Algorithm for implementing energy-efficient traction substations on the subway

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Abstract. The work is devoted to the modernization of traction substations on the subway. The paper deals with the problem of using energy-saving technologies in the subway. The practical value of the work results lies in solving an urgent problem aimed at reducing the level of power consumption in the metro system. The paper considers the possibility of modernizing traction substations by using multiphase solutions that improve the stabilization properties of the rectified voltage and reduce the loss of electricity by energy output to storage devices installed on the vehicle. Circuitry solutions have been developed for transformer-rectifier units (TRU) with 24-fold rectified voltage ripple, which make it possible to reduce active power losses in transformer equipment and valve structures and to increase the stabilizing properties of the rectified voltage.

1. Introduction

The strategic direction of priority development of many areas of industry and sectors of the economy, including the transport industry, in connection with the worldwide rise in energy prices, is the problem of reducing losses in the transformation, distribution and consumption of energy. The liberalization of the Russian energy market implies an increase in energy prices. The inevitable increase in the energy component of costs in energy-intensive industries at a rate of 6%-8% per year will require not only the introduction of energy-saving technologies in all industries, but also the development of fundamentally new solutions aimed at increasing the efficiency of energy conversion. It is possible to create competitive samples in the domestic and global markets only through the use of the latest technologies and developments in the element base, using modern materials for electric rolling stock (EPS) [1, 2].

In recent years, one of these areas has been the development of new types of efficient sources of secondary energy and energy converters with qualitatively new properties that allow them to be effectively used in the transport industry of the country, reducing energy losses, increasing efficiency, increasing the service life of equipment and the reliability of the electric transport complex in the whole.

At the turn of the 20th and 21st centuries, in connection with significant progress in information technologies, it became possible to quickly and efficiently perform complex and laborious
calculations, create software systems that simulate the processes of movement of a vehicle (MV). As a result, it became possible to significantly increase the accuracy of forecast calculations [3].

The main reason for the unprofitability of transport enterprises specializing in passenger transportation is the constant rise in the cost of energy carriers with a high-energy intensity of the metro. Therefore, the introduction of energy-saving technologies is of particular importance.

The main one of the most important tasks at present is to improve the operational indicators of the city Metro, which contribute to:

- reducing the cost of equipment maintenance;
- increasing its reliability;
- the emergence of an opportunity to significantly reduce energy consumption during conversion.

2. Directions of modernization of the substation, contributing to the improvement of technical and economic indicators

Solving these problems requires considering the equipment (converter) as a complex technical system that needs to be modernized in the following areas, taking into account the specifics and modes of operation, the specifics and possible types of failures:

- Increase in phasing;
- As a result of a patent search, circuitry solutions for TRU with 24-fold rectified voltage ripple were found, which allow to reduce active power losses in transformer equipment and valve structure and to increase the stabilizing properties of rectified voltage.

Currently, the overwhelming majority of TRU is outdated, not only in terms of energy saving, but also in terms of reliability and performance. In this paper, the possibility of upgrading the TRU by using the circuitry solutions of the TRU with multiple ripple of the rectified voltage is considered.

The authors proposed the use of 24-pulse TRU. The schematic diagram of a 24-pulse circular TRU synthesized using the method of rotating vector diagrams contains two identical 12-pulse TRU [4].

Figure 2 shows a vector diagram of a 24-pulse ring modular TRU with a series connection of TRU.

Figure 2 presents in the form of amplitude-phase portraits (APP) of the voltages of the secondary windings, which make up two six-phase systems of symmetric voltages by vector diagrams deployed on the phase plane. The applied six-phase EMF systems determine the topology of constructing vector diagrams and form their amplitude-phase characteristics. Gate windings "star" and "triangle" with the ratio of turn numbers 1 to 1/√3 provide the formation of the resulting voltages, the modules of the vectors, which are equal to 30 e. hail on the phase plane, are shifted relative to each other. Then we fix the first system voltage diagram, and rotate the second voltage diagram of the second system around it, thus we get 24 resulting voltage vectors for one period of the mains voltage. For each fixed position on the phase plane of voltage systems, we determine the elements of the valve structure, as well as the order of operation of the valves and secondary windings [5]. The four positions of the rectifier unit systems do not show the order of the formation of the vectors of the resulting stresses S1-S2, S9-S10.S15-S16, S23-S24.

According to the principle of operation of the TRU (Figure 2) and from the features of the formation of the resulting voltages according to the vector diagrams of the voltages of the EMF sources (Figure 2), the alternation of the connection of the load current flow circuits for all twenty-four phases of the rectifying process is shown in Table 1. In this table the numbers of the gates switched on under the influence of the indices of line voltages are highlighted in the order of entry into operation during the formation of ripples Si, they are shown in accordance with the vector diagram in Figure 2.
Figure 1. The schematic diagram of a 24-pulse circular TRU.

Figure 2. Vector diagram of 24-pulse circular modular TRU with serial connection of units.
Table 1. The order of operation of rectifier units TRU with series connection of branches

| Pulsation, $S_i$ | Line voltage indices | Valve numbers |
|-----------------|----------------------|---------------|
| $S_1$           | $bc - a' \rightarrow b_1a_1 - c'_1$ | $D2, D6, D12 \rightarrow D14, D21, D23$ |
| $S_2$           | $bc - a' \rightarrow a_1c_1 - c'_1$ | $D2, D6, D12 \rightarrow D13, D21, D23$ |
| $S_3$           | $bc - b' \rightarrow a_1c_1 - c'_1$ | $D2, D6, D11 \rightarrow D13, D21, D23$ |
| $S_4$           | $bc - b' \rightarrow a_1c_1 - a'_1$ | $D2, D6, D11 \rightarrow D13, D21, D22$ |
| $S_5$           | $ac - b' \rightarrow a_1c_1 - a'_1$ | $D1, D6, D11 \rightarrow D13, D21, D22$ |
| $S_6$           | $ac - b' \rightarrow a_1b_1 - a'_1$ | $D1, D6, D11 \rightarrow D13, D20, D22$ |
| $S_7$           | $ac - c' \rightarrow a_1b_1 - a'_1$ | $D1, D9, D11 \rightarrow D13, D17, D22$ |
| $S_8$           | $ac - c' \rightarrow a_1b_1 - b'_1$ | $D1, D9, D11 \rightarrow D13, D20, D22$ |
| $S_9$           | $ab - c' \rightarrow a_1b_1 - b'_1$ | $D1, D5, D11 \rightarrow D13, D20, D22$ |
| $S_{10}$        | $ab - c' \rightarrow c_1b_1 - b'_1$ | $D1, D5, D11 \rightarrow D15, D20, D22$ |
| $S_{11}$        | $ab - a' \rightarrow c_1b_1 - b'_1$ | $D1, D5, D10 \rightarrow D15, D20, D22$ |
| $S_{12}$        | $ab - a' \rightarrow c_1b_1 - c'_1$ | $D1, D5, D10 \rightarrow D15, D20, D24$ |
| $S_{13}$        | $cb - a' \rightarrow c_1b_1 - c'_1$ | $D3, D5, D10 \rightarrow D15, D20, D24$ |
| $S_{14}$        | $cb - a' \rightarrow c_1a_1 - c'_1$ | $D3, D5, D10 \rightarrow D15, D16, D24$ |
| $S_{15}$        | $cb - b' \rightarrow c_1a_1 - c'_1$ | $D3, D8, D10 \rightarrow D15, D16, D24$ |
| $S_{16}$        | $cb - b' \rightarrow c_1a_1 - a'_1$ | $D3, D8, D10 \rightarrow D15, D19, D24$ |
| $S_{17}$        | $ca - b' \rightarrow c_1a_1 - a'_1$ | $D3, D4, D10 \rightarrow D15, D19, D24$ |
| $S_{18}$        | $ca - b' \rightarrow b_1a_1 - a'_1$ | $D3, D4, D10 \rightarrow D14, D19, D24$ |
| $S_{19}$        | $ca - c' \rightarrow b_1a_1 - a'_1$ | $D3, D4, D12 \rightarrow D14, D19, D24$ |
| $S_{20}$        | $ca - c' \rightarrow b_1a_1 - b'_1$ | $D3, D4, D12 \rightarrow D14, D19, D23$ |
| $S_{21}$        | $ba - c' \rightarrow b_1a_1 - b'_1$ | $D2, D4, D12 \rightarrow D14, D19, D23$ |
| $S_{22}$        | $ba - c' \rightarrow b_1c_1 - b'_1$ | $D2, D4, D12 \rightarrow D14, D18, D23$ |
| $S_{23}$        | $ba - a' \rightarrow b_1c_1 - b'_1$ | $D2, D7, D12 \rightarrow D14, D18, D23$ |
| $S_{24}$        | $ba - a' \rightarrow b_1c_1 - c'_1$ | $D2, D7, D12 \rightarrow D14, D21, D23$ |

According to the operation diagram of the valve windings and valves (Table 1 and Figure 2), it was determined that for the period of the rectified voltage of the group: valve anodes (1, 2, 3, 13, 14, 15) and valve cathodes (10, 11, 12, 22, 23, 24) have a conductivity angle of 120 el. hail.; the conductivity angles of the valves of the ring group are 900 el. hail. (for valves 7, 8, 9, 19, 20, 21) and 30 el. hail. (for valves 4, 5, 6, 16, 17, 18).

When braking, energy is recovered to the drive.
3. Algorithm of fuzzy control logic

One of the most important functional units of modern vehicles is an energy storage device that supplies power to the electric motor, depending on the driving mode. When designing, it is necessary to take into account that the energy storage device should have optimal properties with small weight and dimensions, which are provided by high specific energy and high specific power.

Each type of energy storage device has its own characteristic energy indicators, design and circuit design features, operating modes that determine the rational areas of their application.

Equipping the EPS of metropolitan with storage devices requires a detailed analysis of modern types of storage devices with the definition of the type of storage element, which most satisfies a variety of requirements due to the performance and parameters of vehicles [6].

To compare modern energy storage devices from the standpoint of their use in electric transport, we will formulate the main criteria that they must satisfy the following conditions:

1. Specific energy consumption, measured in Wh/kg or J/kg and determining the mass and dimensions of the storage device.
2. The specific cost of the storage device, which determines the investment.
3. Durability, measured by the total number of charge-discharge cycles or service life.
4. Efficiency in a wide temperature range.
5. Simplicity and availability of maintenance.
6. Charge time of the storage device (the choice is made based on the time of deceleration of the EPS).
7. Time and amount of losses during energy storage.
8. Power reverse time - the time during which the storage element can be transferred from the delivery mode to the accumulation mode, and vice versa.
9. Speed and depth of discharge (the depth of discharge allows to reduce the value of weight and dimensions).
10. Work safety.
11. High efficiency of the storage device.

4. Determination of losses in rectifier units

Based on the values of the current \( I_{av}^{(a)} \) and \( I_{av}^{(b)} \) average valve currents, depending on the angle of conduction of the valves, it is possible to calculate the energy losses in the valves depending on the \( \lambda \) of each valve, taking into account \( L \) in the rectified current circuit [7, 9]:

\[
\Delta P_{av} = P_{av} \cdot \left( \frac{1}{\lambda} \cdot \int_{0}^{\lambda} i(t)dt(t) \right)^2 + E \cdot \left( \frac{1}{\lambda} \cdot \int_{0}^{\lambda} i^2(t)dt(t) \right)
\]

(1)

The total losses in the valves for a 24-pulse circuit solution, depending on their \( \lambda \), can be determined by the expression [8]:

\[
\Delta P_{total} = \sum_{i=0}^{24} \left( P_{av} \cdot \left( \frac{1}{\lambda} \cdot \int_{0}^{\lambda} i(t)dt(t) \right)^2 + E \cdot \left( \frac{1}{\lambda} \cdot \int_{0}^{\lambda} i^2(t)dt(t) \right) \right)
\]

(2)

The influence of the total energy losses in the valves on the efficiency \( \eta \) of the TRU is expressed as follows:

\[
\eta = \frac{P_{av}}{\Delta P_{total} + P_{av}}
\]

(3)

Computational experiments using expressions (1, 2, 3) show that a decrease in energy losses in the valves caused by a decrease in the angle of rotation of valves in the proposed TRU leads to an increase in their efficiency in comparison with the existing 24-pulse rectifier within 0.25 - 0.38 %
At the end of the analysis of ring rectifiers, it should be noted that the primary analysis shows that a decrease in losses in the valve circuit occurs not only due to a decrease in the number of valve arms in the rectified load current circuit, but also due to a decrease in heat losses on the valves with a decrease in the conduction angles of the valves.

5. Conclusion
Comparing the advantages and disadvantages of TRU, we can conclude that, given the characteristics of modern devices, it is advisable to use a newer type at traction substations of the metro, based on 24 pulsations of the circuit. The advantages of such a power supply scheme are obvious - they are reduced maintenance and repair costs, increased reliability and energy savings.

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