ENERGY CHARACTERISTICS OF THE DC DISTRIBUTED POWER SUPPLY SYSTEMS

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Resume

Currently the circuit technology of the DC traction power supply system cannot provide the necessary requirements for introduction of high-speed traffic. Numbers of measures and tools have been developed to improve the traction lines that no longer meet current requirements. One of the most promising means for strengthening the traction DC lines is transition to the distributed power supply of the rolling stock. In this article, a comparative analysis was carried out of energy indicators of the classic centralized power system and distributed power systems with use of one aggregate traction substation and with use of the solar generators. That comparative analysis of these systems was performed on a simulation model with the same parameters of the traction line and rolling stock.

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1 Introduction

The present-day of the traction power supply on the DC railways can be characterized by rapid aging of fixed assets of infrastructure. At the same time, the European efforts of Ukraine require the implementation of measures for introduction of the high-speed traffic, which requires modernization of existing power supply lines. Both the DC and AC power supply systems can provide the high-speed transportation, but to ensure a sustainable high speed one must increase the energy intensity for the electric DC lines in the first place. In Poland railway lines E65, E20, E30 are modernized. Implementation of such investment project requires to fulfil all the requirements indicated in TSI (Technical Specifications for Interoperability).

There is a political will to make a modal shift from the road and air modes of transport to railways. This cannot be achieved without taking into account technical and operational interoperability. There is a set of technical barriers between individual interoperable railway systems in civil engineering structures, traction power supply systems, interlocking devices etc. [1]. First of all, it is necessary to ensure the power supply for trains with a current up to 3.2 kA mean useful voltage at least 2.8 kV [2]. With introduction of the high-speed traffic, as shown by analysis of scientific publications, the main efforts of both Ukrainian and foreign scientists are aimed at providing the necessary mode of voltage in the traction line. However, the means and measures applied today in Ukraine do not allow to solve the problem [3-4].

According to the norms of UIC for the double-track high-speed line with a maximum speed 300-350 km/h, it is estimated that the maximum specific power consumption for traction need is at a level of 3 MW·A/km [5]. The power of traction power devices is recommended to calculate based on the specific power consumption. Thus, there is a gradual evolution of requirements for the traction power supply systems (TPSS): not only the provision of rated voltage, but also providing the necessary energy intensity of the traction line. To ensure these requirements, the scientific idea evolved to the introduction of distributed power supply systems for traction line (DTPSS), which have the best technical and economic characteristics. The use of distributed power supply allows:

- to reduce power losses in the traction line;
- to reduce the cross-section of contact lines;
- to reduce expenses for the construction of external power supply;
- to increase the level of controllability of power processes in the traction line;
- to increase the level of unification of the used equipment.

The distributed power supply scheme of the contact line means the scheme in which consumers on the most loaded zones receive power not only from the nearest but also from a range of remote power points [6]. The work [7] outlines that the key aspects in implementation of the distributed system is assurance of reliable supply

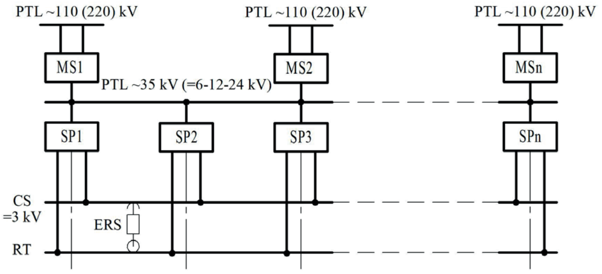

Figure 1 Block diagram of distributed power system: MS - main substation, SP - supply point

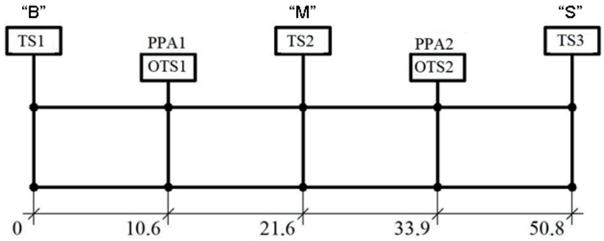

Figure 3 Scheme of the DTPSSS section with single-aggregate substations

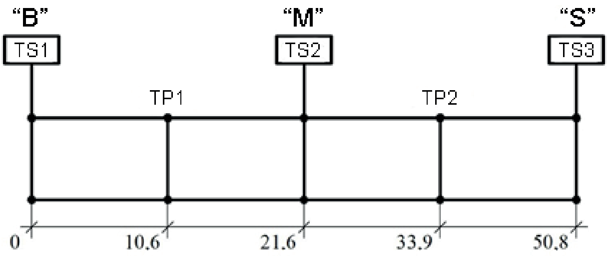

Figure 2 Scheme of the section of CTPSS

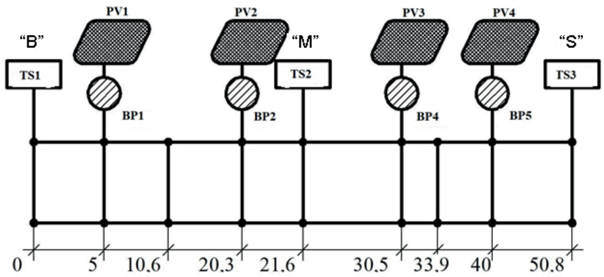

Figure 4 Scheme of tested section of DTPSSA

to prioritized loads. The less the power of traction units installed at one substation is, the greater becomes the participation of such points in supply of adjacent section between the substations (Figure 1).

Now in the Department of intellectual power supply systems in Dnipro National University of Railway Transport were formed two main approaches to circuit of DTPSS: System of distributed power with use of alternative sources of electric energy (DTPSSA) and a system of distributed power using single aggregate traction substations (DTPSSS) [8]. Assessment of feasibility of upgrading of centralized traction power supply (CTPSS) with application of one or another DTPSS should be done based on the energy indicators analysis. The indicators of the direct assessment of quality of energy-exchange processes in the TPSS are following: efficiency, specific electricity consumption, coefficient of equipment usage (load power factor), energy losses, nominal rating, rated voltage and current [9].

It should be noted that for railways with a speed up to 160 km/h the nature of the electric traction load is subject of the normal distribution. Devices of the traction line are chosen based on the maximum values of current loads during the train movement according to the schedule. However, for the high-speed railways and railways with high intensive traffic and increased carrying capacity, the nature of the electric traction load has a different character. Those lines have impulse load that increases peak loads on traction substations, increases losses of voltage and power in TPSS, complicates a current collection and increases the temperature of the contact wires [10]. It has been established that the specific power consumption increases with increasing of the speed as a result of increased aerodynamic resistance to the movement on horizontal section at an peak acceleration of the rolling stock α = 5 km/h/s and speed 250 km/h, the specific electric energy consumption is bigger for more than 3 times than the value at speeds of 120 km/h, which is 50.8 W·h/t·km and 16.01 W·h/t·km, respectively.

Therefore, for comparative analysis of different systems of traction power supply, or their circuit design decisions, it is useful to use specific indicators, for example - specific power consumption, specific power, etc. It is also necessary to evaluate the load capacity of the wires of the contact lines and the equipment of the traction substations, sectioning point and the reinforcement points of traction line.

The purpose of the work is conducting a comparative analysis of the power characteristics of centralized power supply and distributed power supply systems.

2 Evaluation of voltage and power modes in the power supply systems

Calculations were made to evaluate the mode of voltage and power in the case of eventual introduction of the high-speed transportation for DC electrified 50.8 km long section B - C of Pridnieprovskaya railway. The system receives power from the three traction substations in a nodal scheme. The data for calculation are shown in Figure 2 and Table 1. For comparative analysis, the existing CTPSS was transformed into a DTPSSS (Figure 3) and DTPSSA (Figure 4).

The calculations assumed that the train is moving at an average speed of 160 km/h, with an average power consumption of 4.2 MW and a peak capacity of 8.8 MW. The calculations of the voltage level were carried out on a mathematical model [11], with the possibility of taking into account the mutual influence of each load on the associated and, depending on the power scheme, on adjacent tracks:

$$U_j(x) = U_b - I_j(x)\cdot f_R(x) - \sum_{\substack{k=1 \\ k\neq 1}}^{n1} \Delta U'_k(x,x_k) - \sum_{k=n1}^{n1+n2} \Delta U''_k(x,x_k), \quad (1)$$

***Table 1** Parameters of the power supply systems*

power, MW	TS1		OTS1 (PPA1)		TS2		(OTS2) PPA2		TS3
CPSS	12.6		-		25.2		-		18.9
DTPSS	10.4		5.2		10.4		5.2		10.4
PSSA	12.6	6		2.5	12.6	2.5		6	12.6
no-load voltage, V					3500				
traction line					M120+2MΦ100+A185+P65				

where:
k - load number on the corresponding track;
n_1, n_2 - number of loads on the 1st and 2nd tracks;
U_b - voltage on the buses of the traction substation, V;
$\Delta U_k'(x,x_k)$ - voltage drop distribution function from *k-th* load on the passing track, V;
$\Delta U_k''(x,x_k)$ - the same on the adjacent track, V;
I_j - load of the j - th train with x coordinate;
$f_R(x)$ - resistance function.

As a result of calculation in the CTPSS, the minimum value of the voltage on the current collector was 2652 V, which is caused by a complex profile of the section and a sharp rise of the traction power to maintain a constant speed of the train. Thus, the mode of voltage on the electrified section does not meet the requirements for introduction of the high-speed traffic. Even in the cases where a mathematical expectations lay above the nominal value, the level of the voltage does not correspond to rated values, the confidence range of its changes is 875 V, but its lower limit beyond the maximum allowable voltage level for movement is 2900 V [12].

During the calculations, the change in the voltage level on the traction substation buses during the train moving was also determined. The obtained results indicate that the voltage level on the traction substation buses does not exceed the rated values, and its range is 92 V on average for three traction substations.

For estimation of the voltage mode for distributed supply, calculations were carried out under similar conditions of the train movement and track parameters. The difference concerned the power supply scheme of the traction line. For the DTPSSS the controlled transformer units PA-5200 were selected [13], with the number of two units per traction substation and one unit on the sectioning point. Application of the DTPSSS voltage on the current collector of rolling stock was within the permissible values, confidence interval of its changes was 705 V with an average value 3291 V. When applying the controlled rectifier units, the voltage range on the traction substations buses decreased and the average value was 80 V with mathematical expectation of 3490 V.

Evaluation of voltage on the current collector showed that when using the DTPSSA, the mathematical expectation of the voltage was 3397 V, confidence interval was 321 V. The mathematical expectation of voltage on buses of traction substations was 3492 V.

Estimation of the power mode in the case of implementation of the high-speed traffic was carried out based on the above calculations. In accordance with parameters of the comparable systems (Table 1), the total installed capacity of traction substations under centralized power supply is 56.7 MW, distributed power supply with one unit substations - 41.6 MW, distributed power supply with solar generators - 54.8 MW.

The specific power consumed by the rolling stock from 1 km of electrified line is determined by Equation (2):

$$p = \frac{W_e / T}{L}, \tag{2}$$

where:
W_e - consumed electricity by rolling stock during the movement on given section, kW·h;
T - time of movement of rolling stock on section, h;
L - length of the electrified section, km.

The specific power that can be provided by an existing system can be determined by the formula [13]:

$$p_{TS} = \frac{\int_0^T \left(P_{TS1}(t) + P_{TS2}(t) + P_{TS3}(t)\right) / T}{L}, \tag{3}$$

where:
$P_{TS1}(t), P_{TS2}(t), P_{TS3}(t)$ - power generated by the corresponding traction substation during the rolling stock movement.

The power given by the traction substation to the load is determined by the formula:

$$P_{TS}(x(t)) = U_{BTS}(t) \cdot \varphi(x(t)) \cdot I_e(x(t)), \tag{4}$$

where:
$U_{BTS}(t)$ - voltage on the traction substation buses, V;
$\varphi(x(t))$ - current distribution function;
$I_e(x(t))$ - current of the rolling stock, A;
$x(t)$ - coordinate of the rolling stock location depending on time, km.

Functions of current distribution of traction substations are determined using the method of nodal potentials in the matrix form:

$$\overline{F}(x,S) = |G| \cdot |A(S)|^{-1} \cdot \overline{B}, \tag{5}$$

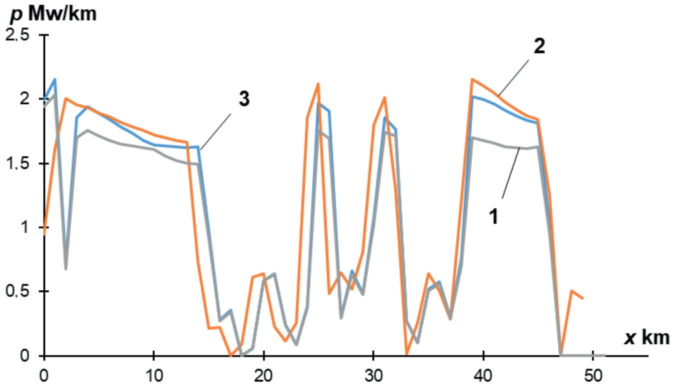

Figure 5 *Specific power on the given section:*
1 - with centralized supply; 2 - with distributed supply;
3 - rolling stock consumption

Table 2 *Traction substation load factor, %*

the value of the load factor	TS1	OTS1 (PPA1)		TS2	(OTS2) PPA2		TS3
CPSS	48.2	-		25.3	-		27.2
DTPSS	77.2	91.9		50.4	98.8		51.4
PSSA	72.4	89.7	84.5	43.1	78.6	97.4	48.3

where:
$|G|$ - diagonal matrix of conductivity of traction substations;
$|A(S)|$ - basic matrix of the scheme, constructed using the method of nodal potentials;
$\overline{B}$ - vector of predetermined currents (loads) in nodes.

Matrices $|A(S)|$, $|G|$ and are dynamic and change their size depending on the train situation on the given section and location of the individual load.

In turn, the voltage on the traction substation buses can be defined as:

$$U_{BTS}(t) = U_{iv} - \rho \cdot \varphi(x(t)) \cdot I_e(x(t)), \tag{6}$$

where:
U_{iv} - the idle voltage of the traction substation, which is determined by the position of the regulation device of the transformer and can be calculated according to [14], V;
ρ - internal resistance of the traction substation, Ω.

Hence, taking into account the foregoing formulas, one can compose an expression for determining the power generated by the traction substation as a part of a distributed power supply system, taking into account the current distribution in the given section:

$$P_{TS}(x(t)) = P_{zg}(x(t)) - AP_{zg}(x(t)) \cdot \\ \cdot \left(\frac{P_{zg}(x(t))}{S_{\kappa 3}} - \frac{u_{kz}}{100} \cdot k_z(x(t)) \right), \tag{7}$$

where:
$P_{zg}(x(t))$ - power generated by traction substation for feeding the rolling stock, $P_{TS}(x(t)) = U_{iv} \cdot \varphi(x(t)) \cdot I_e(x(t))$;
$k_{zg}(x(t))$ - load factor of the traction substation, $k_z(x(t)) = \dfrac{P_{zg}(x(t))}{S_{nom} \cdot n}$.

Based on the above expressions the curves of changes of power generation by traction substations of a centralized and distributed system for feeding the rolling stock moving along the section were obtained (Figure 5).

As it follows from analysis of Figure 5, the centralized power system is not able to meet the needs of the high-speed train for the consumption of power per kilometer of track, which, in turn, leads to impossibility of providing a standardized voltage level in the traction line.

3 Analysis of energy indicators

3.1 Traction substation load factor

The above calculations indicate that installed power in traction substations (for centralized power supply system) allows the high-speed transportation on the given section, but at the same time, the average value of the traction substation load factor is less than 50% (Table 2).

With distributed power, by reducing the installed power of the traction substations, and almost equal power, generated by traction substations, the load factor increased for 1.5 times, on average.

3.2 Loading capacity of the wires of the contact line

In many sections of electrified DC rail, the cross section of the wires of the contact line approaches the value of 600 mm^2 in copper equivalent. With growth of the peak electrical loads, it is impossible to provide the thermal stability of the contact line and reduce the voltage losses by suspending additional wires. So, on to the DC 1 - in

Table 3 *Load capacity of contact lines*

power system	centralized				distributed			
contact line type	M-120+2M-Ф100+A185	M-120+2M-Ф100+A185	M-120+2M-Ф100+A185	M-120+2M-Ф100+A185	M-120+2M-Ф100+A185	M-120+2M-Ф100+A185	M-120+2M-Ф100+A185	M-120+2M-Ф100+A185
acceptable current of contact line at 15% wear, a	1630	2120	2710	3290	1630	2120	2710	3290
maximum rated current in the contact line, a	2341.6				1880			
load capacity at current,%	- 43.7	- 10.6	13.6	28.8	- 15.3	11.3	30.6	42.8

*The minus sign indicates an excess of the load capacity of the contact line by current.

Table 4 *Power indicators of traction power supply systems*

Parameter		CPSS	DTPSS	PSSA
Voltage mode for current on pantograph of rolling stock, V	M(U)	3130	3291	3397
	max(U)	3418	3500	3500
	min(U)	2643	2901	3255
	The value of the confidence interval of the change	875	705	321
Electricity consumption for traction, kWh		1495	1437	944.8 (from TS)+ 486.3 (from SP)
Average power losses, kW	Excluding higher harmonics	524	372	351
	Taking into account the higher harmonics	631	428	409
Electricity losses, kWh	Excluding higher harmonics	174.9	123.9	113.6
	Taking into account the higher harmonics	210.6	142.7	126.1
cosφ		0.77	0.79	0.81
Efficiency		0.92	0.95	0.97

Lviv railways to provide the standard voltage level on the pantograph of rolling stock and to assure the compliance with the conditions of the thermal resistance of contact, with the passage of two electric locomotives 2ES10 and 2ES6, five additional reinforcement wires were installed. According to the experimental data, the currents of heavy-weight trains can significantly exceed the load capacity of the contact line.

According to the calculation results for the centralized and distributed power system, the reserve load capacity of the wires for typical contact lines used on electrified Ukrainian railways are:(Table 3).

3.3 Investigation of the electric power losses in the distributed power system

The power losses or energy efficiency of traction power systems are one of the main criteria for assessing the energy efficiency of a powertrain network. They determine the operating costs of the electrified section.

Increasing the intensity of the movement, as is known, leads to an increase in current loads on all the elements of the traction power system and, consequently, to increase of energy losses and reduction of energy efficiency. However, in some interurban interval, efficiency reaches a maximum and then it is reduced due to the prevalence of losses independent of current. In any case, with other equal conditions, the energy efficiency of a distributed system of the traction power supply is higher, the distance between the supply points is smaller, despite the fact that with decrease of the distance between them their power is decreasing, as well [15]. The loss of electricity is obtained by integrating the distribution power losses in the traction line, which, in turn, is defined as the product of the current flowing through the area of contact and losses of voltage on this area.

In accordance with [11], the current distribution in the traction line is determined by the received potentials in the nodes of the scheme in Equation (5), the resistance of the branches between them and the schedule of trains:

$$i_{K1} = \frac{\varphi_1 - \varphi_2}{r_1} \tag{8}$$

where:

φ_1, φ_2 - potentials of the first and second nodes, V;

r_1 - the value of the resistance of the branch between the first and second nodes, Ω.

Further, in the presence of another load on the calculated section, using the principle of superposition, the distribution of currents in the contact line from all the trains is determined:

$$I_{K1}(x) = \sum_{I=1}^{n1} I_{K1}(2i-1,x) + \\ + \sum_{I=1}^{n1} I_{K1}(2i,x) + I_{lev}, \qquad (9)$$

where:
$2i$ - 1, $2i$ - determine the numbers of the odd and even train;
n_1, n_2 - number of trains correspondingly on the first and second track;
I_{lev} - leveling current on the section, A.

Determination of the voltage loss distribution function involves use of the currents distribution function in the contact line with the accumulated gain for the corresponding distance and the resistivity of the line.

$$\Delta U_{K1}(x) = \sum_{i=1}^{n1} \Delta U_{K1}(2i-1,x) + \\ + \sum_{i=1}^{n1} \Delta U_{K2}(2i,x) + I_{lev} \cdot r_0 \cdot x, \qquad (10)$$

where:
$\Delta U_{K1}(2i-1,x)$ - voltage losses in the traction line from trains moving in the even direction, V;
$\Delta U_{K2}(2i,x)$ - voltage losses in the traction line from trains moving in the odd direction, V;
$I_{lev} \cdot r_0 \cdot x$ - voltage losses in the traction line from the compensating currents, V.

The statistical data in Table 4 were obtained from the results of processing 5200 values during the simulation. Losses of power from the higher harmonics for comparative analysis of STE were calculated according to [16].

A comparative analysis of the energy performance of the proposed distributed systems and the existing centralized supply system is summarized in Table 4.

4 Conclusions

The conducted research has established that in the case of passing one high-speed train on calculated section with the given parameters, introduction of the distributed power system allows:

- to ensure the necessary level of specific power in traction line within 2 - 2.15 MW/km, allowing to provide the rated minimum voltage on current collector at the level of 2900 V;
- to reduce the load on the wire of the contact line thanks to the decentralization of power sources;
- to reduce inactive power and power losses in traction line thanks to improvement of voltage mode in the system of traction power supply;
- to achieve electricity savings of 57.2 kWh, representing 4.3% of the electricity consumed by the train.

Thus, application of the distributed power systems for the traction loads can provide the necessary requirements for introduction of the high-speed traffic and should be a priority direction for reinforcement of the DC traction power supply.

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