The theory development for determination of rational parameters of the capacitive energy storage for a metro train

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Abstract. In the article a comparative analysis of existing methodologies and approaches on the parameters determination of the capacitive energy storages for a metro train with energy recovery systems was performed, disadvantages of each of them were determined. A complex approach for estimation of the on-board capacitive energy storage parameters was proposed; the point of approach consists in determination of the rational power and energy capacity for two parameters of the storage system at once – mass and payback period. The complex approach is based on theoretical researches, which require simulation of the metro train equipped with recuperation system operation by mean of developed software. The objective function was represented and boundary values for the power and energy capacity during determination of the rational parameters of the on-board capacitive energy storage using a complex approach were specified. The recuperation system with rational parameters of the on-board capacitive energy storage for specified service conditions in Public Utility Company “Kyiv Metropolitan” and chosen research metro train was specified. Amount of energy stored due to the installation of the energy storage system with rational parameters was estimated.

1. Introduction
At the moment, one of the priorities and urgent tasks in the subway is to reduce electricity consumption by its rolling stock. To this end, scientists have focused their work on increasing the use of regenerative braking electricity in the following areas: optimizing the train schedule, streamlining the train mode, the introduction of inverters and energy storage. In works [1,3] the organizational method on reduction of energy consumption and increase of efficiency of use of the electric power of regenerative braking which is based on optimization of movement of the subway trains is offered. Also, in these works the technical measures of reduction of electricity consumption by trains - introduction of inverters on traction substations and energy storage devices are considered in detail. In work [2] the automatic system of control of movement of the subway train is offered. Rational mode of train operation allows to significantly reduce electricity costs. Over the last years companies of the USA, Japan, Korea, European Union countries and domestic manufacturers have greatly increased electric power characteristics of the capacitive energy storages (CES), which are also called super capacitors, ultra capacitors, ionistors, electric double-layer capacitors. It led to performance of a great number of researches concerning their practical use as power supply sources, including underground railway systems for saving electrical energy of the regenerative braking and its recovery by the electric
traction drive during train acceleration. However, determination of necessary parameters of the on-board CES for a metro train, remains one of the insufficiently studied and current problems.

2. Literature review

Researches [4-6], which concern an issue of determination of the on-board CES parameters, particularly its power and energy capacity. In works [7-9] determination of the on-board CES parameters is recommended to be performed using theoretical researches as well as date analysis results of experimental researches of energy processes between the overhead line and the electric traction drive under standard operational conditions of the rolling stock. These researches and research are presented in the works [10, 11] are based on the use of such methods and key points: a point of the electric traction theory and numerous methods of integration techniques, methods of the analysis of density characteristics for power division and amount of recuperated energy, points of the probability theory, theoretical basis of the electrical engineering etc.

However, according to the results of works [12-14] it is known that, these methods and points don’t let to take into account a number of factors of the actual operational conditions completely. Key factors of these are: gauge profile, cars load, change of the train schedule during within 24 hours, composting braking. The main disadvantage of methods and approaches proposed in mentioned works is impossibility of the determination of rational parameters of the on-board CES. The analysis of advantages and disadvantages of each method is given in work [14] in more detail.

In existing works [12, 13] the choice of the on-board CES parameters is recommended to be done according to the criterion of the minimum payback period of the storage system. The storage system consists of the on-board CES, the reversible static converter and the control system of the energy-exchange processes between the on-board CES and the electric traction drive. The principle of the approach if in the parameters determination according to the result of the analysis of the payback period diagrams for chosen storage systems. The advantage of the approach use is in the determination of the rational parameters of the on-board CES. For this purpose, actual operating conditions of the metro train equipped with recuperation systems are taken into account. The disadvantage of this approach is the determination of the rational parameters of the on-board CES according to one criterion – the payback period of the storage system.

In work [14] a complex approach for the rational parameters estimation of the on-board CES was proposed, which allows choosing it according to two important factors of the storage system – weight and payback period. This approach requires performance of the experimental researches in the standard actual operating conditions. In addition to this the complex approach lets to take into account those factors, which were not considered in the above-mentioned works.

However, the complex approach, proposed in work [14], which is based on the analysis of the experimental researches data also has disadvantages. Main disadvantages of the experimental research’s performance are great time consumption and financial expenses. One more important disadvantage that does not allow getting a truthful overview is the impossibility to consider load change of the train during its operation, because performance of such researches in conditions of the regular traffic is rather problematic. As a rule, during experimental researches it is assumed that a train is operated with minimum, nominal and maximum load per day. And accordingly, experimental researches of the energy processes at the best case are performed during standard train operation for three loading modes. Therefore, during performance of researches for determination of the rational power and energy capacity of the on-board CES by using data of the experimental researches there is an inaccuracy, which rises because the change of the train load during its operation was not performed. That is why in this paper in order to decrease financial expenses, time for researches and increase the accuracy of obtained results we proposed to perform researches on the determination of the rational parameters of the on-board CES using a developed mathematical model of the metro train operation equipped with recuperation systems.

Purpose – to determine rational power and energy capacity of the on-board CES using a complex approach of the parameter’s estimation, which based on methods of theoretical researches.
3. Matter and methods of research
The complex approach for determination of the rational parameters of the on-board CES assumes a stage-by-stage procedure of research (Figure 1). As it was mentioned above, the point of the approach is in the determination of the rational parameters by two parameters of the storage system at once – weight and payback period.

![Figure 1. Procedure of the rational parameter’s determination of the on-board CES using the complex approach.](image)

While the main difference from the approach described in paper [14] is that this procedure is based on theoretical researches, the point of which is in simulation of the metro train operation with recuperation systems using the software.

A generalized mathematical description of the objective function of the complex approach with determination of the rational parameters of the on-board CES can be represented the following way:

\[
F(\bar{X}) \rightarrow \text{extremum} \quad \bar{X} \in D_1...D_k
\]

Where, \(F(\bar{X})\) is the main criterion of the optimality, \(D\) is area of feasible solutions, which is determined by boundaries of corresponding values (parametric limitation), \(k\) is amount of accepted limitations for a search of the optimum solution.

In our case the payback period of the storage system was chosen as the main optimization criterion. Taking into account the chosen criterion definition of the optimization task: to find such values of the power and energy capacity of the on-board CES\((P_{\text{CES}}, A_{\text{CES}})\), at which:

\[
T_{pp} = F(P_{\text{CES}}, A_{\text{CES}}) \rightarrow \text{min.}
\]

In this case the following boundary values of the parameters were specified for the objective function: \(P_{\text{CES}} \in [0...P_{\text{Am}}]\), \(A_{\text{CES}} \in [0...A_{\text{Am}}]\), \(P_{\text{CES}} \in [0...P_{\text{max}}]\), \(A_{\text{CES}} \in [0...A_{\text{recmax}}]\), where \(P_{\text{Am}}\), \(A_{\text{Am}}\) is maximum values of power and energy capacity by weight, which depend on the metro train type with recuperation systems and condenser modules; \(P_{\text{max}}\), \(A_{\text{recmax}}\) is maximum values for power and energy recuperation amount for specified standard train operation.

Provided that the objective function has several minimum values, the storage system which can save maximum amount of the electrical energy must be chosen, that is:
\[ \alpha = \begin{pmatrix} T_{pp1} \\ T_{pp2} \\ \vdots \\ T_{ppj} \end{pmatrix} \rightarrow \max, \] (3)

where \( j \) is a number of storage systems with the same minimum payback period; \( \alpha \) is amount of the saved electrical energy due to storage system installation.

Further using this approach, we analyzed determination of the rational power and energy capacity of the on-board CES for specified operation conditions of the metro rolling stock with energy recovery systems.

First stage. A section between terminal depots Sviatoshynsko-Brovarska line of PU “Kyiv Metropoliten” was chosen as a test section. The test rolling stock is a train of 5 five cars with asynchronous electric traction drive and energy recovery systems in which engine cars – trailer cars, middle – motor cars (train, which consists of cars models 81-7080, 81-7081, 81-7081-01).

Second stage. Performance of the traction calculations, which are based on principles of the traction effort choice (deceleration) taking into account limitations on the maximum motor torque, wheel – rail adhesion and providing specified train operation dynamics by traction motors.

Thus, according to the results of the traction calculations for specified conditions it was determined that weight of the storage system for a chosen type of the train should not exceed 7.86 t.

Forth stage involves metro train simulation. Developed and certified software Motion Simulation (further – SW “Motion Simulation”) was used to perform modeling of the dynamic and energy processes under standard specified metro train operation conditions. Input data, values of dynamic and energy processes, and resulting output values, which are determined during simulation, calculation formulas for these values are reviewed and reported in paper [15] in details, so there is no need to stop on this issue in more detail. That is why it is not necessary to dwell on this issue. It should be noted that the input data implies setting: energy characteristic (dependence of the efficiency factor of the traction motor on running speed), a number of set train operation modes on a line, gauge profile parameters, static and dynamic parameters for each train operation mode.

At the fifth stage, mathematical modeling data is processed. Data processing was performed using SW “Motion Simulation”. The main result is the determination of the following values: the amount of electric energy consumed for traction \( (A_{\text{traction}}) \), the amount of electric energy generated by the train during regenerative braking \( (A_{\text{reg}}) \), the maximum power in recovery mode \( (P_{\text{max}}) \).

Therefore, the first boundary values of the on-board CES parameters based on the obtained data results were established: \( P_{\text{CES}} \in [0...3.88] \), \( A_{\text{CES}} \in [0...45.09] \). Other boundary values of power and energy capacity are determined taking into account weight limitations and depend on chosen types of CES.

In the sixth stage parameters of CES are chosen (power and energy capacity. In our case area of power and energy capacity boundary values of the on-board CES is determined under conditions of using storage systems, assembled on the basis of condenser modules produced by such well-known manufacturers as EKOND (Russia), Nesscap (Korea), Maxwell (USA), Epcos (Germany). General appearance of chosen condenser modules is given in Figure 2. Storage systems of the necessary value of the service voltage, power and energy capacity were formed by means of series-parallel connection of specified condenser modules. Weight of storage systems were determined by summing up weight of condenser modules (on-board CES), operated transducers, metallic structures, connecting wires (bars), stress gauges and current transducers, cooling systems components, control systems and other additional materials.
Therefore, other boundary values of the on-board CES parameters were set, taking into account weight limitations. Taking into account determined limitations after processing data of the mathematical simulation and weight, the following boundary values of the parameters of the storage systems with operating voltage of 450-900 V were set:

- for storage systems of condenser modules type 10EK303 – $P_{CES} \in [0...3.88]$, $A_{CES} \in [0...15.3]$;
- for storage systems of condenser modules type 30EK404 – $P_{CES} \in [0...3.88]$, $A_{CES} \in [0...10.9]$;
- for storage systems of condenser modules type ESHSR – 3000C0-002R7A5 – $P_{CES} \in [0...3.88]$, $A_{CES} \in [0...26.9]$;
- for storage systems of condenser modules type BMOD0063P125 B08 – $P_{CES} \in [0...3.88]$, $A_{CES} \in [0...13.0]$;
- for storage systems of condenser modules type BMOD0165P048 BXX – $P_{CES} \in [0...3.88]$, $A_{CES} \in [0...21.7]$;
- for storage systems of condenser modules type B49300L1276Q – $P_{CES} \in [0...3.88]$, $A_{CES} \in [0...13.5]$.

Based on the obtained boundary values of the on-board CES parameters, for further calculations, depending on the type of condenser modules, on-board CES with the level of power and operating energy capacity were chosen according to Table 1.

### Table 1. Chosen parameters of the on-boards CESs.

| Type of the condenser module | Power, MW | Energy capacity, kW·h |
|------------------------------|-----------|----------------------|
| 10EK303                      | 1.7; 3.4  | 6.4; 12.7            |
| 30EK404                      | 0.8; 1.7; 2.5; 3.4 | 1.7; 3.4; 5.0; 6.7  |
| ESHSR – 3000C0 – 002R7A5    | 1.1; 2.2; 3.3 | 1.0; 1.9; 2.9       |
| BMOD0063P125 B08            | 1.5; 3.1  | 1.1; 2.2             |
| BMOD0165P048 BXX            | 1.7; 3.3  | 1.1; 2.2             |
| B49300L1276Q                | 0.7; 1.5; 2.2; 2.9; 3.6 | 0.7; 1.3; 2.0; 2.6; 3.3 |
In this case, the total number of chosen storage systems with different levels of power and energy capacity of the on-board CES that satisfy the conditions (defined by limitations) is 18.

Seventh stage. Estimation of the cost of storage systems is performed according to the results of a technical and economic analysis of the selected on-board CESs cost, reversible converters and other ancillary equipment produced by manufacturing companies of this production. So, the cost of each chosen storage system was determined. In addition, the cost factor of chosen storage systems, depending on their parameters and the type of condenser modules used comprises 1.1-3.9 mln. UAH for 1 t.

The eighth stage is to research the amount of saved energy due to implementation of the chosen storage systems. Certain research is performed for each type of a chosen storage system. Initially, for each typical operational condition and a chosen storage system, a power limitation check is performed, the results of which, if necessary, are used to recalculate the amount of recuperated electric energy to the capacitive storage. Next, an estimation of the amount of stored electric energy is performed, taking into account the energy capacity limitations using the sub-program "Energy Recovery". The operation algorithm of the above-mentioned sub-program is particularly described in paper [16].

The following values have been determined during research: amount of stored electric energy for one cycle of storage (regenerative braking and its accumulation during the train acceleration), amount of the stored electric energy for each standard operating condition, the amount of stored electric energy over a year. Thus, using the mentioned sub-program we determined the amount of stored electric energy as a result of chosen energy storage systems implementation.

The ninth stage involves creating characteristic (diagrams) for the payback period of the storage systems depending on the operating power and energy capacity of the chosen CES.

The payback period value is determined by relation of the cost of the storage system implementation and the cost of energy stored. Calculation results of the payback period for chosen storage systems are represented by diagrams in Figure 3.

The tenth stage (determination of the system with rational parameters). According to the results of the analysis of the payback period diagrams for storage systems it is obvious that for specified operating conditions of the metro train the most suitable is the system with operating energy capacity of 1.7 kW·h and maximum power of 0.8 MW assembled from the condenser modules type 30EK 404. The payback period of this system is minimal and comprises 3.2 years and its weight is about 1.2 tons.
On condition of implementation of the storage systems with rational parameters we have calculated the amount of stored energy in relation to consumed electric energy according to formula [16]:

\[
\alpha = \frac{E_r}{A_{\text{traction(year)}}} \times 100, \tag{4}
\]

where \( A_{\text{traction(year)}} \) is amount of consumed electric energy per year, kW·h.

According to formula 4 it was determined that for specified operational conditions the implementation of storage systems with rational parameters on the on-board CES allows to store 11.4% of the consumed electric energy volume of the traction. In this case the weight of the storage system with rational parameters is about 0.5% and 0.8% of the metro train weight at maximum load and when empty respectively. As a result of this storage system implementation dynamics of the train acceleration will be reduced by 0.5%.

4. Conclusions

1. Using a complex approach for parameters estimation, which is based on methods of theoretical researches, rational parameters of the on-board CES were determined (maximum power and operating energy capacity) for specified operational conditions of the metro train with energy recovery systems.

2. Methodology of the complex approach for determination of the rational parameters of the on-board CES during theoretical research was improved; the object of the research is a simulation of the metro train operation with energy recovery systems using software which helps to reduce financial expenses, research time and improves their accuracy.

3. According to results of performed researches it was determined that for specified train operation modes it is rational to use storage systems with the on-board CES with operational energy capacity of 1.7 kW·h, and maximum power of 0.8 MW. It was determined that the payback period of this system is 3.2 years, and its weight is 1.2 tons.

4. Implementation of the storage system with rational parameters for specified operation conditions allows to save up to 11.4% of the electrical energy amount consumed by traction. In addition, the weight of the storage system with rational parameters is about 0.5% and 0.8% of the metro train weight at maximum load and when empty respectively. As a result of this storage system implementation dynamics of the train acceleration will be reduced by 0.5%.

5. It is proposed to develop a theory for determination of rational parameters of CES for a metro train in case of using theoretical research, which allow modeling of the metro train operation with energy recovery systems instead of experimental research. Further research should be focused on the development of theory for determination of rational power and energy capacity values of the on-board capacitive energy storages taking into account energy-optimal operating conditions of the metro rolling stock equipped with the energy recovery systems.
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