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STUDYING OF THE POWER MODES IN THE TRACTION LINE FOR ENSURING THE HIGH-SPEED TRAFFIC

Об'єктом дослідження є режими потужності у системах тягового електропостачання як централізованого, так і розподіленого живлення при запровадженні швидкісного руху. Розпочате впровадження швидкісного руху на електрифікованих залізницях України має низку обмежень у застосовуваній системі тягового електропостачання централізованого живлення. До них можна віднести не тільки неможливість забезпечення необхідного рівня напруги 2,9 кВ, а й низьку ефективність використання агрегатної потужності тягових підстанцій. При цьому застосовувана система тягового електропостачання не дозволяє забезпечити необхідний рівень питомої потужності в тяговій мережі. Застосовувані технічні засоби та заходи для підсилення тягової мережі не дозволяють, в більшості випадків, забезпечити нормативні вимоги до організації швидкісного руху.

Аналіз сучасних досліджень показує, що подолання вказаних недоліків можливе за рахунок застосування системи розподіленого живлення тягової мережі. На сьогоднішній день розроблено достатньо варіантів побудови таких систем, але в даній роботі, в якості альтернативного варіанту, розглядалась система з розподілом наявної в системі централізованого живлення агрегатної потужності по міжпідстанційній зоні. При цьому була обґрунтована доцільність зменшення потужності тягової підстанції до рівня 10 МВт.

В ході дослідження режимів потужності в порівнюваних системах тягового електропостачання використовувалися результати експериментальних досліджень та імітаційне моделювання режимів роботи порівнюваних систем. При розрахунках враховувались не тільки специфіка тягового навантаження, а й його вплив на навантажувальну здатність контактної підвіски. В результаті такого підходу було показано, що розподілена система тягового електропостачання дозволяє виконати нормативні вимоги щодо забезпечення швидкісного руху. При її застосуванні зменшується витрата електричної енергії на тягу поїздів на 40 %, питома потужність тягової мережі збільшується на 90 %, а коефіцієнт завантаження тягових підстанцій – на 60 %.

Запропонований інноваційний підхід до забезпечення необхідного режиму потужності в тяговій мережі дозволяє зберегти існуючу інфраструктуру при організації швидкісного руху на існуючих електрифікованих ділянках постійного струму. Такий підхід враховує різні типи електрорухомого складу, а також дозволяє забезпечити необхідну пропускну здатність залізниць.

Ключові слова: *система тягового електропостачання, централізоване живлення, розподілене живлення, питома потужність, рівень напруги, швидкісний рух.*

1. Introduction

The current DC power supply is caused by the rapid aging of the fixed assets of the infrastructure. At the same time, the European integration efforts of Ukraine require measures to introduce high-speed traffic, and require the modernization of electrified lines. High-speed traffic can be provided by traction power supply systems of both direct and alternating currents used in Ukraine, but to ensure constant speed, it is necessary to increase the power consumption of the traction network, primarily for electrified sections of direct current.

The current system of centralized traction power supply of direct current is not always able to ensure the transfer of the necessary power for high-speed trains. The main restrictions include reducing the voltage on the current collectors of the locomotive below the allowable for high-speed movement of 2900 V and heating the wires of the contact network, contribute to the loss of their mechanical strength [1].

Analysis of scientific publications shows that the main efforts of scientists are aimed at ensuring the required voltage regime in the traction network. But the technical means and organizational measures used today in the territory of Ukraine do not allow solving the set task. As shown by the results of experimental studies and calculations, the impossibility of providing the voltage required for high-speed movement when using low-cost amplification means is caused by insufficient power consumption of the traction network in the centralized traction power supply system. When organizing high-speed traffic on DC lines, one of the most important requirements for traction power supply is also ensuring the required level of specific power of the traction network within 1.5–2 MW/km. However, the fulfillment of the stated requirements is impossible without the improvement of the electric traction system, its modernization and reconstruction.

Hence, the urgent need, in the face of rising energy prices, is ensuring the effective use of the available aggregate power in the DC traction power supply system. That is why scientific thought is evolving towards the development of distributed power systems for traction network (DPN), which have the best technical and economic characteristics [2].

Therefore, research and analysis of power modes in traction networks to ensure high-speed traffic is relevant.

2. The object of research and its technological audit

The object of research is the power modes in the traction power supply systems of both centralized and distributed power during the introduction of high-speed traffic.

In the works [1, 2] it is noted that the existing circuit design solutions for the construction and amplification of the power supply system of the traction load have a number of limitations. These include: the inability to provide the necessary voltage mode, large losses of power and voltage, low efficiency of use of the existing aggregate power. One of the requirements of today is the need to ensure the required level of power density of the traction network. Now this figure should be in the range of 1.5–2 MW and tends to increase.

The existing traction power supply system (TPSS) of the centralized type is not able to meet the set conditions. Hence, the most advanced means of increasing the energy efficiency of the traction network is the use of a distributed traction power supply system.

Of particular importance is the topic of research due to the fact that the DC system electrified a significant part of the railways not only in Ukraine, but also in Poland, Czech Republic, Slovakia, Belgium, Italy and the like. Therefore, the technical solutions proposed in this paper to provide the necessary power regime in the traction network can be extended to these countries, in particular, Central and Eastern Europe.

3. The aim and objectives of research

The aim of research is modeling and analysis based on the developed innovative circuit solutions of the traction power supply system of power modes in the traction network to ensure high-speed traffic. To achieve this aim it is necessary to perform the following objectives:

1. To perform experimental studies to assess power modes in the traction network.
2. To assess the energy processes in the traction power supply systems.
3. To consider the power modes of the proposed distributed type system.

4. Research of existing solutions of the problem

As is known, the improvement of technical and economic indicators of existing sections of electric railways of direct current can be achieved during certain technical and organizational measures [3, 4]:

- use of parallel connection points;
- increase in the cross section of the wires of the contact network;
- construction of additional traction substations [5, 6];
- use of blocks of distributed power;
- complete replacement of six-pulse rectifiers with rectifiers with twelve pulsations in the rectified voltage curve;
- development and production of rectifiers with an optimal scale of nominal capacities;
- expansion of the scope of regenerative braking and the operational development of twelve-pulse rectifier-inverter converters [7, 8];
- operational development of effective schemes of smoothing filters for traction substations of direct current;
- installation on the feeder zone of voltage-adding devices (VAD) with voltage regulation;
- use of converter transformers with voltage regulation under load.

The basic concepts and principles of enhancing the 3.0 kV traction system are described in the 60–80s of the last century [9, 10]. Modern 3.0 kV TPSS amplification has not undergone significant structural changes, and only the element base has changed due to the development of science, technics and technology. In [11, 12], comparative calculations of various traction power supply systems are carried out, the proposed methods for amplifying direct current power amplifiers, built on the basis of modern achievements, their advantages and disadvantages are fully highlighted, and the results of operating experience are given.

The effect of the use of individual measures is different and, as a rule, not enough [13]. To enhance the power supply of a particular line in order to achieve the required power density indicators and to ensure the movement of high-speed trains, a whole range of measures must be taken. Therefore, more and more often, developers are turning to distributed traction load power systems. In a distributed power supply network of the contact network, they understand that when consumers in the busiest zones receive power not only from their relatives, but also from a number of distant power points [4]. The participation of such items in the power supply of adjacent inter-substation zones is obtained the greater, the smaller the power installed in one substation traction units.

The concept of distributed power provides high efficiency and reliability, allows to remove the limitations of power supply devices. With such a system, it is still possible to use existing rolling stock, and large expenses for re-equipment of the contact network are not needed.

One of the main differences between the centralized and distributed power supply schemes is the number of units at substations and methods for backing up their power. With a centralized power supply, the number of substation units is at least two. In the distributed supply scheme, all substations are one-unit [14, 15]. In this regard, in the first scheme, a reserve is provided for the case of shutdown of the unit, and in the second – for the case of a substation shutdown. In order for a distributed power supply with one disconnected substation to provide normal movement dimensions, it is necessary that the substations are located much closer to each other than in the centralized power supply circuit. Accordingly, the power of each substation will be lower, and their number will be greater. Therefore, such a scheme becomes expedient under the condition of maximum unification of the traction substations, with single-unit substations easily achieved.

Thus, the results of the analysis allow to conclude that the system under consideration requires a much smaller cross section of the wires of the contact network and, at the same time, the energy and voltage losses are reduced. These qualities are the most important advantages of a distributed power system. In addition, the protection of the contact network against short-circuit currents is greatly facilitated, the potentials of the rails relative to the ground, and, accordingly, the danger of destruction of underground structures by stray currents. In a distributed power supply circuit, single-unit traction substations are of the same type and are simplified to the maximum. This makes it possible to perform full automation and include them in the information technology service system.

5. Methods of research

Experimental studies are the main source of information for studying energy-generating processes in the traction power supply system of electrified DC railways and for constructing mathematical models of the processes of conversion and consumption of electrical energy [16, 17]. As well as specific electrical devices. The set of observed values of the above parameters is the primary statistical material and is called a statistical or time series. A time series is an ordered sequence of observations at specific points in time. The nature of the series and the structure of the calling process determine the order of the specified sequence. Usually, time series are formed on the basis of a discrete sequence of observations at regular intervals of time. The results of such measurements are presented in the form of a continuous variable (random function), which obeys some probability law. Realizations of the random process may include observation errors. It should be noted that in many cases, time series simultaneously with fluctuations and irregularities (outliers) have some tendencies of change (trend) that can be described by different models.

Experimental studies of power consumption modes are carried out according to the methodology developed at the Department of Intelligent Power Supply Systems (IPSS) of the Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan (Ukraine) using the developed hardware and software complex [11].

Determination of power and voltage modes and assessment of its impact on the operation of electric rolling stock and power supply devices is one of the most important tasks in building a modern intelligent traction power supply system. At present, the analysis of the functioning processes of variations in the TPSS is carried out using simulation modeling. The purpose of constructing a mathematical model of TPSS is determination of the electric power consumption during train movement and electric power losses in the elements of the traction power supply system, the voltage control of current collectors of electric locomotives and currents in the elements of TPSS [17]. The development of a mathematical model of a controlled distributed TPSS should provide for the placement of a number of amplifying points (AP) at the inter-substation zones with the possibility of controlling their output power in real time.

The mathematical model developed at the IPSS department [18] allows performing electrical calculations of the traction power supply system of a site with any number of traction substations and inter-station zones. And also to take into account the various values of the no-load voltage of the traction substations and their internal resistance, various schemes for connecting generating capacity in the traction network. The mathematical model is based on the determination of the regularity of the change in the resistance of the traction network with N traction substations/reinforcing points and N–1 inter-substation zones with analytical functions. The mentioned functions together with the functions of current distribution and distribution of potentials in the nodes of the system make it possible to formalize the calculations of the electric traction systems and go from discrete to continuous representation. The definition of the main indicators of the traction power supply system $U_{\min}$, ΔP, ΔW is proposed to perform using the current distribution function, the calculation of which is carried out in a matrix form, which allows to easily describe any system configuration with its corresponding parameters. The result of the calculation of this function is a vector consisting of the potentials in the nodes of the design scheme at the points of connection of the feeders of the traction substations, the points of connection of the contact hangers of the tracks and the electric rolling stock (ERS), which is located in the area of the station. The possibility of using direct calculation of electrical quantities allows to significantly simplify further optimization calculations of the operating modes of the traction power supply systems.

6. Research results

6.1. Analysis of experimental data. One of the main parameters of the traction power supply system is the number and power of traction substations and the distance between them. The total installed capacity of the traction substations, for example, for the experimental sites of the Dnipro railway (Ukraine) is within 12÷50 MW. But the current state of the DC traction power supply is characterized by the growing shortage of necessary power to ensure the applied voltage in the traction network when introducing high-speed traffic. At the same time, as the conducted studies show, the utilization rate of regime power and equipment of traction substations does not exceed 15 %. This is confirmed by the experimental data that are obtained at the traction substations of the Dnipro railway (Table 1) [19].

Table 1

Research results of the load of traction substations

Traction substation	Power P_I, kW	Average power consumption P_A, kW	Load factor K_I, %
TS 1	20800	2868	13.7
TS 2	20800	1080	5.2
TS 3	19800	956	4.8
TS 4	19800	422	2.1

The study of the operating modes of the traction network and the power consumed by electric locomotives is carried out on the Dnipro railway:

- on the site Nizhniodniprovsk (ND)-Vuzol – Piatikhatky. The length of the section is 128 km, the contact network is M-120+2MF100+A185. The site receives power from 9 traction substations. The movement of trains took place in pair and odd directions;
- on the site of the ND Knot – Demurino. The length of the section is 135 km, the contact network on the site M-120+2MF100+A185. The site receives power from 9 traction substations. The movement of trains took place in pair and odd directions;
- on the site Sinelnikove – Demurino. The length of the section is 96 km, the contact network is M-120+

+2MF100+A185. The site receives power from 6 traction substations. The movement of trains took place in doubles and odd directions.

The summarized results of studies of power modes in the traction network are presented in Table 2 and Fig. 1, 2.

Table 2

Consumption of power and current when movement on experimental areas

No.	Locomotive	Movement direction	Train mass, t	Power consumption of ERS, MW/km			Current in traction model, A		Permissible continuous current of the contact suspension M120+2MF100+A185, and when the contact wire is worn, %		
				Minimal	Average	Maximal	Average	Maximal	0	15	30
1	VL8	P-ND	4117	–2.52	1.46	5.06	900	1610	2280	2120	1960
2	VL8	ND-P	2887	–2.04	1.5	6.2	934	2000			
3	VL8	P-ND	4441	–3.05	1.08	5.2	913	1750			
4	VL8	ND-P	3372	0.032	1.67	5.98	977	1900			
5	VL8	P-ND	4022	–3.42	1.29	8.7	952	1800			
6	VL8	ND-P	1462	–0.85	1.07	4.55	707	1400			
7	VL8	P-ND	4446	–4.44	0.67	5.28	801	1750			
8	VL8	ND-P	2451	–2.25	1.23	4.4	736	1385			
9	VL8	ND-P	4532	–2.96	1.4	5.34	445	1750			
10	VL8	P-ND	4251	–3.61	0.95	6.12	310	1800			
11	Chs7	ND-P	550	0.11	2.25	7.18	690	2100			
12	Chs7	P-ND	495	0.1	1.7	5.87	528	1925			
13	Chs7	P-ND	550	0.1	1.64	6.07	499	1750			
14	2VL11	S-D	5957	0.08	2.74	10.37	914	3541			
15	2VL11	D-S	5957	0.04	2.54	8.29	806	2797			
16	2VL11	ND-D	5935	0.75	3.17	11.6	1077	3860			
17	2VL11	D-ND	6004	0.01	2.05	9.64	687	3158			

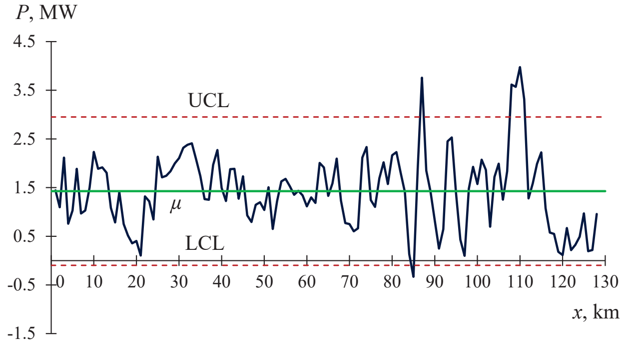

Fig. 1. The average change in power consumption per kilometer when moving the Nizhniodniprovsk-Vuzol-Piatikhatki section in the pair and odd directions: UCL – upper confidence limit; LCL – lower confidence limit

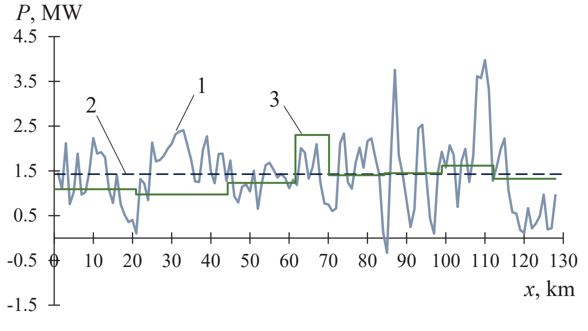

Fig. 2. The average change in power consumption per kilometer when moving the moving the Nizhniodniprovsk-Vuzol-Piatikhatki section in the pair and odd direction: 1 – power of electric rolling stock consumed at each kilometer; 2 – ERS power consumption; 3 – power at the inter-substation zone, which can provide adjacent traction substation

Analysis of the results shows that in the traction network there are areas of limited power consumption, that is, areas where the power consumption of the ERS exceeds the TPSS capacity to transfer the required power level. In turn, this leads to a sharp decrease in the voltage of the current collectors of electric locomotives and a decrease in the speed of movement, which is unacceptable when introducing high-speed movement. It is necessary to indicate that the obtained results correspond well with the data given in [20]. At the same time, it is paradoxical that the aggregate capacity of the traction substations is not fully used. It should also be noted that in some inter-substation zones (ISZ), the current consumed by the ERS is approaching critical values, which in conditions of the existing wear and tear of the TPSS infrastructure can lead to emergency situations.

6.2. Power mode requirements. High-speed railways and railways with heavy traffic, increased passage, with short intervals (3–5 minutes) between trains and a power consumption of 10–12 MW or more, have a pulsed nature of electric traction [21].

This increases the peak load on the traction substation, increases the loss of voltage and energy in the traction power supply, complicates the conditions of current collection and increases the heating of the contact network wires.

The specific power consumption of high-speed lines is 1–1.3 MW/km, and for railway double-track lines with increased passage it can reach 1.7–2.5 MW/km. According to the norms of the International Union of Railways (IUR), developed in 1996, for a double-track high-speed line with a maximum speed of 300–350 km/h, the maximum specific power consumption of electricity for traction of 3 MVA/km is provided [21]. The power of traction power supply devices is recommended to be taken on the basis of the specified specific power consumption. That is, there is a gradual evolution of the TPSS requirements – not only the provision of normalized voltage, but also the provision of the required energy intensity of the traction network.

It is necessary to take into account that the choice of technical solutions for the creation or reconstruction of a traction power supply system (TPSS) to ensure high-speed passenger traffic is based on the main parameters of the designed line, which include:

- maximum permissible and operational speeds;
- type of electric rolling stock (ERS) and its characteristics;
- principles of transport organization and train schedules [22].

The load capacity of individual power supply devices and the system as a whole essentially depends on the listed parameters. The TPSS parameters and the power supply circuit of the catenary are selected in accordance with the accepted standards for the allowable load of the power equipment of the traction substations, the voltage of the EPS current-collectors and the heating temperatures of the wires of the traction network.

The characteristics and parameters of the rolling stock for high-speed railways (HSR) are due to the fact that with increasing speed the aerodynamic component of the main resistance to movement increases quadratically [21]. So, if at a speed of 120–140 km/h the main specific resistance when moving ordinary passenger trains does not exceed 4 kgf/t, then for high-speed ERS (250–300 km/h) it is 10–17 kgf/t. In accordance with this, for the realization of high speeds, it is necessary to substantially large specific (per ton of gross mass) power of the train equipment.

The ratio of the set maximum speed at the site and the power of the train, as well as the method of controlling the force of traction on the ERS (stepwise, smooth) have a great influence on the mode of current consumption from the contact network. When a regular passenger train is moving, for example, with an EP1 electric locomotive, the change in current in the contact network is pulsed, due to the alternation of traction and coasting modes. The electric train EPS250 (design analogue of the «Sapsan» train) with a smooth adjustment of the traction force consumes the maximum current only during acceleration, and in other areas it realizes the power necessary to maintain a given speed depending on the current track gradient. At a speed of 300–350 km/h, the ISE3 train [23] consumes most of the time, due to the large resistance to movement, the maximum current is almost independent of the section profile.

The results of numerous traction and electrical calculations show that the current loads in the power supply systems at the same interval between the whole and on the circulation lines of freight trains of increased weight are almost commensurate. The necessary electric traction power depends on many factors, the main of which are:

- train mass;
- movement speed;
- main resistance to movement;
- intervals between trains;
- frequency of arrivals and accelerations;
- possibility of regenerative braking;
- plan and profile of the path;
- characteristics of the traction power supply network.

But with high-speed (200–250 km/h) and high-speed (300 km/h and above) movement, the power realized by the train's traction engines is almost equal to the power realized by heavy-weight electric locomotives [24].

However, due to the faster rate of change of loads during the passage of trains on the high-speed rail, the heating intensity of the power equipment of substations and wires of the contact network is slightly less than in the sections of heavy traffic.

As noted above, the drive of modern high-speed ERS implements a smooth control of the traction force. For such an ERS, the maximum traction characteristic (dependence of the traction force on speed) is set, which in a simplified form has two sections [23]:

- acceleration – from zero speed to a certain value V, with a constant or linearly incident traction force;
- constant power – automatic characteristic when changing the traction force is inversely proportional to speed.

Depending on the current conditions (profile slope, voltage in the contact network) and train management mode, the control system selects the desired point in the area limited by the maximum traction characteristic. Increasing the speed of the train leads to a significant increase in the force of resistance to movement. In this regard, to increase the speed, one should increase the traction force, and an increase in the traction force leads to an increase in the current consumed by the ERS. When accelerating to speeds more than 200 km/h, the resistance to movement, and consequently, the current is almost constant. The current reaches 3 kA or more. For trains equipped with converters, with a decrease in voltage on the ERS current collectors for realizing the installed power at a given speed, more current must be consumed and, conversely, with increasing voltage, the current decreases. For this reason, from the power supply system, it is necessary to ensure the maintenance of voltage to the ERS current collectors, which is close to nominal. It is possible to perform this task only with sufficient energy consumption traction network.

In connection with the entry of Ukraine into the world trade organization (WTO), efforts to integrate into the European community and the development of transnational railway corridors in the coming years, it is necessary to make changes in the infrastructure of railway transport. But qualitative changes on the Ukrainian railways and the introduction of high-speed traffic are possible only with an increase in productivity in the economy and the welfare of society [25]. According to world experience, the cost of high-speed rail is about 30 million USD per kilometer. In all countries, the construction of such infrastructure facilities is within the power of the state only and is financed from the state budget. So in Europe and Asia there is significant passenger traffic, and the development of high-speed transport has a progressive nature [26]. At the same time, Ukraine has no passenger traffic of 24.000 people per day, so that trains run at least once an hour. Thus, for Ukraine, the best option is forming a network of rail transportation with a maximum speed of up to 160 km/h, in the future up to 180–200 km/h [25]. From here, it is necessary to develop measures for the modernization of railway lines for the use of high-speed trains Hundai and Škoda in Ukraine.

Fig. 3–6 show sample data from experimental trips confirming the above reasoning.

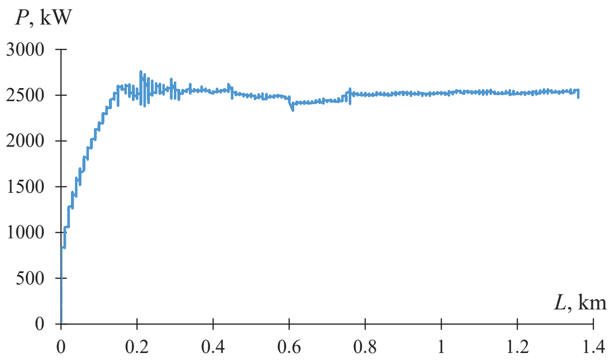

Fig. 3. Power consumption from the contact network of Škoda electric locomotive

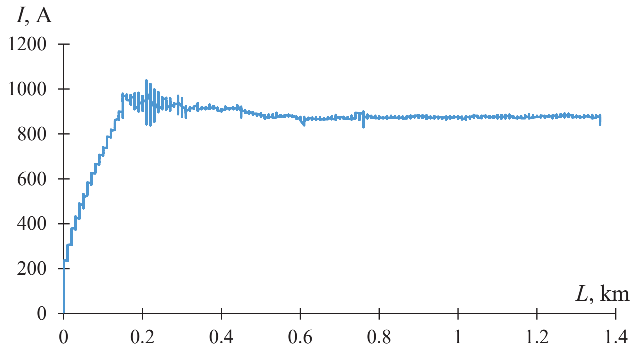

Fig. 4. Current consumption by Škoda electric locomotive

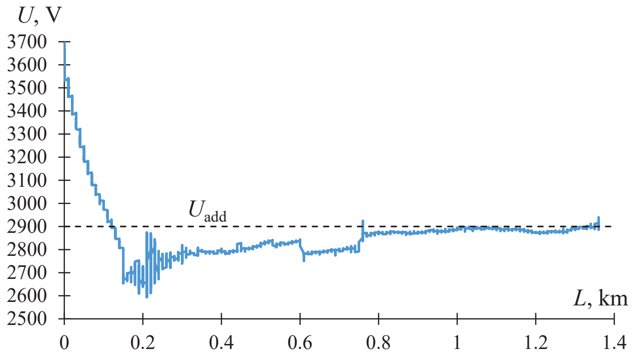

Fig. 5. Voltage on current collectors of Škoda electric locomotive

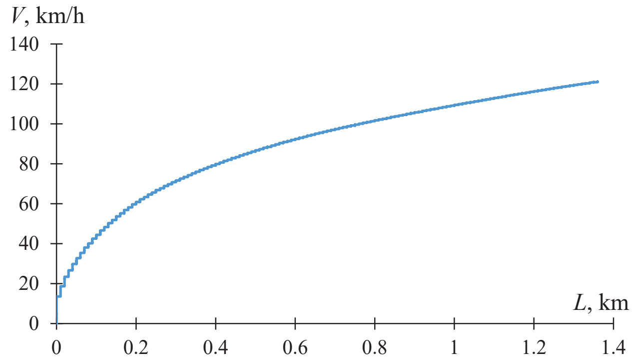

Fig. 6. Speed of Škoda electric locomotive

As follows from their analysis, when a high-speed electric locomotive reaches a steady state, the tension in the traction network decreases below the established standard value.

It can be assumed that in this case there is an insufficient energy intensity of the traction network. Table 3 shows an analysis of the aggregate capacities of the traction substations in the areas of high-speed movement, and the data for calculating the specific power of the inter-substation zones are presented.

It can be stated that almost half of the ISZs do not meet the established standards for specific power.

In practice, this leads to the need to increase the interfacial intervals [20] and sets the task of upgrading such zones in TPSS.

Table 3

Information about the aggregate power of traction substations

Name	Power, MW	The length of the inter-substation zone, km	Distances to sectioning posts, km	ISZ estimated specific power, MW/km
Donetsk direction				
Pyatikhatki	37.3	20.9	10.2/10.7	1.95
Erastivka	44.4	23.4	9.8/13.6	1.89
Verkhovtsevo	44.4	17.3	7.6/9.7	2.0
Verkhnodniprovsk	24.9	22.7	8.6/14.1	1.48
Bagley	18.6	14.7	–	1.27
Sukhachivka	18.7	13.1	–	2.14
Goriainovo	37.4	16.1	–	2.7
NDVuzol	50	6.9	–	4.34
Igren	16	11.2	–	2.25
Ilarionove	44.4	21.6	11.1/10.5	2.18
Sinelnikove	50.0	17.3	8.5/8.8	2.21
Razdory	26.52	17.8	9/8.8	1.59
Pysmenna	30.28	20.8	10.4/10.4	0.72
Ulianivka	30.28	18.6	9/9.6	–
Pokrovsk direction				
Balivka	12.6	30.9	14.4/16.5	0.61
Novomoskovsk	25.2	27	14.9/12.1	0.7
Mineralna	12.6	24.4	13.0/11.4	1.03
Pavlohrad-1	37.8	24.2	11.5/12.7	1.04
Boguslavsky	12.6	21.6	10.6/11.0	0.87
Nikolaivka	25.2	29.2	12.3/16.9	0.75
Slavianka	18.9	17.2	8.3/8.9	1.28
Passing loop number 5	25.2	23.8	10.1/13.7	–

6.3. Distributed traction power system. As noted above, when building DPN to ensure the required level of specific power of the traction network at the current stage of the development of the investment climate when introducing high-speed traffic, it is necessary to make maximum use of the existing infrastructure of traction power supply. First of all, it is possible to talk about the location of the traction substations and gain points. At the first stage of DPN implementation, it is advisable to maintain the existing coordinates of their location. At the same time, it is necessary to resolve the issue of the appropriate power of traction substations and amplification points.

To date, formed two main approaches to the DPN construction are formed:

- the use of reference substations with power points located between them at certain distances [2, 3];
- the use of single-unit substations of the same type with equal distances between them [27].

Each of these concepts has the right to apply. At the same time, conducted studies, due to the real absence of 24 kV rectifiers, have shown that the use of single-unit traction substations (SUTS) is the most appropriate [28]. To minimize capital investments in DPN, power supply to the SUTS should be provided by longitudinal power supply lines (LPSL) 35 kV. Thus, the DPN structure recommended at this stage will be the form shown in Fig. 7.

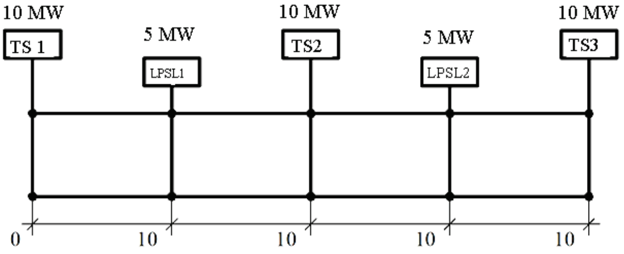

Fig. 7. The proposed structure of the distributed power system

At the existing centralized power supply system, the power of the traction substations is calculated according to the method given in [29]. This technique is also approved in the existing regulatory documents of Ukrzaliznytsia. At the same time, the power calculated in this way significantly exceeds the level of necessary expediency and redundancy. So, in 1985–1989, when a significant amount of traffic was observed on the USSR railways, the installed capacity utilization rate of two converter units of traction substations [30]:

- October road was 11.6 %;
- Moscow – 19.25 %;
- Kuybyshev – 17 %;
- Sverdlovsk – 11.8 %;
- South Ural – 16.3 %;
- West Siberian – 21.9 %.

It can be stated that at the present stage, the utilization rate of the installed capacity is rather low (Table 1) and does not exceed 20 %. The experience of introducing high-speed direct current proves this trend. Thus, the average current of the Soniashnykova substation located between the Klyn and Kriukovo substations in the Moscow-St. Petersburg section is 2021 A, the maximum is 3086 A, one-minute is 2936 A, three-minute is 2515 A, the twenty-minute load is two conversion units is 0.32, and one – 0.64 [30]. Thus, the substations are underused, and even with one operating converter unit, its power is used by 64 %, that is, the power used is 7.68 MW. In this case, the minimum voltage in the contact network on the Klyn-Kriukovo section is 2907 V, the average (one-minute) is 2962 V. Under such loads, the work of the above-mentioned traction substations with one converter unit is justified.

As already noted, at the initial stage of introducing high-speed traffic with speeds of 200–250 km/h, it is necessary to make better use of already existing devices of the 3.0 kV DC system with the lowest capital and operating costs. Based on the above considerations, the calculated used power of traction substations according to Table 3 with the available short circuit, it will be in the range of 2.5...10 MW, and the average power will be – 6.26 MW.

As part of the work currently underway to modernize traction substations in electrified DC sections, outdated rectifiers are replaced with more modern 12-pulse rectifiers manufactured by the «Converter» research and production association of В-ТПЕД-М-12П-3,15к-3,3к У4 type, which capacity is 10.395 MW. When applied according to the requirements of [29], the aggregate power of the traction substation will be 20.79 MW, which is much higher than the required values for high-speed movement.

To date, the development [31] of more advanced rectifiers with a capacity of 5.2 (4.2) MW is known. Their use will provide the necessary power to power the DPN, and fulfill the conditions of redundancy, since in the DPN, reservations are made due to the redistribution of power between substations. To ensure the necessary reserve at the traction substation, it is advisable to use two CU operating in parallel in the forced mode. As LPSL, one CU5200 (4200) can be used.

At the next stage of the synthesis, it is necessary to solve the problem of determining the number of LPSL between the supporting substations (SS). With this criterion of optimization is the need to comply with the applied voltage level and the specific power of the traction network (TN). In [27, 28] it is proved that the distributed traction system of trains with a power supply line of alternating current of industrial frequency has one indisputable advantage: it can be implemented «right now», all the necessary equipment is manufactured by industry. The power of the traction substation (TS) and the LPSL and the distance between them are factors that are interrelated and must ensure the specific power norms and normalized voltage levels. In accordance with the accepted concept of minimizing the cost of the proposed system, the distance between the TS and the LPSL is determined by the existing power supply circuitry of the traction network. For estimated calculations, a symmetrical power supply system is used, which is shown in Fig. 7.

6.4. Power mode evaluation. It is necessary to point out that the regulation of the power consumption regimes in the existing sections of electrified railways for the passage of high-speed trains is carried out by increasing the inter-train interval. In this case, the specific power varies as follows [32] (Table 4).

Table 4

Influence of inter-train interval on power density

Interval, min	8	12	18
Power density, kW/km	480	330	220

When analyzing the data of Table 4 it is necessary to take into account that when the trains move in the section of the specified category, only one train is located at the ISZ. From here, for the given traffic conditions, the location of one LPSL at the section posts (SP) is sufficient. To confirm this hypothesis, let's perform the following calculation.

Using the dependences obtained in [33], it is possible to determine the voltage loss to the ERS current collector, which is located on the calculated ISZ subject to the consumption of constant power:

$$\Delta U = \frac{U_b - \sqrt{U_b^2 - 4f(x)P}}{2d(x)} \cdot f(x), \qquad (1)$$

where U_b – the voltage on the buses of traction substation, V; $f(x)$ – the resistance function of the calculated ISZ; P – the power that ERS consumes, W.

In the above expression, the resistance function determines the ISZ power supply circuit. The definition $f(x)$ for various power supply circuits for ISZ and for an electrified section with any number of traction substations and inter-station zones is given in [17, 33]. Despite the fact that with a distributed power supply system, the ISZ supply circuit will be two-way, further calculations are given for this power supply circuit. Thus, the resistance function for a two-sided circuit is:

$$f(x)=r_0\left(x-\frac{x^2}{L}\right), \qquad (2)$$

where r_0 – the specific resistance of the traction network, Ohm; x – distance from TS to ERS, km; L – ISZ length, km.

Substituting expression (1) into (2), one can determine the distance from the traction substations to which power can be transferred to supply the ERS at a given level of voltage losses in the traction network:

– for the first TS:

$$x_1=-\frac{L\left(\dfrac{\sqrt{Pr_0(4\Delta U^2-4U_b\Delta U+LPr_0)}}{\dfrac{L}{2}}-\dfrac{Pr_0}{2}\right)}{Pr_0};$$

– for the second TS:

$$x_2=\frac{L\left(\dfrac{\sqrt{Pr_0(4\Delta U^2-4U_b\Delta U+LPr_0)}}{\dfrac{L}{2}}+\dfrac{Pr_0}{2}\right)}{Pr_0}.$$

The distance to which it is possible to transmit the consumed power of the ERS at a given level of voltage loss is shown in Fig. 8. The required power of the traction substations (taking into account the power loss) necessary to ensure the regime of sustainable power consumption during the ERS movement with a given level of voltage loss:

$$P(x)=\left(U_b\cdot\frac{U_b-\sqrt{U_b^2-4r_0\left(x-\dfrac{x^2}{L}\right)P}}{2r_0\left(x-\dfrac{x^2}{L}\right)}\right)-$$

$$-\frac{U_b-\sqrt{U_b^2-4r_0\left(x-\dfrac{x^2}{L}\right)P}}{2r_0\left(x-\dfrac{x^2}{L}\right)}\cdot r_0\left(x-\frac{x^2}{L}\right). \qquad (3)$$

In these calculations, the following initial data were used: voltage on TS buses – 3300 V, ISZ length – 20 km, allowable voltage loss – 400 V, traction network – M120+ +2MФ100+A185+P65, ERS power consumption – 10 MW.

In Fig. 9 points indicate the limits of power transmission with permissible voltage losses.

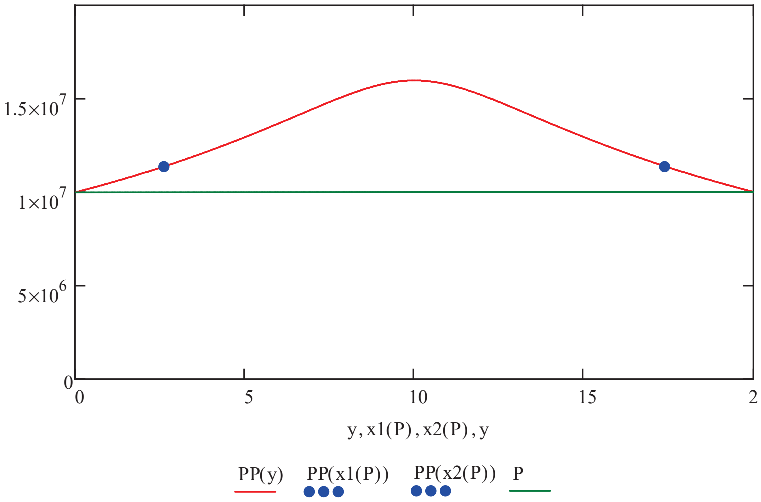

Fig. 9. Power of traction substations to ensure the consumption mode of constant power

As can be seen from Fig. 9, during the passage of ERS on the most part of the ISZ, compliance with the voltage standards on the ERS current collectors is not ensured due to the insufficient level of specific power that the traction substations can provide. Therefore, the introduction of a distributed system with shorter lengths and adjustable CU can solve this problem. The location of the additional CU in the middle of the ISZ allows for an overvoltage on the TS buses with 40 V to ensure the ERS passage of 10 MW at a given level of voltage loss (Fig. 10).

At the same time, the required level of specific power of the ISZ for the ERS passage, depending on the voltage on the TS buses, changes as follows (Fig. 11).

As a result of the performed calculations of the proposed circuitry of the distributed power supply system, it is shown that this system allows passage over a section of electric rolling stock with normalized levels of specific power and voltage loss.

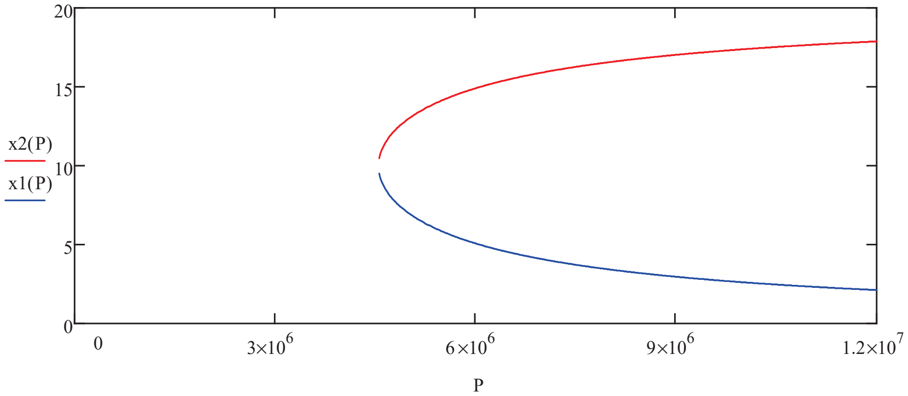

Fig. 8. Permissible power transfer distance

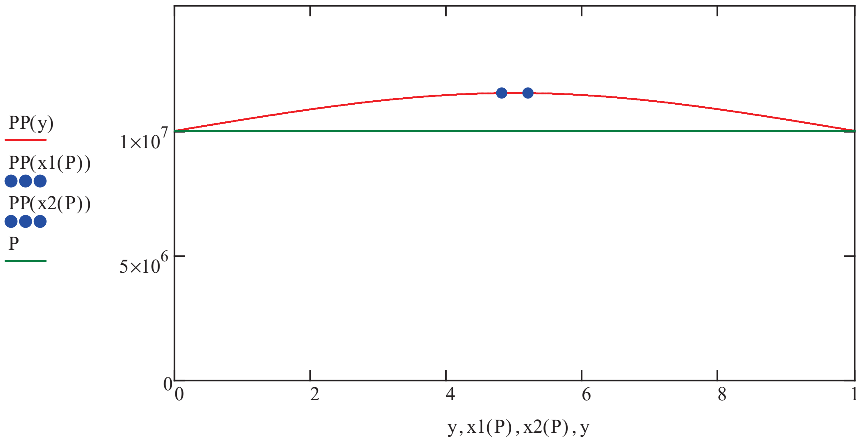

Fig. 10. The total power of the traction substation and the additional converter unit to ensure the consumption mode of constant power with distributed power

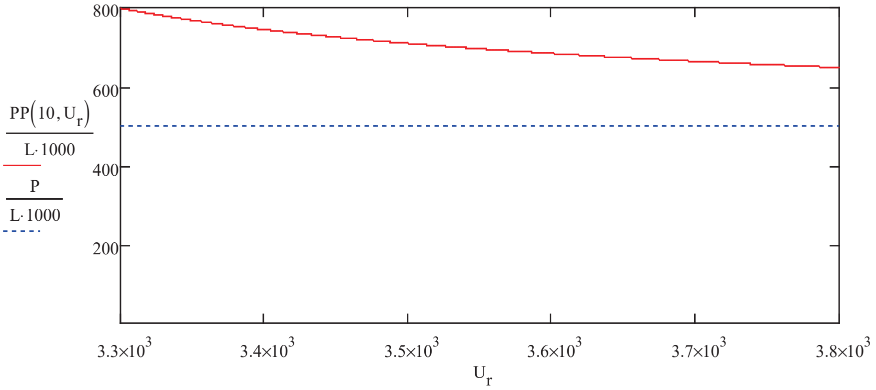

Fig. 11. The change in the level of specific power of the inter-substation zone from the voltage level on the buses

7. SWOT analysis of research results

Strengths. Compared with the traction power supply system with centralized power, the application of the proposed distributed power supply system allows to provide the necessary level of specific power of the traction network in compliance with the normalized voltage level for high-speed traffic conditions. At the same time, the total aggregate power of the traction substations decreases and its utilization rate improves.

Weaknesses. The weaknesses of the proposed technical solution include the need for initial capital investments in the traction power supply system to replace the existing converter units. It is also unwise to envisage the costs of dismantling the old conversion units and the need to install a single-unit traction substation at the location of the partition post. Also to the weaknesses of the proposed solutions include the refurbishment of the power supply line.

Opportunities. The proposed technical solutions to improve the efficiency of the use of aggregate power supplied to the traction substations help reduce energy losses in the traction network. This, in turn, will significantly reduce the amount of payments for consumed electricity for train traction. In this case, all regulatory requirements for the organization of high-speed traffic will be provided.

Threats. The railway will be required to make initial capital investments in the distributed power supply system to replace the existing traction units of lower power at the traction substations. Also required are the costs of their installation at the location in accordance with the circuit innovations in the power supply system. The negative impact on the object of study of external factors is the lack of mass production of the proposed conversion units. Although they are protected by patents of Ukraine for inventions on a device, it confirms their innovation among similar world prototypes, but it may be necessary to purchase conversion units of the proposed capacity abroad.

8. Conclusions

1. Experimental studies of power modes in traction networks is made. It is established that the voltage and power modes in the DC power supply system using centralized power do not allow to fully provide the necessary conditions for the introduction of high-speed traffic on existing lines. Voltage levels, both on the buses of traction load and in the traction network, have a significant range of fluctuations, which is determined by various factors: both the effect of changes in the operating modes of the external power supply system and the modes of operation of the traction network. At the same time, if there is a significant reserve of installed aggregate power at the traction substations of Ukraine, there are no means for regulating the voltage modes in the traction network.

2. The evaluation of energy processes in the traction power supply systems is made. The analysis has shown that for building a distributed power supply system at the present stage, it is most appropriate to use single-unit traction substations with power of their longitudinal power lines by 35 kV. It is made from AC-35 wires.

3. The power modes of the proposed distributed type system are analyzed. Based on the analysis of power modes, it is proposed to make the transition from the centralized power supply system to a distributed system while preserving the existing power infrastructure of the traction network: namely, the location of the traction substations in place of the existing, and single-unit substations at the section posts. In this case, in a distributed power supply system at the traction substation, it is necessary to use two converter units with a total capacity of 10 MW, and for a single-unit substation – 5 MW. As a result of the performed calculations of the proposed circuitry of the distributed power supply system, it is shown that this system allows passage over a section of electric rolling stock with normalized levels of specific power and voltage loss.

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