Asymmetric power supply circuit design for electric rolling stock on the electrified DC rail

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***Abstract*— Modern requirements for the traction power supply system of direct current in providing the high-speed movement are reduced to the need of ensuring a normalized voltage level of 2900 V on current collectors of electric locomotives. At the same time, the power supply system has to be stable on changes in power consumption and have the necessary specific energy intensity. The purpose of the work is to explain the transition to a new circuit design of the traction network using additional generators of electric energy. The proposed asymmetrical power supply system of the electric rolling stock allows to provide the required voltage level on the electric locomotive current collectors, to reduce the range of its changes and to reduce the power losses by 14.3% compared to the symmetrical centralized power supply circuit design with passive boosting of the traction network.**

Keywords— traction power system, voltage rating, boost point, asymmetric power supply circuit design for electric rolling stock.

I. Introduction

Current trends in the development of society's requirements place high demands on traction power supply devices, which should provide the applied volume of transportation work throughout the year, taking into account the uneven movement and the difference in the weight of trains. Organizing high-speed traffic on the DC lines, one of the most important requirements for traction power supply is to maintain the voltage level of 2900 V on the current collector on the train. To fulfill this condition, the traction network must have sufficient energy intensity and ensure stability in operation when the volume of the transportation process changes, it requires the improvement of the DC traction power supply system (TPSS), its modernization and reconstruction.

It should be noted that on Ukrainian railways, TPSS boosting comes down to transferring sections to a parallel power supply circuit, increasing the cross-section of the contact network, replacing a 6-pulse rectifier unit with a 12-pulse one and increasing the open circuit voltage of traction substations. But even with the complex application of these methods, the 3.0 kV power supply system isn`t efficient and economical enough. It is unable to provide adequate voltage quality in the traction network. The fact is that with centralized power, the power is concentrated at traction substations (TS) and is not fully used. On average, daily TS loading while providing a schedule of intensive train movement does not exceed 20-25%, with energy losses in the traction network at peak loads increasing and reaching 10-15% of the consumed energy. The analysis of the results of the performed calculations [1] allows us to draw the following conclusions: first, none of the applied power circuits provides a normalized voltage level in the traction network when performing a high-speed motion with a 10 MW electrical rolling stock at the rated voltage on the traction substation buses (3300 V); secondly, increasing the voltage on the traction substation buses to 3800 V will allow to realize high-speed traffic on the DC sections only at the nodal and parallel power supply circuits, thus, in fact, recuperation will be impossible. It is also necessary to take into account the fact that on the traction substation buses of Ukraine, the voltage is mainly maintained at the level of 3500-3600 V [2], it limits the control of voltage modes during the introduction of high-speed traffic. As a result of the studies performed [3], it was shown that the existing power supply system using any power supply circuit is not voltage stable and needs to be modernized, since the post parallel conjunction (PPC) and sectioning post (SP) are located in the voltage instability zone, application which is called, among other things, to improve the voltage regime in the traction network (Fig. 1 [3]). It is necessary to note that the existing practice of designing the TPSS of the SP location is provided inside the feeder zone to ensure the selectivity of relay protection. In most cases, PPS is located at equal distances between the TS and the SP. That is, the existing symmetrical circuity engineering of DC TS is not always able to provide the necessary power and high-quality power transmission for high-speed trains [3].

Assessing voltage stability is a major issue in stability analyzes and in general energy systems. In well-known works [4-6], various voltage stability indexes (VSI) are proposed. These indexes can be used to optimize decentralized traction power supply systems (DTPSS), identify weak points and take

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countermeasures to increase sustainability. [4] considered VSI from different aspects, such as concepts, assumptions, critical values, etc.

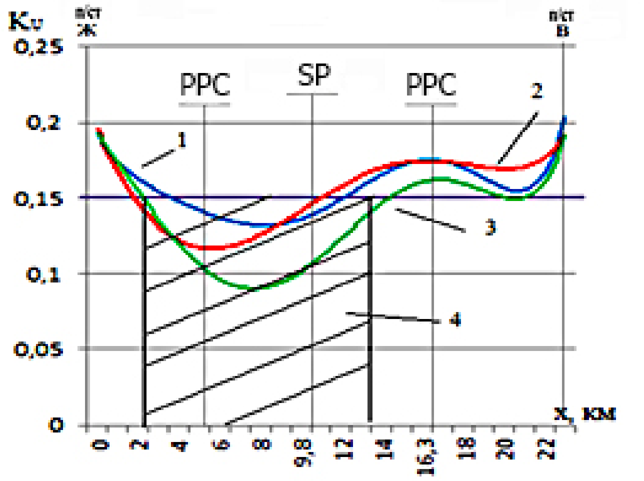

Fig. 1. Static stability when applying different power circuits of the traction network: 1 - parallel circuit; 2 - node diagram; 3 - two-sided circuit; 4 - instability zone.

The work [5] describes methods for monitoring the stability of a power system by voltage under conditions of incomplete information on the base of artificial neural networks. It stands to mention that the problems of sustainability in power systems are given much more attention than in traction systems. One of the methods of increasing the stability of power supply systems is the usage of voltage regulators (VR). The work [6] proposes to use a genetic algorithm to determine the amount, location, and nominal power of VR. In turn, it was shown in [7] that the use of a nonlinear regulator is most appropriate for voltage regulation.

From there in order to ensure the stability of the TPSS operation modes in connection with the widening of the high-speed range as the load increases, it is necessary to form new approaches to the modernization of the TPSS structure and circuitry engineering. One of such modernization directions is the use of additional power sources in the unstable zones, that is, an asymmetrical circuit design of the traction network.

II. Material and Method

Obtaining the results of studies [3, 7] was based on the time dependence of current and voltage during the experimental trips on real sections of electrified railways with the existing train schedule. The justification of the need to develop a new approach to TPSS circuitry engineering and variant calculations were carried out by us on a simulation model [8]. Computational studies were carried out for an electrified section with a length of 20 km, it receives power according to a parallel circuit with a symmetrical arrangement of parallel connection posts and sectioning posts (Fig. 2) and for a given train schedule (Fig. 3). The open circuit voltage of traction substations is 3500 V, the traction network is M-120 + 2MF100 + A185 + P65. Temporary implementations of the consumed currents of the electric rolling stock are shown in Fig. 4. The results of the calculation of the voltage mode for the output circuit (Fig. 2) are presented in Fig. 5.

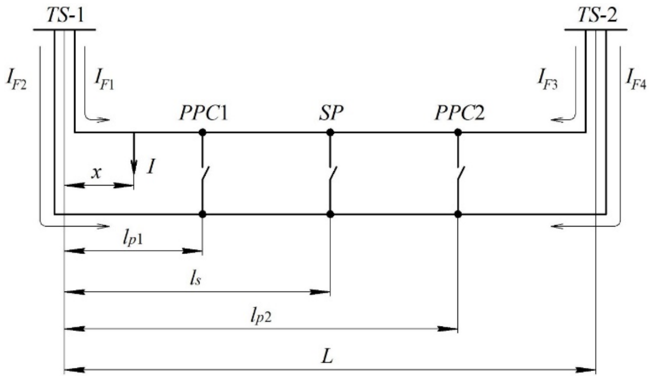

Fig. 2 - Calculation model where: lp1 = 5 km, ls = 10 km, lp2 = 15 km, L = 20 km

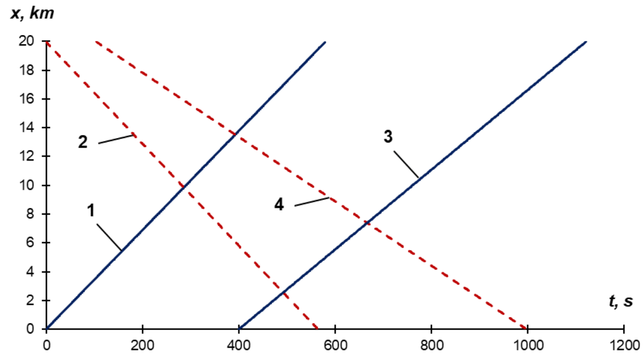

Fig. 3 - Train schedule

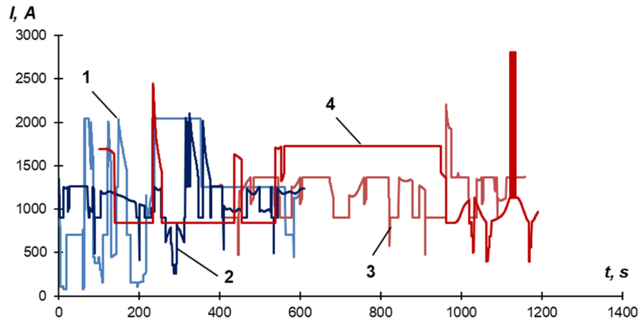

Fig. 4 - Time realization of the currents consumed by the electric rolling stock in accordance with the train number

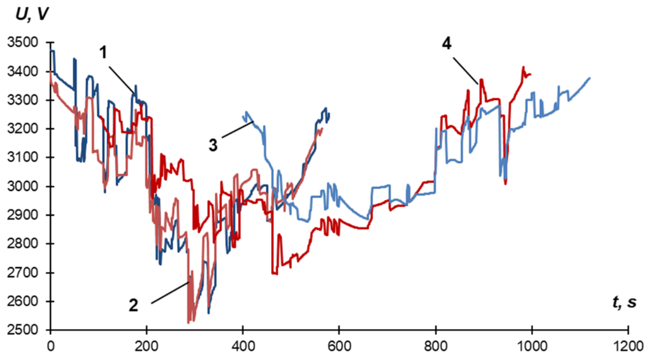

Fig. 5 - Voltage at current collectors of electric rolling stock according to train number

Analysis Fig. 5 shows the inability of a symmetric centralized traction system to provide a normalized voltage level (2900 V) at the current collectors of the rolling stock when performing the specified train schedule. In this regard, in order to improve the voltage mode of current collectors of electric rolling stock, it was decided to place a sectioning post and parallel connection posts at the points of the design section where the greatest reaction to a change in traction load is observed. The point with the maximum amplitude of the voltage corridor, that is, the point corresponding to condition (1), was determined as the most sensitive sensor node for a given area [9].

$$s = \max\left(U_{\max_j} - U_{\min_j}\right) \qquad (1)$$

where j – the number of the test node;
$U_{\max_j}$ – the maximum value of the voltage in the j -th node;
$U_{\min_j}$ – the minimum voltage value in the j -th node;

Based on the calculation results, we obtained optimized coordinates for the location of the UCS and PPS at the level lp1 = 4 km, ls = 10 km, lp2 = 13 km (displaced relative to the original scheme of Fig. 2). The results of the voltage calculation show that changing the location of SP and PPC does not significantly affect the improvement of the voltage mode - the maximum increase in the voltage level was only 13.8 V. That is, the passive circuits of the traction network do not allow to provide the necessary voltage regime.

Hence, in order to improve the voltage regime and reduce energy losses, it is necessary to make the transition to the active way of boosting the traction power supply system, namely, to place a boosting point at the sectioning post [10]. Moreover, for the calculation we adopted a scheme with the calculated coordinates of the SP and PPC location (Fig. 6). The maximum generated current of the boosting point is 1500 A, the voltage is limited to the level of 2900 V. The determination of the currents of the boosting points was carried out by solving the optimization problem with minimizing the objective function to reduce electric energy losses in the traction network [11]:

$$\Delta W_{\text{TM}}\left(\vec{I}_{\Pi\Pi}\right) \rightarrow \min \qquad (2)$$

Since electricity losses were defined as the sum of power losses at a certain time interval, the following optimization conditions were made: at specific moment of time, at lowering the voltage at the ERS current collector below the normalized level, it is necessary to determine the boosting point currents providing under these conditions a voltage equal or higher specified (2900 V) with the lowest possible level of instantaneous power loss in the traction power supply system with restrictions. $U_3 \le U_{e_i} \le U_{\max}$ (3).

$$\begin{cases} \Delta P\left(t_1, \vec{I}_{\Pi\Pi}\right) \rightarrow \min,\ U_{t_1} \le U_3 \\ \Delta P\left(t_2, \vec{I}_{\Pi\Pi}\right) \rightarrow \min,\ U_{t_2} \le U_3 \\ \qquad \ldots \\ \Delta P\left(t_n, \vec{I}_{\Pi\Pi}\right) \rightarrow \min,\ U_{t_n} \le U_3 \end{cases} \qquad (3)$$

The calculation results show that with the location of the SP and the PPC to Fig. 6 and active boosting of the traction power supply system, the maximum increase in the voltage level was 273 V, and the total electricity loss decreased by 6.15% compared to the basic circuit of Fig. 2.

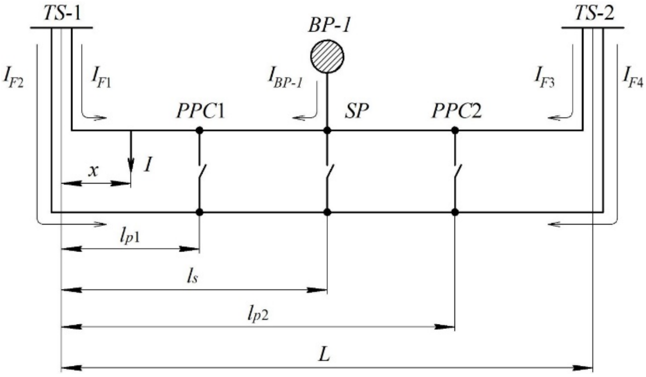

Fig. 6 - Calculation scheme for active system boosting by the boosting point where: lp1 = 4 km, ls = 10 km, lp2 = 13 km, L = 20 km

However, when calculating the voltage stability coefficient for the circuit of Fig. 6 according to the methodology [3], it was found that on the feeder zone there is a zone in which there is no stability of power supply of electric rolling stock with a normalized voltage level at a distance of 3.2-4.5 km from the traction substation, that is, in the area of the PPC location. Thus, the results obtained necessitate the application of a boosting point on the PPC, which leads to an asymmetrical boosting circuit (Fig. 7). It is necessary to indicate that the obtained results of simulation sufficiently correspond to studies carried out not only in [3], but also in [12].

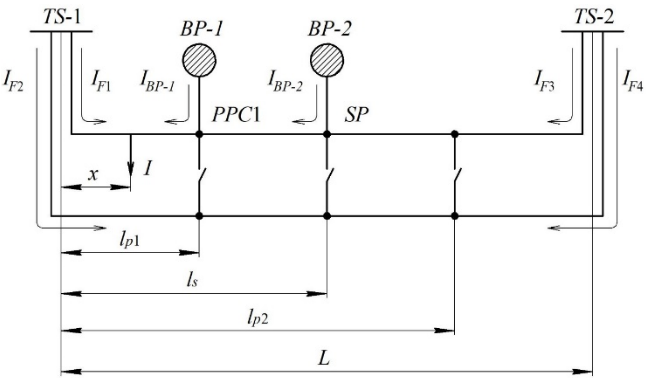

Fig. 7 - Calculation scheme for asymmetric boosting, where:lp1 = 4 km, ls = 10 km, lp2 = 13 km, L = 20 km

As a result of the calculation of the proposed asymmetric boosting scheme of the traction network, it was found that the voltage level of the current collectors of electric locomotives is in normalized limits. In this case, the maximum voltage deviation does not exceed 124 V from the normalized level, it is allowed by the operating conditions of traction electric motors, and the energy loss in the system decreased by 14.3% relative to the basic scheme of Fig. 2.

III. Conclusions

In the introduction of high-speed movement, the traction DC power supply system does not have to provide only a standardized voltage level on the electric locomotive current collectors, but also to have the necessary energy intensity of the traction network to ensure the stability of operation when changing the traction load.

It is shown that when using passive methods of boosting the traction network, it is impossible to provide standards for high-speed movement, even when applying optimization approaches to placing boosting means (sectioning posts and posts of parallel conjunction) in "voltage-tight" places based on the sensory approach.

The use of active methods for boosting a direct current traction network (with additional generators of electric energy) is justified and it is shown that the asymmetric arrangement of boosting points allows eliminating voltage bottlenecks, provides normalized requirements for a direct current traction power supply system for high-speed movement, and has better energy characteristics.

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