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Energy Efficient Traction Electrotechnical Complex at Various Voltages of Power Sources

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***Abstract*—This paper shows the results of the current distribution analysis in the DC traction network with multi power supply from different sources, the methods of the current distribution determination at the substation spacing for two-way power circuits of the contact network sections are presented.**

***Keywords*—electric transport, rolling stock, power supply source, contact network, recuperation, current distribution**

I. Introduction

Traction networks of electric transport receive power from a large number of power sources. Such sources include substations, recuperarse rolling stock, increasing the voltage, independent sources.

All power sources have notable differences in the parameters and voltage levels, and their interaction leads to random distributions of the voltage at the current collectors.

In this regard, in the design of traction networks, the problem of the current distribution determination of the power sources and the contact network sections appeared. The cognition of electric loads in the power supplies and conductive networks is necessary to choose their parameters (power sections), as well as technical and economic calculations.

The objective of the current distribution calculations is complicated in connection with the use of the regen mode, transfer electrical braking energy in the contact network and the use of energy storage to improve the system energy efficiency.

Nowadays, the interaction between power sources and developed methods of calculation of the current distribution have not investigated. The conditions for regenerative braking of rolling stock, appropriate circuits of traction network have not defined.

Thus, in the system of electric traction there are two types of energy such as external energy of energy systems and internal energy of electrical braking of the electric rolling stock. The overlap of the two energies led to changes in modes of current and voltage in the traction network. Processes of change are becoming increasingly stochastic.

Electrical calculations of power supply devices are one of the primary means of the correct choice economically reasonable parameters of the system, as well as the only instrument to check the compliance of the selected parameters to all electrical requirements and conditions of the actual implementation of a given volume of traffic.

The importance of a well-developed technique of electrical power calculations is evident. In recent years, a number of works on the problem of using electrical braking energy and current distribution optimization in the traction network [1–3]. The issues of current distribution, and has previously been discussed in several monographs and educational literature [4-6]. A common disadvantage of these works is investigation of operation modes only the one the substation spacing. The objective of this research is to develop a common methodology for the assessment of the current distribution on the transport lines ground.

II. The Influence of Different Traction Networks Schemes to the Current Distribution

The power supply and the partitioning circuits of the traction network can be performed in unilateral and bilateral sections supply. The using of a particular type of power supply is determined by technical factors: reliability, power losses, protection from overcurrents etc. In connection sections of the contact network the scheme are: separate, with connection of electric connectors or in-line devices (nodes of the diagram).

Power supply circuit of the network contact sections significantly influences the current distribution. In traction power supply systems the following power and partitioning schemes in the substation spacing of a double-track site are used [7, 8]:

- one sided separate or parallel supply;
- two sided separate or parallel supply;
- nodal supply with sectioning point and parallel connection points.

In circuits, single supply section is connected to the same feeders traction substation. The general scheme of the current placing is shown in Fig. 1.

The challenge is to estimate currents on sections of the network taking into account the following factors:

- the recuperative voltage difference and the feeder substation $U_r \geq 1.2 \cdot U_f$;
- recuperative currents chopping – $I_r \leq I_{T1}+I_{T2}+I_{Tn}$, n – the number of traction currents;
- recuperative currents depletion to slowdown till the stop or harmful gradients.

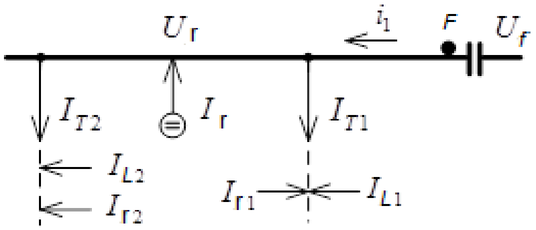

Fig. 1. Scheme of the current placing: I_{T1}, I_{T2} – electric traction; $I_r = I_{r1}+I_{r2}$ – energy recuperation; i_l, I_{L1}, I_{L2} – lines

Sections with dual power have a number of advantages compared to unilateral power: the energy losses decrease up to 20-25%; the sections power supply of the contact network reservation is provided (reliability of supply). Converter units of traction substations power is reduced; the substation spacing increases and beneficial use of energy recovery during its transmission through a contact network also increases.

Thus, a more correct mode of supplied to the rolling stock creates, improved automation and reduced operational costs due to the reduction of electricity losses.

Nodal schemes are formed using the positions of the partitioning and parallel connection points. Here it is advisable to use points on transistor keys. The nodes in the contact network can significantly change the picture of the current distribution.

The feature of the electric traction system of the double-sided power sections is the combining of the contact network in the electric circuit with multiple power sources. When the sections are connected in series with two-way power, a number of problems arise. The system becomes sensitive to the voltage levels of the power sources, there are uncertainties in the current distribution on the sections of the network. When different voltages of the parallel power sources are use, there are so-called "surge currents", which can significantly degrade the performance efficiency of power supply in connection with growth of losses of electric power, the negative impact on the operation of electric rolling stock, the complication of the relay protection, overheating of the contact network, accelerated wear and aging of the insulation of traction equipment etc. Depending on the parameters of the power supply section, the value of power losses from the equalizing current in the two-way circuit will be different, with high asymmetry of the current distribution it can exceed the value of the total losses of the one-way power supply circuit..

Such routing schemes are used on electric railways, subways, trams, and trolleybuses. In research [4] it is shown for the traction substations of urban electric transport in traction substations parallel operation the voltage difference on the DC buses is steadily 10-40 V, and the highest waves reach 60-80 V.

III. Analysis of the Power Supply Voltage

The voltage levels of power sources are formed under the influence of several factors, such as continuous large fluctuations of the load, the difference in the number of enabled Converter units for traction substations, their external characteristics, the resistance of the supply lines. In addition, traction substations subway, tram, trolleybus and parts of electric Railways receive electricity from isolated centers with various output voltage. For example, Fig. 4 shows a write voltage at the 10 kV input adjacent substations connected to one section.

Metering was obtained by energoregistrator PKE-1. From these measurements it follows that the voltage difference is 300-350 V. In conversion to the voltage of 600 V DC the difference is 18-21 V.

The second factor is the difference in the external characteristics due to internal resistance [6]:

$$\rho = \frac{U_{d0}}{I_{dnom}}\left[A\left(\frac{U_k\,\%}{100\,\mathrm{N}_r}+\frac{S_{nom}}{S_{sc}}\right)+\frac{\Delta P_0\,\%}{100}\right]+R_0+R_1, \quad (1)$$

The equation contains: $A\approx0.5$ – a factor to account for the slope of the external characteristic; S_r, S_{sc} – rated power and short circuit on 10 kV buses of combined traction-secondary substation; $\Delta P_0\%$ – power loss in transformer windings; U_{d0}, I_{dr} – idling voltage and rated current of the converter; R_1 – the resistance of the power line which is converted to DC side; R_0 – the resistance of the cables from the buses of traction substations.

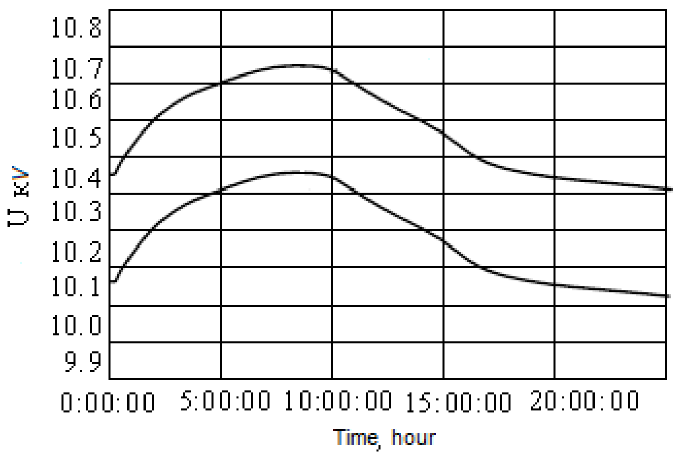

Fig. 2. The voltage at the 10 kV input of underground adjacent substations

The parameters of the adjacent traction substations are different; it is shown in figure 1.

The output voltage at the current collectors of electric rolling stock in the braking mode receptive take 20% above the nominal network [9, 10]. Traction and regenerative currents cause voltage losses in the supply lines, the contact network and traction substations units. Thus, the problem of determining voltage levels on the power supplies and the current collectors of electric rolling stock is complex and refers to the area of stochastic processes.

IV. Calculation of Current Distribution in Substation Spacing

A. Calculated Scheme of Transport Network Section

The calculated scheme for two-way separation power supply of sections is shown in Fig. 3.

However, by using parallel connection points and section pillar, it is possible to go to the node circuits and circuits with the complete connection of sections of parallel ways.

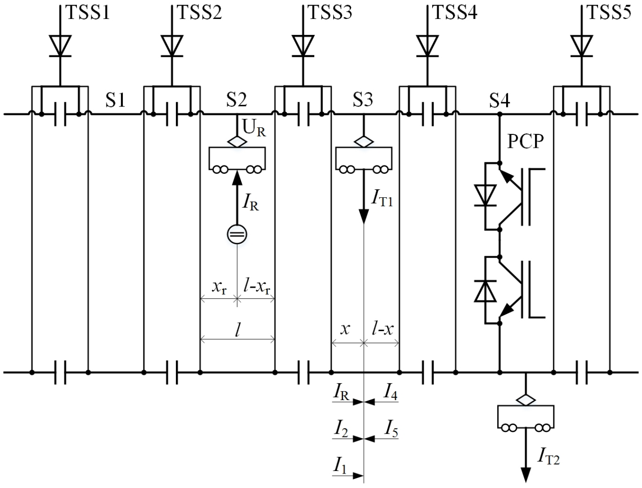

Fig. 3. Calculated scheme for two-way separation power supply of sections

The objective of the calculations is to find the percent of power sources currents in traction current (I_{T1}, I_{T2}). The diagram shows the currents of power sources, including regenerative currents. We take the following assumptions to estimate the current distributions: the train current is a constant value equal to the average value. The movement of trains is uniform. The section is one train; the length of the sections is the same and equal *l*, the positions of the trains *x* и x_r; the traction network parameter – *r*, Ω/кm.

B. Calculation of Current Distribution

Consider the current distribution in the first way sections which are also consistent to sections with a complete parallel connection.

The calculated scheme is shown in Fig.4.

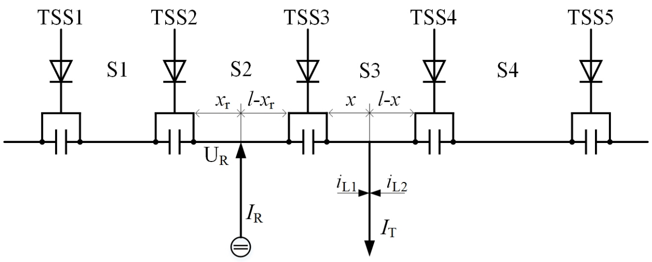

Fig. 4. Calculated scheme of traction network section

Consider the current distribution on section S3 in substation spacing TSS3–TSS4. In the case of the equipotential mode when *U3 = U4* currents *iL1* and *iL2* will be distributed inversely to the distances, when *μ = const*:

$$i_{L1} = I_T \cdot (l - x) / l \, ,$$

$$i_{L2} = I_T \cdot x / l \, ,$$

when n – traction currents on section. The lines currents are determined by the formula:

$$I_{L1} = 1/l \Sigma I_T \cdot x \, ,$$

$$I_{L2} = 1/l \Sigma I_T \cdot (l - x) \, .$$

For further analysis let us turn to the system of relative units. Let us define:

$$x / l = x_* , \ 1/l = 1 \, ,$$

$$i_{L1} / I_T = i_{*1} , \ i_{L2} / I_T = i_{*2} \, ,$$

$$U_3 - U_4 / r \cdot I_T \cdot l = i_{*y} \, .$$

If *U3 = U4* – equipotential mode, that the equation of current distribution in relative units are:

$$i_{*1} = 1 - x_* \, , \tag{2}$$

$$i_{*2} = x_* \, . \tag{3}$$

Nomograms of the current distribution are shown in Fig. 5.

The nomogram is useful for instant schemes calculations., It will be quickly to find the currents proportion of the trains assigned to the feeders if the position of the train on sections is known (TSS3–TSS4).

In the case of non-equipotential mode U3 ≠ U4: for power supplies, one can write the voltages on the current collector:

$$U_T' = U_3 - i_{L1} \cdot r x \, ,$$

$$U_T'' = U_4 - i_{L2} \cdot r (l - x) \, ,$$

$$i_{L1} + i_{L2} = I_T \, .$$

Given the fact that $U_T' = U_T''$ we obtained equations in the following form, if $U_3 > U_4$:

$$i_{L1} = I_T \cdot (l - x) / l + (U_3 - U_4) / rl \, ,$$

$$i_{L2} = I_T \cdot x / l - (U_3 - U_4) / rl \, .$$

In relative units the equations (2, 3) took the form:

$$i_{*1} = 1 - x_* + V_{*y} \, ,$$

$$i_{*2} = x_* - V_{*y} \, .$$

Components of the current V_{*y} – can be called a coupling voltage coefficient.

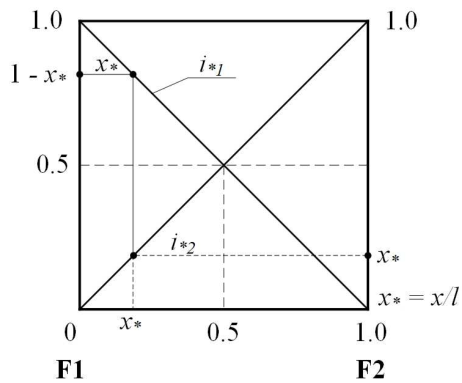

Fig. 5. Nomograms of the current distribution for equipotential mode

For the case of non-equipotential mode, the current distribution nomogram can be described in Fig.6.

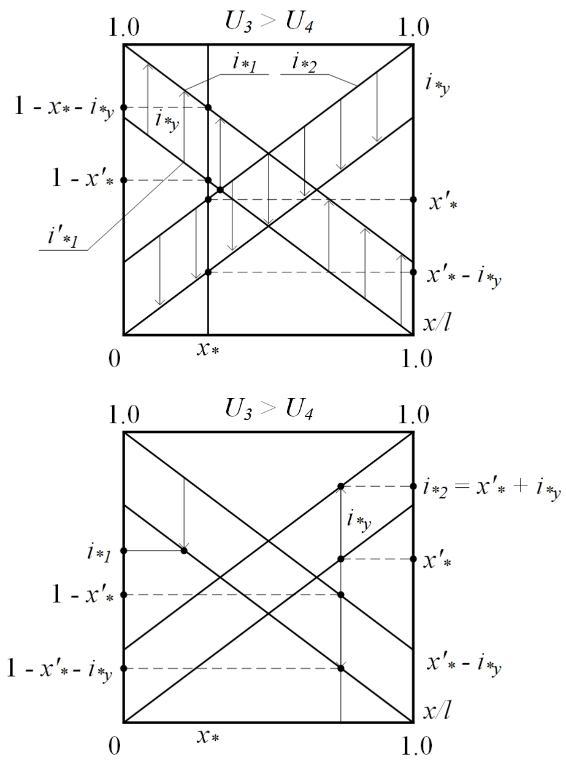

Fig. 6. Nomograms of the current distribution at various voltages of power sources

Example. Let us consider the methodology of current distribution estimation on the traction network of tramway. The scheme of the section with two traction currents is shown in Fig. 7. Let us assume the following source data:

l = 1,5 км – the length of the section;
$r = 0{,}11\cdot 10^{-3}$ Ω per km the traction network parameter;
x_1=0,5 км, x_2= 1 км;
I_{T1} = 100 A, I_{T2} = 80 A;
$\Delta U = U_1 - U_2$ = 10 V.

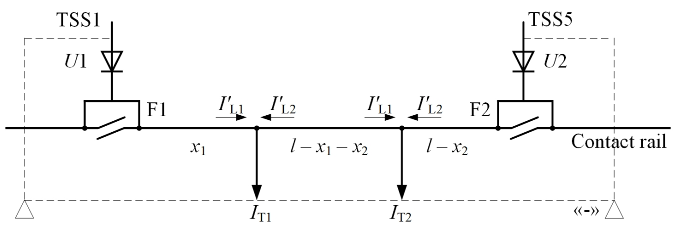

Fig. 7. A calculated scheme for example

Decision: <u>Equipotential mode $U_1 = U_2$.</u> The relative value of coordinate I_{T1}, the proportion of current $F1$, the current I_L’ and the current which is flowing from F2 to $i_{*2}' = x_*$, respectively:

$$x_* = 500\ /\ 1500 = 0{,}33\,;$$

$$i_{*1}' = 1 - x_* = 1 - 0{,}33 = 0{,}67\,;$$

$$I_{L1}' = 0{,}67\cdot 100 = 67\ \text{A};$$

$$I_{L2}' = 0{,}33\cdot 100 = 33\ \text{A}.$$

Similarly, let us determine the line current for I_{T2}:

$$x_* = 1000\ /\ 1500 = 0{,}67\,;$$

$$I_{L1}'' = (1 - 0{,}67)\cdot 80 = 26{,}4\ \text{A};$$

$$I_{L2}'' = 0{,}67\cdot 80 = 53{,}7\ \text{A}.$$

The currents in the feeders:

$$I_{L1} = 67 + 26{,}4 = 93{,}4\ \text{A};$$

$$I_{L2} = 33 + 53{,}7 = 86{,}7\ \text{A}.$$

<u>Non-equipotential mode $U_1 > U_2$.</u> Let us define surge current:

$$I_{sg} = \Delta U / rl = 10\ /\ 0{,}11\cdot 1{,}5 = 60{,}6\ \text{A}.$$

The current distribution on the feeders:

$$I_{L2(2)} = 86{,}7 - 60{,}6 = 26\ \text{A}.$$

When ΔU = 20 V, $I_{L2(2)}$ = 0, that corresponded to one-sided supply.

The method of current distribution calculations in the traction network is suitable for the analysis of processes in one section for two-sided power supply, but practically it is difficult to apply to extensive networks. Traction network sections with two-sided power supply are loop on all transport route, where power sources can be substations, energy storage, electric rolling stock in the brake mode. A problem of estimation of current distribution from power sources with different voltage levels and location of trains is raised.

V. Determination of Current Distribution in Traction Networks with Several Power Supplied Centers

To determine the current distribution in traction networks, it can use the method of equivalent electromotive forces and current sources [9]. The essence of the method consists of determining the equivalent electromotive forces and conductivities, estimate of currents in branches:

$$U_e\cdot q_e = \Sigma U_i\cdot q_i\,,\ q_e = \Sigma q_i\,,$$

$$U_e = \Sigma U_i\cdot q_i\ /\ \Sigma q_i\,,$$

$$i_{Li} = U_i\cdot q_i\ / \Sigma U_i\cdot q_i\,,$$

where U_e, q_e – equivalent electromotive forces and conductivities; U_i, q_i – electromotive forces and conductivities of i-ой branch of electrical circuit.

Let us consider the traction network of a single way (Fig. 6), take the following assumptions: section lengths are all the same and equal to l with parameter r, Ohm/km; traction current I_{T1} is in the middle of sections C3, C4, that is, the coordinate $x = l/2$, electric rolling stock in the braking mode – U_r is in the middle of section C2 with the coordinate $x = l/2$, the length of the section is given, that is, the resistance of the supply lines and the internal resistance of the substations are taken into account.

Equivalent circuit for evaluating the current distribution along the route is shown in Fig. 8. The conductivity of the branches is determined by the formula:

$$q_i = 1 / r{\cdot}l_s{\cdot}n_s,$$

when n_s = 1, 2, 3 – the number of sections in the branch; r = $0{,}11{\cdot}10^{-3}$ Ω per km – the traction network parameter; $U_1=U_2=U_3=U_4=U_5=U_1{\cdot}U_r=1.2{\cdot}U$.

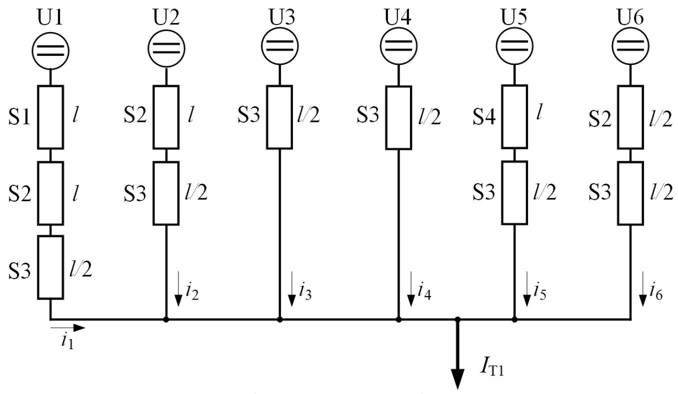

Fig. 8. The equivalent circuit for the evaluation of the branches currents

TABLE I. CONDUCTIVITY AND FRACTION OF CURRENT BRANCHES IN THE CURRENT THRUST

№ branches	The conductivity of the branches, SIM	The share of current branches in the traction current, %
1	2,4	6,0
2	4	9,9
3	12,1	29,7
4	12,1	29,7
5	4	9,9
6	6	17,8

The results of calculations of conductivities and fractions of branch currents are mentioned in Table I. The table data shows that the proportion of currents from connected sections of the power sources is less than 60%, and deleted on one section of approximately 20% (power supplies 2 and 5). Thus, 80% is the energy of adjacent to the section of 4 power sources.

VI. CONCLUSION

As a result of the research it was revealed that the difference in voltages of parallel power supplies can lead to practically one-sided feeding of the section, which increases the technological costs of electricity. The node network scheme allows one to level voltages, since the potential in the node is formed by sections of both power supplies. For the subway, it is advisable to use the device of the point of parallel connection on contactless transistor switches in the middle of the inter-substation zone. For urban electric transport, it is possible to use such a device as a point for connecting parallel contact networks of the tram and trolleybus. In the case of circuit schemes of the traction network, the electric braking currents can flow into areas with the removal of trains for 2-3 sections and constitute a share in the traction current of 5-10%.

The current distribution in traction networks is determined by the voltage levels of power supplies and power schemes, and partitioning the network. The reasons for different voltage levels of power sources are non equivalent power centers, the difference in external characteristics, energy use electric braking. Non-equipotential mode power sources is the natural state of the system. To determine the distribution of currents in substation space can be an acceptable method with the use of nomograms.

For assessment and analysis of the current, distribution in landfills, including a number of power sources, is applied here; the modified method is equivalent to the electromotive forces and conductivities. This method allows one to solve the problem of choosing the schemes of sections of the contact network and to determine electrical quantities with reduced error.

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