The Use of Energy Storage Devices of Uncontrolled Type on the Moscow Metro (Theory and Practice)

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Contribution to the state of the art

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Abstract: The problem of increasing energy saving and energy efficiency in the system of traction power supply of the Moscow Metro is considered due to the use of energy storage devices of uncontrolled type. The results of simulation modeling of the operation of an energy storage device of uncontrolled type in the system of traction power supply of the subway are presented. A particular line of the Moscow Metro, Filevskaya, was studied, on which experiments on the introduction of energy storage devices based on electrochemical super capacitors were conducted.

With the help of experimental measurements, the electric power indicators of the operation of a stationary energy storage device had been obtained at regular service on the traction substation of the Filevskaya line of the Moscow Metro for several months. The maximum levels of the converted energies, the cyclicity, the efficiency of the plant operation, and the amount of the energy economy are determined.

By statistical processing of the instantaneous values of the performance of the traction substation with the accumulator and the analysis of the data of the energy monitoring of the Moscow metro, an important parameter of reducing the installed capacity was investigated. The similarity of the data of theoretical calculations and experimental measurements is shown.

Keywords: modeling of the operation, energy storage devices, capacitive energy storage, regeneration of braking energy, traction power supply, underground.

Introduction

The system of traction power supply (STPS) of the Moscow Metro is one of the most powerful electricity consumers of the megapolis. The main part of the metro energy consumption is the consumption of train traction. In addition, the STPS has the most uneven energy consumption schedule - within a few minutes or even seconds, the power consumption of one of the four feeders of the traction substation (TS) can range from 0 to 10 MW. Such fluctuations in the load have a very negative effect on all electrical equipment. It should also be noted that, due to the lack of reliable receivers of the braking energy of the rolling stock (BERS) in the STPS of the underground, from 5 to 25% of the recovery energy is excessive and is lost in the braking rheostats in the form of heat.

Methods For Solving The Problem

One of the most complex methods for solving the stated problems is the local buffering of electricity at various stages of its delivery to the consumer, that is, the introduction of energy storage devices (ESD) in the STPS of the underground, capable of reducing capital investments in the main traction electric equipment, saving 30% of the electricity used

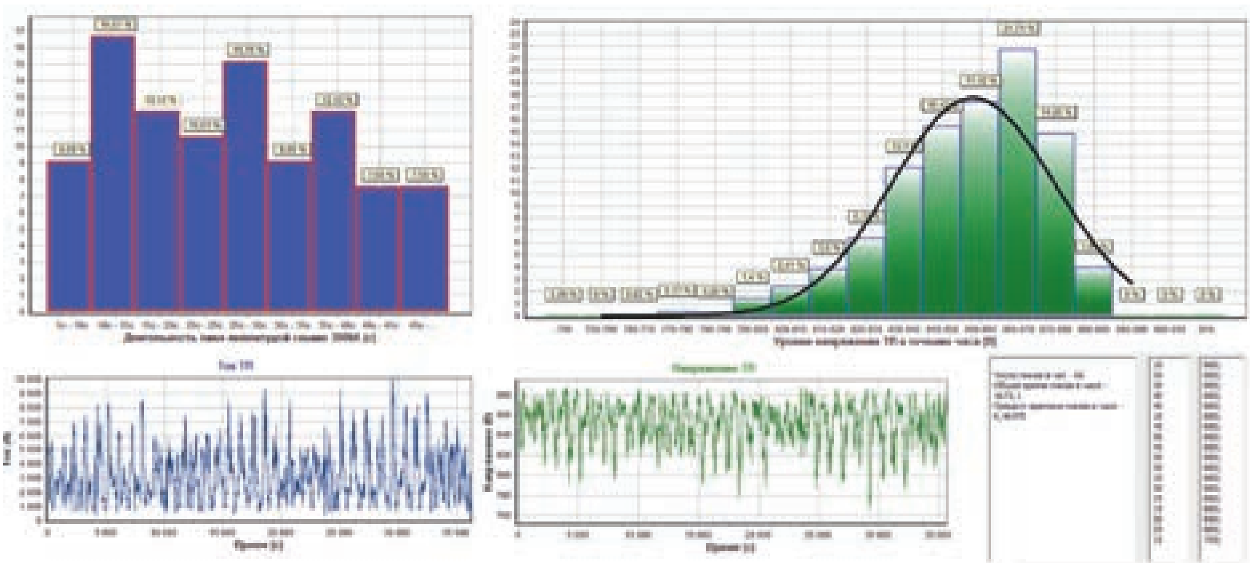

Figure 1. *The interface of the program for statistical processing of experimentally measured data*

for traction, and increasing the energy efficiency of STPS as a whole [4-7].

For assessing the efficiency of the use of ESD in STPS of the underground, in this paper has been developed a software-measuring complex (SMC) intended to solve a wide range of objectives of designing, operating and electric power processes in STPS, both the undergrounds and electrified railways. The main features of SMC include the functions of probabilistic modeling of the track profile for a given category of complexity, modeling the movement of the train, the automatic formation of deterministic and probabilistic train traffic schedule, the calculation of the parameters of the substitution circuit for the TS and the traction network, configurations and simulation of its operation, calculation of current loads of transformers and semiconductor converters of TS and comparison with permissible norms, calculation of current loads of feeders, determination of minimum and maximum stresses on current collectors, calculation of parameters of ESD, indicators and the choice of mode of operation, and so on. It should be noted that it is possible to use in SMC data of experimental measurements of the performance of electric power facilities of the underground.

To improve the accuracy of theoretical calculations, along with purely imitation modeling, the methods of statistical modeling were also used to estimate the characteristics of ESD, based on the processing of the results of the experimentally measured data on the operation of TS and BERS of the underground. In this case, the processing of TS operation (feeder and traction aggregate currents, as well as bus bar voltage) is performed as a function of time for several days with a small time sampling step (about 1 ms) - determination of the duty cycle of the starting currents and braking energy regeneration currents of BERS, currents of TS, their peak and average values for different periods of time, as well as the parameters of the laws of distribution of the investigated quantities.

Figure 1 shows an example of the processing of data on the performance of the TS-917 (*Rimskaya* station) of the Moscow Metro – the dependence of the current and voltage on the TS time for an hour during the intensive traffic period, the probability distribution of the peaks of the traction currents, the probability distribution diagram voltage levels of TS, selection of the laws of probability the density distribution.

With the help of the presented program of statistical processing and modeling (Fig. 1), experimental data on the performance of several TS at various hours of the day and under different Moscow metro power supply systems (centralized and decentralized) were investigated and the necessary dependencies were constructed.

A similar statistical analysis was performed from the given measurements of the performance of BERS. As a result, experimental data on the starting energies (As) and the deceleration energies (Ad) per one BERS car were obtained (Fig. 2).

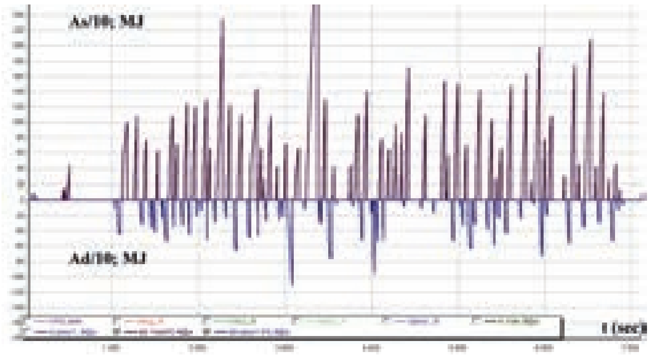

Figure 2. *The energetic indicators of BERS operation of the underground*

Further statistical modeling made it possible to combine experimental data on TS and BERS performance indicators, as a result of which it was possible to estimate the order of excess energy of recovery in STPS, as well as the power capacity and the power of the stationary ESD needed for its adoption at TS.

In this case, the theory of processing systems of random functions was used, on the basis of the "Normal" (*Gaussian*) distribution law, and the required two-parameter dependence obtained the following form:

$$f(A,P)=\frac{1}{2\pi\sigma_A\sigma_P\sqrt{1-r_{AP}^2}}\cdot$$

$$\cdot\exp\left[-\frac{1}{2\sqrt{1-r_{AP}^2}}\cdot\left[\frac{(A-m_A)^2}{\sigma_A^2}-\frac{2r\cdot(A-m_A)\cdot(P-m_P)}{\sigma_A\sigma_P}+\frac{(P-m_P)^2}{\sigma_P^2}\right]\right]$$

$$r_{AP}=\frac{K_{AP}}{\sigma_A\sigma_P};\qquad K_{AP}=\sum_i\sum_j(A_i-m_A)\cdot(P_j-m_P)\cdot p_{ij} \tag{1}$$

Where:

- $m_{A,P}$ и $\sigma_{A,P}$ – are the mathematical expectation and the standard deviation of the energy intensity and power of ESD;
- rAP is the correlation coefficient;
- KAP is the correlation moment;
- pij is the probability that the system (A, P) takes the values Ai and Pj, and the summation extends over all possible values of the random values A, P.

The proposed method and model of statistical processing, based on pre-measured or modeled distribution laws, allows using the original metro line data (profile, location of stations and TS, type of BERS, dimensions of motion, etc.) and experimental measurement data to determine energy and capacity of storage facilities, as well as assess the preliminary technical and economic effect.

Figure 3 shows the spatial surface of the probability distribution density (p;%) of the excess energy recovery as a function of the energy capacity (A; MJ) and the power (P; MW) of the ESD for TP of the underground. In this case, the simulation was made for TS-917 *Rimskaya* station of the *Lublinskaya* line of the Moscow Metro. It is clearly seen from the schedule that for a given substation the energy intensity of the ESD for taking almost all the excess energy of recuperation should be about 70 MJ, and its power should be about 2.5 MW.

Preliminary statistical modeling (Fig. 3) made it possible to determine the parameters of ESD for its use at the TS of the *Filevskaya* line of the Moscow metro. Figure 4 presents the results of simulation of the ESD operation during the day, which were subsequently used for comparison with the experimental data.

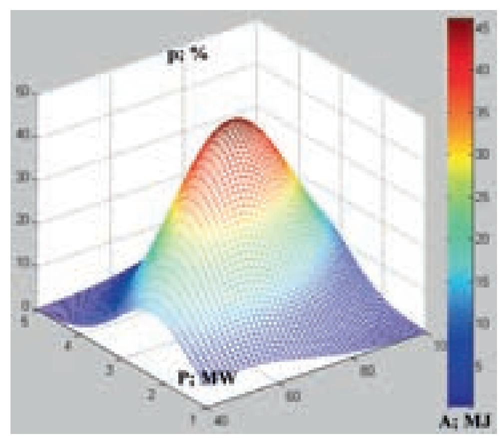

Figure 3. *The surface of the distribution of the probability density of accepting excess energy of recuperation in the dependence on the energy intensity and power of the ESD for the TS of the underground*

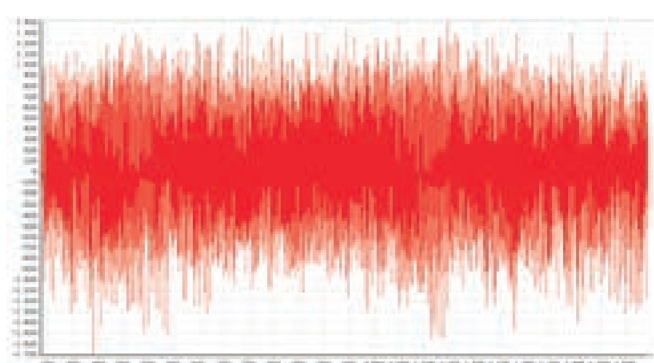

Figure 4. *The ESD current as a function of time during the day by the results of simulation*

Thus, SMC with ESD and additional applied programs make it possible to carry out the whole range of research and design work related to the calculation of all the performance indicators of the STPS, and the SMC modules that are part of the SMC and individual ESD modeling application programs at any points of the STPS allow to investigate their operation modes and the processes of energy exchange in the network, that makes it possible to estimate the necessary parameters of ESD and the technical and economic efficiency of their use accurately enough.

Evaluation of the Results in Practice

After lengthy studies on the basis of experimental measurements and simulation experiments, it was decided to install two ESD of an uncontrolled type on traction substations T-23 and T-24 of a low-loaded *Filevskaya* line of the Moscow underground of an open type [1-3]. Energy accumulators of an uncontrolled type are those ESD, the accumulating element of which is connected directly to the TS buses, and the modes of charge or discharge of ESD are determined by the conditions of circulating energy in the traction network.

The accumulating element of each ESD consists of electrochemical capacitors of the Russian company *OOO EKE (Elton)*. Each of the storage units consists of 14 cabinets manufactured by the Russian company *JSC Zavod konvertor*. Each cabinet contains 11 storage modules connected in series. The total capacity of ESD (14 cabinets) is 187 F, and the maximum operating voltage is 990 V.

Energy storage devices were included in the regular operation in January 2014. With the purpose of analyzing the functioning of ESD, the work of the new device was monitored, namely, for many days continuously measured and recorded the currents of charge and discharge of ESD, voltages on its buses, followed by statistical processing of the received data.

Figure 5 shows the dependence of the TS, ESD current and their positive sum, i.e. the current that goes to the traction network for powering the trains, in the function of time for 2 minutes.

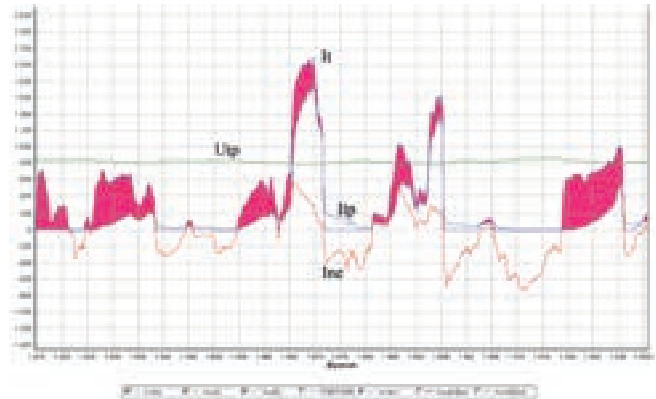

Figure 5. *Currents TS, ESD and their sum (access to the traction network for powering trains) as a function of time for 2 minutes based on the results of the full-scale experiment*

The processing of the results of experimental measurements showed that the reduction of the consumed peak power of TS (for a specific measurement period) was about 13.4%. At the same time, the maximum value of the consumed current from TS, due to feeding of the storage device, decreased from 7 kA without ESD to 5.5 kA in the presence of ESD (that is, by 27%).

Figure 6 shows a continuous diagram of the consumption of electricity (power) for meters on traction units of the T-23 substation at half-hour intervals for two days. From the diagram, the fact of a decrease in power consumption is shown visually when alternating days with disconnected and switched on ESD are alternating.

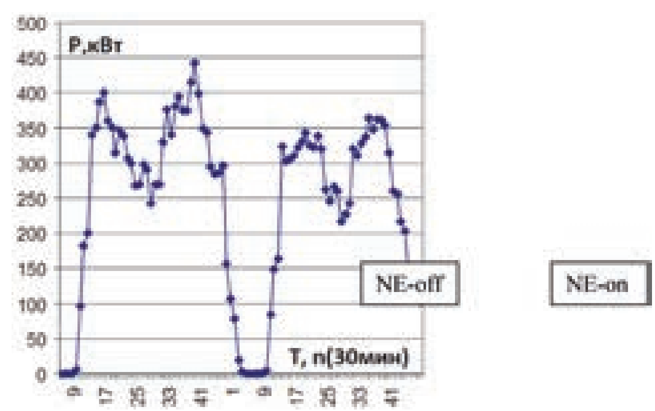

Figure 6. *Power on metering devices at substation T-23*

The indicator of TS power reduction due to ESD is very important, as it affects the reduction of power losses, the increase in the efficiency of traction aggregates, the reduction of power consumption and the reduction of capital costs for the main traction equipment of TS, as well as the reduction of fare for paying for electricity at an average power level .

The average power level of the TS for a certain period of time, usually 30 minutes, taking into account the work of ESD ($P_S^{(30)}$) can be estimated by the following formula:

$$P_S^{(30)} = \frac{A_T^{(30)}}{T^{(30)}} = \frac{A_{TP}^{(30)} + A_{NE}^{(30)}}{T^{(30)}} \quad (2)$$

$$P_S^{(30)} = \frac{1}{T^{(30)}}\left(\int_0^{T^{(30)}} p_{TP}(t)dt + \int_0^{T^{(30)}} p_{NE}(t)dt\right) = \frac{1}{T^{(30)}}\left(\int_0^{T^{(30)}} i_{TP}(t)u_{TP}(t)dt + \int_0^{T^{(30)}} i_{NE}(t)u_{NE}(t)dt\right)$$

Where:

- $A_T^{(30)}$ - is the energy that goes to BERS traction;
- $A_{TP}^{(30)}$ - is the energy from TS;
- $A_{NE}^{(30)}$ - is the energy from ESD;
- $T^{(30)}$ - integration time;
- P_{TP} и P_{NE} –instantaneous power of TS and ESD;
- i_{TP} и u_{TP} – instantaneous current and voltage values of the TS;
- i_{NE} и u_{NE} –instantaneous values of current and voltage ESD.

During the operation of ESD, the integrated performance of the drive was also evaluated, namely, energy characteristics and efficiency - the charge and discharge energies of ESD can reach values of the order of 10-12 MJ per charge-charge cycle, and the mean daily efficiency of ESD was about 0.95. The saving of power consumption by feeder network tractors reached about 0.5-2.5% in the winter and 5.6% in the spring period of the underground operation.

To assess the adequacy of the simulation results of the ESD operation on the TS, the calculated data (Fig. 4) were compared with the experimental measurements. Figure 7 shows the current ESD diagram during the day and the selected law of probability density distribution of ESD current. Studies have shown that the distribution of the value of the ESD current in the experiment and in the simulation is in accordance with the normal law. The hypothesis about the "Normal" (*Gaussian*) distribution was tested using the *Pearson* agreement criterion.

It should be separately noted that a comparison of the experimentally obtained results and the results of simulation showed good convergence in the selected statistical characteristics. The table presents comparative data of statistical processing of results of simulation and experimental measurements.

Chart 1. *Comparative results of statistical processing*

Index	Experiment	Calculation
Expected value, A	-2.071	-2.525
Standard deviation, A	282.457	293.945

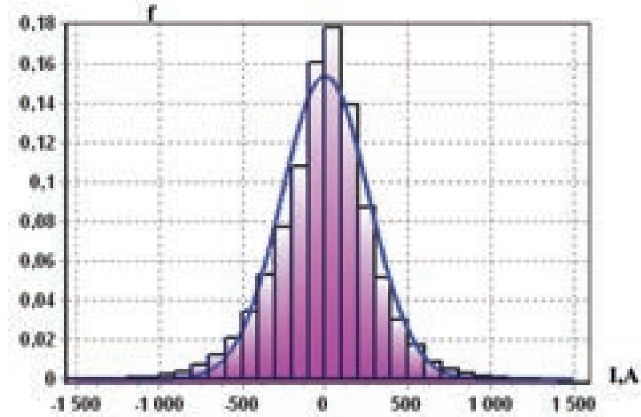

Figure 7. *Distribution of the probability density of the current ESD*

CONCLUSION

Thus, the ESD performance indicators in the regular mode reflect a high correlation with the calculated data and have the following values:

- the maximum charge currents were about 1800A;
- the maximum discharge currents amounted to about 2300A;
- the maximum received energy per one recharge cycle was 10.5 MJ;
- the maximum energy given for one recharge cycle was 11 MJ;
- the average daily efficiency of the ESD was 95.5%;
- energy savings amounted to 0.5-2.5% in the winter period and 5.6% in the spring period;
- reduction of the peak power consumption of the transformer substation was 13.4%.

Monitoring of initial operation showed that the installation of ESD on the T-23 allowed to partially smooth out the schedule of TS power consumption, to reduce the voltage drop on the TS buses and to increase the overall energy reliability of the traction power supply of the Moscow Metro.

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