that the placement of storages on the rolling stock (ES5) is the most efficient for the underground conditions. The significant investment and impact on the acceleration and braking characteristics of the rolling stock are among the main drawbacks of placement ES5. However, significant investments can be compensated for the highest technical and economic effect by maximizing energy efficiency, minimizing the established capacity of power equipment, minimal influence on electric energy quality and durability of elements of underground power supply system and etc. The impact on acceleration and braking characteristics of the rolling stock can be solved by various methods depending on the project, in particular by allowing the program increase of the maximum traction (braking) value.

Conclusions

On the basis of the implementation of the generalized analysis of existing research, their comparative analysis and the proposed approach using a scoring scale, it is established that in the underground the most efficient placement of energy storage units is on the rolling stock.

References

1. Fomin O. V. (2014) Modern requirements to carrying systems of railway general-purpose gondola cars. Scientific and technical journal «*Metallurgical and Mining Industry*». No5, p.p. 31-43.
2. Kelrykh, M. (2014) Perspective directions of planning carrying systems of gondolas. Scientific and technical journal «*Metallurgical and Mining Industry*». No6, p. p. 64-67.
3. Fomin, O. V. (2015) Increase of the freight wagons ideality degree and prognostication of their evolution stages. *Scientific Bulletin of National Mining University*. No 2, p. p. 68-76.
4. Fomin, O. V. (2015) Improvement of upper bundling of side wall of gondola cars of 12-9745 model, «*Metallurgical and Mining Industry*». No1, p.p.45-48.
5. Fomin, O. V. (2015) Development and application of cataloging in structural design of freight car. «*Metallurgical and Mining Industry*». No. 2, p. p. 250-256.
6. Shevlyugin M. V. (2013) *Resurso- i energosberegayuschie tehnologii na zheleznodorozhnom transporte i metropolitenah, realizuemyie s ispolzovaniem nakopiteley energii* [Resource and energy-saving technologies in rail transport and undergrounds, implemented with the use of energy storage units]. Abstract of thesis. Moscow. 49 p.
7. But D. A. (1991) *Nakopiteli energii: Ucheb. posobie dlya vuzov* [Energy storage units: Manual for universities]. Moscow: Energoatomizdat. 400 p.
8. Astakhov Yu. N. (1989) *Nakopiteli energii v elektricheskih sistemah: Ucheb. posobie dlya elektroenerg. spets. vuzov* [Energy storage units in electrical systems: Textbook for electricity specialist]. Moscow: Vyisshaya shkola. 159 p.
9. Rybalko A. Ya. (2008) Vyibor emkosti nakopitelya energii dlya obespecheniya snizheniya maksimuma potreblyaemoy moschnosti [Selecting the energy storage capacity to ensure maximum reduction of power consumed]. *Gornyiy informatsionno-analiticheskiy byulleten (nauchno-tehnicheskiy zhurnal)* [Mining informational and analytical bulletin (scientific and technical journal)]. No8. p. p. 356-361.
10. Zhemerov G. G. (2013) Sistemyi elektrosnabzheniya metropolitena s sovremennyimi poluprovodnikovyimi preobrazovatelyami i nakopitelyami energii [The underground power supply systems with modern semiconductor converters and energy storages]. *Elektrotehnika i elektromehanika* [Electrical engineering

and electromechanics]. Kharkiv: NTU “KhPI», No 1, p. p. 41-49.
11. Bychkova M. P. (2010) Energosberezhenie v metro [Energy saving in the underground]. *Transport Rossiyskoy Federatsii. Spetsialnyiy vyipusk «Nauka i transport. Metropolitenyi buduschego»* [Transport of the Russian Federation. Special Edition “Science and Transportation. Underground of future]. P. 67.
12. Schurov N. I. (2008) Primenenie nakopiteley energii v sistemah elektricheskoy tyagi [The use of energy storages in electric traction systems]. *Sbornik nauchnyih trudov NGTU* [Collection of scientific works of NSTU]. Novosibirsk. No1 (51). p. p. 99-104.
13. Sablin O. I. (2014) Doslidzhennya efektyvnosti protsesu rekuperatsii elektroenergii v umovah metropolitenu [Research of recovery efficiency of the electric energy in underground conditions]. *Vostochno-Evropeyskiy zhurnal peredovyih tehnologiy* [East European Journal of advanced technologies]. No8 (72). Vol. 6. p.p. 9-13.
14. Kolb A. A. (2010) Akkumulirovanie energii rekuperatsii elektrifitsirovannogo transporta s pomoschyu emkostnyih energonakopiteley [Accumulation of recovery energy of electrified transport by means of capacitive energy storages]. *Visnik Dnipropetrovskogo natsionalnogo universitetu zaliznichnogo transportu im. akademika V. Lazariana* [Bulletin of Dnipropetrovsk National University of Railway Transport after academician V. Lazaryan]. Dnipropetrovsk. No31. p.p. 89-94
15. Sulim A. A. (2015) *Povyishenie effektivnosti energoobespecheniya podvizhnogo sostava metropolitena s sistemami rekuperatsii putem primeneniya emkostnyih nakopiteley energii* [Improving the efficiency of energy supply of rolling stock underground recovery systems by applying the capacitive energy storage]. Candidate thesis. Kyiv. 188 p.
16. Rodkin D. I. (2000) Osobennosti osuschestvleniya elektroprivoda s nakopitelyami energii [Peculiarities of the electric drive with energy storages]. *Naukovi pratsi Kremenchutskogo derzhavnogo politehnichnogo unIversitetu* [Scientific Papers of Kremenchug State Polytechnic University]. Kremenchug: KSPU. No2/2000 (9). p.p. 124-132.
17. Shevlyugin M. V. (2008) Snizhenie rashoda elektroenergii na dvizhenie poezdov v Moskovskom metropolitene pri ispolzovanii emkostnyih nakopiteley energii [Reduction of power consumption for the trains movement in the Moscow underground by using capacitive energy storages]. *Nauka i tehnika transporta* [Science and Transportation Equipment]. Moscow. No1. p.p. 15-20.
18. Donchenko A. V. (2013) Do pitannya vitrat elektroenergii na tyagu vagoniv metropolitenu KP «Kiyivskiy metropoliten» [On the issue of electricity consumption for traction of underground carriages of KP “Kyiv Metropolitan”]. *Zbirnyk naukovih prats DETUT: «Transportni systemy i tehnologii»* [Proceedings of DETUT: “Transport systems and technologies.”]. Kyiv: DETUT. No22. p. p. 5-8.
19. Kostin N. A. (2014) Avtonomnost rekuperativnogo tormozheniya – osnova nadezhnoy energoeffektivnoy rekuperatsii na elektropodvizhnom sostave postoyannogo toka [The autonomy of regenerative braking - the basis of a reliable energy-efficient recovery in DC electric rolling stock]. *Zaliznichniy transport Ukraini* [Railway transport of Ukraine}. No 3. p.p. 15-23.
20. Cheremisin V. T. (2013) Vyibor mest ustanovki nakopiteley elektroenergii na poligone postoyannogo toka po kriteriyu energoeffektivnosti [Selecting of energy storages placing in DC range according to energy efficiency criteria]. *Nauka i transport. Modernizatsiya zheleznodorozhnogo transporta* [Science and Transportation. The modernization of rail transport]. No2 (6). p.p. 48-52.
21. Stang A. A. (2012) Primenenie nakopiteley energii v sistemah elektrosnabzheniya gorodskogo elektricheskogo transporta [The use of energy storage in the power supply system of public electric transport]. *Transport Rossiyskoy Federatsii* [Transport of the Russian Federation]. No3-4 (40-41). p.p. 68-70.
22. Klinov V. Y. (2008) Emkostnyie nakopiteli v sisteme elektrosnabzheniya metropolitena [Capacitive storage in underground power supply system]. *Russkiy inzhener* [Russian engineer]. No2 (17). p.p. 62-64.
23. Shevlyugin M. V. (2007) Povyishenie energeticheskih pokazateley rabotyi sistemyi tyagovogo elektrosnabzheniya zheleznyih dorog s pomoschyu nakopiteley energii [Improving the energy performance of traction power supply system of railways using the energy storages]. *Nauka i tehnika transporta* [Science and Transportation Equipment]. No1. p.p. 68-72.

24. Cheremisin V. T. (2015) Povyishenie energeticheskoy effektivnosti sistemyi tyagovogo elektrosnabzheniya v usloviyah rabotyi postov sektsionirovaniya s nakopitelyami elektricheskoy energii [Improving the energy efficiency of the traction power supply system in conditions of work of section pillar posts with electrical energy storage units]. *Izvestiya Tomskogo universiteta. Inzhiniring georesursov* [Bulletin of the Tomsk University. Engineering of georesources]. No10 (326). p.p. 54-64.

Determination of up-to-date directions of development of domestic system of testing and certification of railways rolling stock

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