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Adaptive Systems of Traction Power Supply

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Abstract—At present, a great variety of traction power supply systems (TPSSs) are being used, planned, and developed for the future. This is because of the specifics of the electric transport system, as well as scientific and technological progress. The variety of TPSSs became possible as a result of the development of power semiconductors for transforming electricity parameters, as well as due to significant improvements in switching and power equipment. On the whole, control over their regimes of operation and the provision of desired quality parameters of electricity on electric rolling stock (ERS) bow collectors are still problems to be solved in traction power supply systems. Quality parameters for electricity are given in detail in different standards, specifications, rules for design and operation, and *GOSTs* (State Standards), but optimization of operating regimes of transport systems has not been considered. "Regime optimization" may refer to (1) the voltage of ERS collectors and its deviations and oscillations affecting travel speed and traction characteristics, (2) consumption of electricity during transportation in conducting mains and load-bearing members of the system, and (3) use of electric braking energy. To ensure optimization of operating regimes, adaptive traction power supply systems are necessary, which should be understood as an uninterrupted evolution of traction power supply for energy consumption by trains. In this paper, an adaptive traction power supply system with voltage converters in the intersubstation zone is analyzed. The circuits and characteristics of the system's elements are shown, and its electrical quantities are determined.

Keywords: electric rolling stock, traction power supply system, traction network, supply station, sectioning post, equivalent resistance

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At present, a great variety of traction power supply systems (TPSSs) are being used, planned, and developed for the future [1]. This is because of the specifics of the electric transport system, as well as scientific and technological progress. The variety of TPSSs became possible as a result of the development of power semiconductors for transforming electricity parameters (PSCs) [2], as well as due to significant improvements in switching and power equipment. First of all, this range includes fully controlled PSCs—namely, transistors and IGBT modules, in particular, as well as vacuum circuit breakers and dry-type transformers. After the invention of supercapacitors with a double electric layer (SCDELs), it became possible to use more electric braking energy more efficiently. The development of EDC-based information technologies and microprocessor devices makes it possible to design automated systems of high informative value. Thus, TPSSs are provided with a new processing basis making it possible to introduce radical changes into work processes.

Current and projected TPSSs are intended for certain target parameters of railroad operation. This is determined by data in the form of calculated intervals, train schedules, number of trains en route, etc. Proceeding from this data, the necessary type of TPSS is chosen for which schematic circuit diagrams are designed and interstation zones, traction substation (TSS) capacities, and sections of catenary line (CL) wires are evaluated [1]. The system must follow standards for electricity quality set as rated voltages of ERS bow collectors.

On the other hand, restrictions on TSS capacity, CL wire heating, voltage losses in railroad tracks (RRTs), and TC protection from a short-circuit current (SCC) must be followed.

Issues connected with energy efficiency issues and operational costs are considered to be evaluative in nature and are not usually considered to be optimization problems. On the whole, control over their regimes of operation and the provision of desired quality parameters of electricity on electric rolling stock (ERS) bow collectors are still problems to be solved in traction power supply systems. Quality parameters for electricity are given in detail in different standards, specifications, rules for design and operation, and *GOSTs* (State Standards), but optimization of operating regimes of transport systems has not been considered.

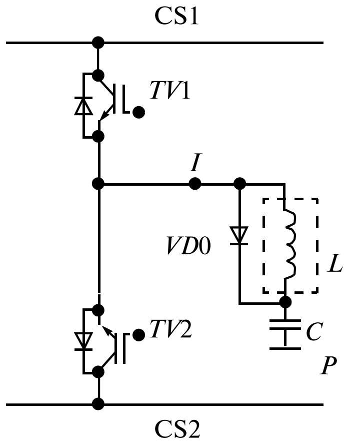

Fig. 1. Point of catenary suspension (CS1 and CS2) connection with a capacitive storage.

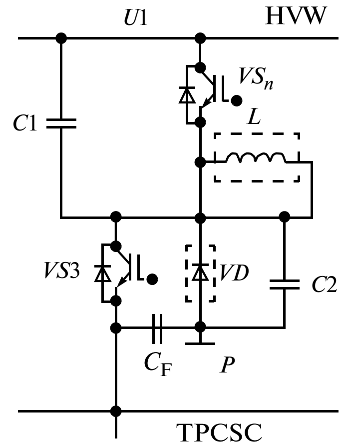

Fig. 2. Voltage converter circuit.

To ensure optimization of operating regimes, adaptive traction power supply systems are necessary, which should be understood as an uninterrupted evolution of traction power supply for energy consumption by trains.

It is known that there are decentralized power supply systems with 100% distributive-type backup as in 2 × 25- and 94-kV systems. These systems do not have characteristics of adaptability understood as the conformance of TPSS circuits and parameters to actual parameters of railroad operation and traction loads including braking modes. Let us characterize the main elements that can be used to form the system.

The basic element is a power transistor designed as a high-capacity IGBT module for currents of 400–3600 A and voltages up to 3300 V. In circuit diagrams, compound modules are represented as single keys.

The next basic elements for using electric braking energy are supercapacitors with a double electric layer (SCDEL) from which batteries can be assembled for capacities of up to 500 F and voltages of up to 10 kV.

These basic elements can be used to design the following main subsystems: a node for connecting catenary suspensions of parallel tracks (parallel connection point (PCP)), a transformer-free point of voltage conversion, and an ac/dc converter with controlled output voltage. Let us consider these subsystems in brief.

For the circuit of the transistor point of catenary suspension connection (TPCSC) with a capacitive storage, see Fig. 1. The functional principle of the TPCSC is as follows: at different voltages of CS1 and CS2, the currents flow to common point *1* and then pass through transistors *TV*1 and *TV*2 to the contact circuit. Excessive electric braking energy is built up in the reserve from which it is supplied to the ERS in the traction regime. The transistor keys are also used as protective devices, i.e., they close (interrupt) the electric circuit in the event of overvoltage. When power supply leads to common point *1*, the TPCSC runs as a distributive unit (DU).

A transistor-based dc voltage converter (VC) is shown in Fig. 2.

In this device, VS_n is the converting transistor, the inductance loops determine the frequency characteristic, VS_3 is the protective key, and *VD* is the reverse diode for voltage removal [3].

The ac/dc converters are designed for target voltages on transistor keys in accordance with the 12-peak mesh circuit.

For the circuit diagram of the TPSS, see Fig. 3. The main devices in the TPSS are presented as follows. Two converters with two different voltage levels, i.e., a rated voltage converter (RVC) and a high-voltage converter (HVC), are installed on basic substations TSS1 and TSS2 restricting the intersubstation zone (ISSZ) of the traffic line. A high voltage is taken from technical and economic indicators and can be as high as quadruple or higher rated voltage. The high-voltage units are connected to the HVW laid between the TSSs.

The HVW can be laid on catenary supports or as a cable.

The operating regimes of the system are determined by internal processes and external action. The catenary line between sectional parts *S*1–*S*6 is connected to three power supply sources. The number of power supply sources for the sections may vary. The energy efficient circuit and the voltage mode on bow collectors are determined by coordinates of trains on railroad track (CS) sections and traction current values. Positions and types of trains en route are determined by GLONASS. Circuit and regime control is exercised by an automated system similar in design to SCADA systems used in the oil and gas industry. In other words, this system includes three or four levels:

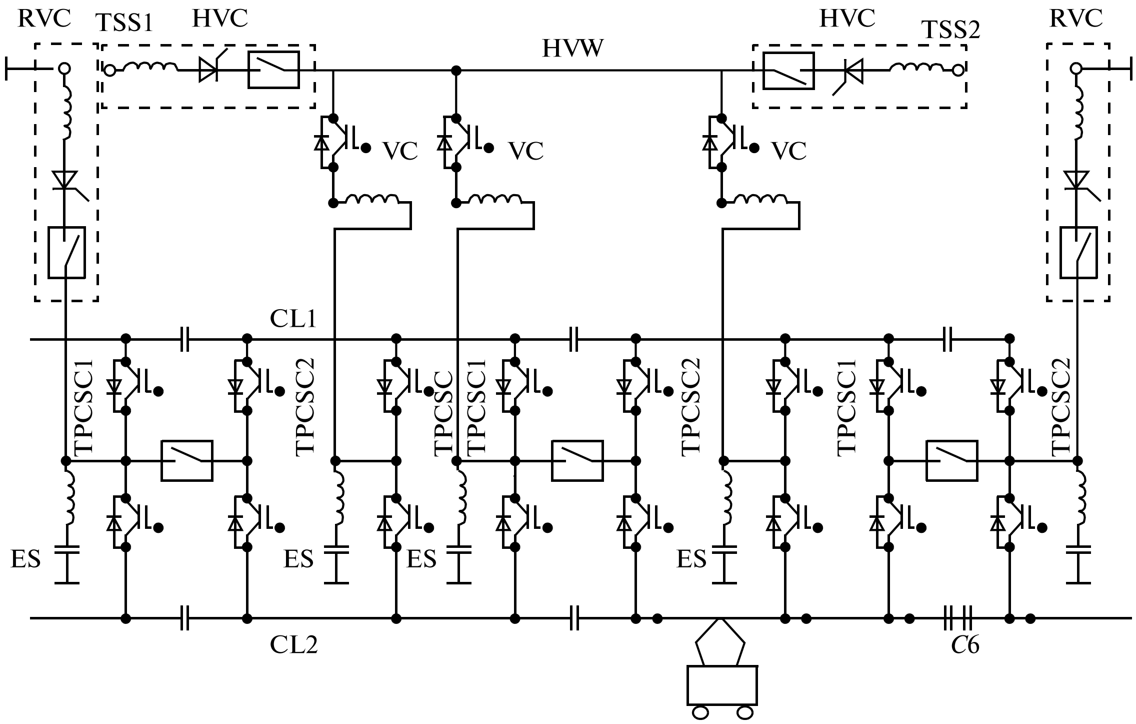

Fig. 3. Circuit diagram of the adaptive TPSS for the ISSZ.

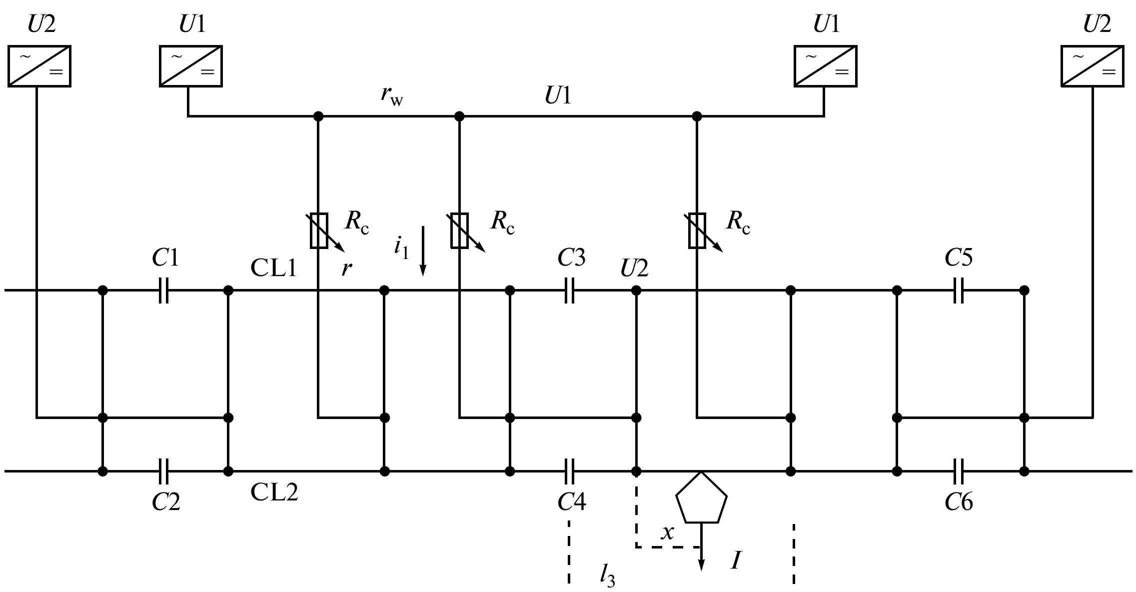

Fig. 4. Design circuit of the adaptive TPSS.

sensors, bottom- and upper-level controllers, servers, and workstations (WKSs).

For the design circuit of the system, see Fig. 4.

In this system, the intersubstation section of the traction network divided into zones. The number of zones is determined by the number of catenary line (CL) power supply sources (PSS). If there are four PSSs, as in this case, the zones will be four in number as well. Depending on their coordinates, trains are always located between the two nearest PSSs switched on in the operating regime and the connection points are maintained in the equipotential mode. Thus, the CS supply zone is $I = l_{\mathrm{ISSZ}}/(N-1)$, where N is the number of PSSs in the ISSZ.

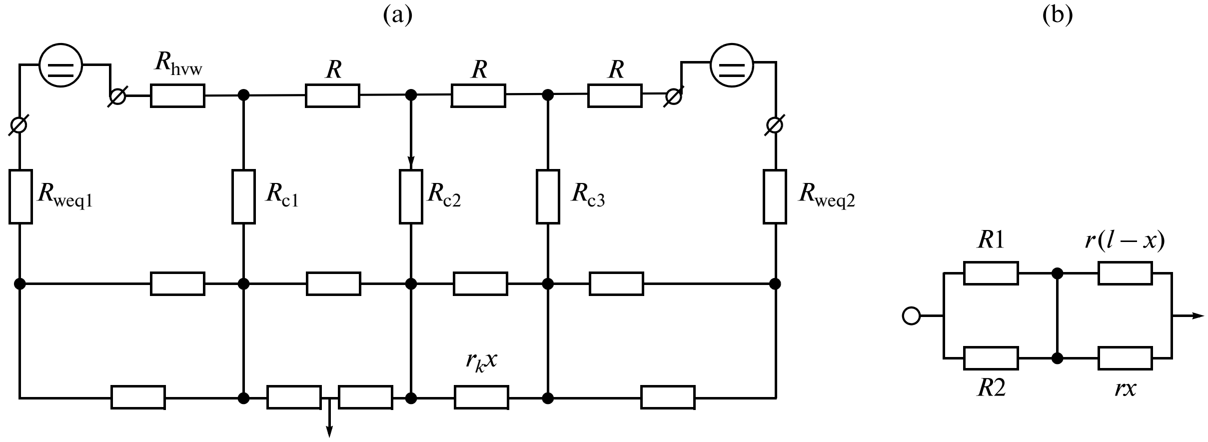

Fig. 5. Equivalent diagram for the calculation of equivalent resistances: (a) is the straight-line diagram; (b) is the collapsed diagram.

In the design scheme (Fig. 4), the CU and TSS are shown as EMF sources (*U*1 and *U*2), voltage converters (VCs) controlling resistance R_c, high-voltage wire resistance r_w, and catenary line resistance *r* (Ω/km). The calculations for TPSSs consist in determining the electrical loads, voltage losses, and level of processing electricity losses. These data are used to determine the parameters of electric circuit elements, quality of electricity in bow collectors, and the energy efficiency of the system. Energy reserves designed as capacitor batteries allow collection, transfer, and storage of electric braking energy, as well as voltage stabilization at power supply points. Let us consider some aspects of the system design according to the circuit in Fig. 4.

Train currents *I* are distributed between the power supply points in inverse relation to distance:

$$i_1 = I\frac{l_2 - x}{l_2}, \quad i_2 = I\frac{x}{l_2}. \tag{1}$$

Average and effective line currents will be found as follows:

$$\left.\begin{aligned} I_{01} &= I_{02} = \frac{1}{l_2}\int_0^{l_2} I\frac{l_2 - x}{l_2}dx = \frac{I}{2}, \\ I_{eq1} &= I_{eq2} = \frac{1}{l_0}\int_0^{l_2}\left(I\frac{x}{l_2}\right)^2 dx = \frac{I^2}{2}. \end{aligned}\right\} \tag{2}$$

The line current efficiency factor per train in the zone and equipotential mode will be found as follows:

$$E = \left(\frac{I}{\sqrt{3}}\right)\Big/\left(\frac{I}{2}\right) - \frac{2}{\sqrt{3}} = 1.16.$$

The average and efficient supply line current for *n* single-type trains in the regime can be found as follows:

$$I_0 = nI_{01} = \frac{In}{2}, \tag{3}$$

$$I_{eq} = \frac{In}{2}\sqrt{1 + \frac{E - 1}{n}}. \tag{4}$$

Analytical methods or methods based on train schedules can be used to calculate electrical quantities [1]. The peculiarity of these methods consists in replacing the section length with the length of the zone between power supply points. In addition, the electrical braking energy and parameters of accumulative devices distributed along the section must be calculated separately. When technological energy consumption is determined, losses in the high-voltage wire and converter points should also be taken into account.

The system will be assessed according to equivalent resistances [1] by varying the number of zones between active power supply sources.

The structure of replacing elements with active resistances is shown in Fig. 5.

In this instance, *R*1 and *R*2 are the equivalent resistances from the power supply sources to the boundary of the train location zone and *l* is the length of the zone between the power supply sources.

The equivalent resistance for the given circuit will be calculated as follows:

$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2} + \frac{r_x(l - x)}{l}. \tag{5}$$

Changes in equivalent resistance depending on the number of zones between RS power supply sources

Number of zones between power supply sources		1	2	3	4
Equivalent network resistance in fractions of rl without R_N taken into account	peak	1/4	1/2	3/4	1
	average	1/6	1/3	1/2	2/3

The first component will be recorded as equivalent network resistance R_N so that

$$R_N = R_N + r\left(x - \frac{x^2}{l}\right). \quad (6)$$

The average resistance will be

$$R_{eq.avg} = R_N + \frac{2r}{l}\int_0^{1/2}\left(x - \frac{x^2}{l}\right) = R_N + \frac{rl}{6}. \quad (7)$$

The changes in equivalent resistance depending on the number of zones between the power supply sources of ERS are given in the table below.

The changes in resistance depending on the number of zones between the power supply sources of ERS are given in Fig. 6.

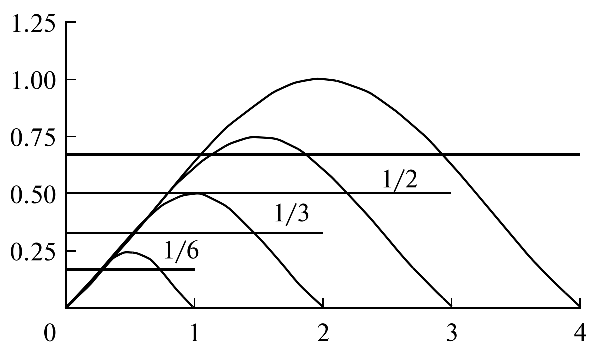

Fig. 6. Change in equivalent resistance depending on number of zones.

According to the analysis of equivalent resistances for the time of train travel along the sections between the power supply sources, the zonal structure of the system ensures efficient operation by voltage level indices on ERS bow collectors and indices of technological electricity consumption. These indices are proportional to average equivalent resistances.

CONCLUSIONS

The adaptive TPSS has a number of specific features that the already-known TPSSs do not. dc distributing gears are carried to traction network linear devices, which makes the system far simpler in terms of both conducting lines and switching equipment. The division of the ISSZ into individual subzones between power supply points supplied with energy at high voltage stabilizes ERS bow collector voltage and greatly reduces technological power consumption.

Distributed installation of energy reserves on linear devices will make it possible to use almost 100% of electrical braking energy. The key transistor circuit allows one to take complete control over power supply regimes and makes the system flexible and controllable.

Adaptive TPSSs can be used on electrified railroads in high-speed and heavy train operation, as well as on high-speed tram routes.

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