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Energy Efficient Distributed DC Traction Power Supply System

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Abstract

The classical systems of centralized power supply do not allow to provide the necessary conditions for the introduction of high-speed traffic on existing lines. Voltage values both on the buses of the traction substation and in the traction lines have a significant range of oscillations. Having a significant reserve of installed aggregate power at traction substations in Ukraine, there are no means of voltage modes regulation in the traction lines. Existing foreign and Ukrainian means for increasing of the energy efficiency of DC traction power supply systems require significant capital investments and do not take into account the peculiarities of the organization of high-speed traffic. Therefore, it is necessary to develop energy-saving technology of distributed power supply with the maximum use of existing infrastructure, taking into account the features of the high-speed trains load.

KEY WORDS: *voltage and power modes, traction power supply system, DC, distributed power, power losses.*

1. Introduction

Efficient transport is a fundamental condition for sustainable wealth and prosperity in Europe. Transport drives employment, economic growth and global exports. It provides European citizens, societies and economies with essential resources and means of mobility, while technological advances in transport stimulate and accelerate knowledge acquisition, innovation and European integration. All of this makes transport a corner stone of the European Union's strategy for achieving the greatest knowledge-based economy in the world.

But the increasing demand for mobility is also a major challenge. Rising levels of traffic bring increased safety and health concerns. The environment suffers from transport activities, with CO2 emissions now having a real impact on climate change. Meeting transport challenges will require radical solutions, highlighting the essential role of research. The recent enlargement of the EU has raised the total population of the Union by 27%, while the land surface is some 34% larger. People and goods need access to mobility across Europe to ensure economic development and free movement of resources [1]. The competitive advantages of our transport industries need to be ensured and enhanced. And, of course, transport is an important factor in many international agreements and key policies, including trade, competition, employment, cohesion, security, maritime and internal market policies, as well as the Kyoto Agreement and it successors.

Thus, the railway transport should constantly find effectively the reserves for decreasing the cost of the transportation process to compete with other means of transport. Support of environmentally friendly, energy saving technologies in the sphere of railway transport is the European trend.

Energy consumption for passenger and freight transport has exploded together with transport demand in the last decades – worldwide as well as in Europe – putting heavy pressure on fossil fuel resources as well as increasing the emission of industrial greenhouse gases. Railways are very energy efficient compared to other modes of motorized transport mainly due to lower rolling and air resistance combined with a controlled driving pattern. In order to stay economically competitive and act socially responsible towards the environment, railways must increase their energy efficiency – not the least to enjoy continued strong political support. Three main reasons for the railway sector to act now are [2]:

1. Rising energy costs. The European railway networks are spending billions of Euros annually on energy and the energy costs have increased significantly over the last few years (more than 10% per year). The continued increase in oil prices to a level of 100 $ per barrel underlines the necessity for improved energy efficiency, also because the electricity prices are highly influenced by the prices on coal, crude oil and gas.
2. Energy security & independency. Energy security is getting more important as well. More and more countries want to be independent of foreign energy supplies. Also for the railways, reducing the energy demand will reduce the dependency. In addition, with improved energy efficiency the railways in some cases could be able to accommodate more traffic growth before reaching the technical limits of the railway (electrified or nonelectrified) infrastructure (e.g. maximum power feed etc).
3. Climate protection. Climate change has become a strategic cornerstone for the railways. Railways are fortunate to run 80% on electricity in Europe but it is not possible for all industrial electricity consumers to switch to

renewable energy sources at once. Therefore, improved energy efficiency is vital when the railways want to achieve their individual CO2 targets.

Energy saving on railway transport under the conditions of market economy is one of the priorities of scientific and technical policy. Currently, the traction power systems evolve towards intellectualization and Smart - grid systems.

2. Existing Measures to Increase Energy Efficiency in the DC Traction Power Supply Systems

In the organization of high-speed and heavy-duty traffic on DC lines one of the most important requirements for traction power supply is to provide the necessary level of the specific power of the traction network within the limits of 1,5-2 MW / km, while maintaining the voltage on the current collector of the train not lower than 2,9 kV. However, the fulfillment of the set requirements is impossible without improving the system of electric traction, its modernization and reconstruction.

The improvement of technical and economic indicators on existing sections of electric DC railways can be achieved by carrying out certain technical and organizational measures [3]:

- using of parallel connection points;
- increasing of the section of wires of the contact line;
- construction of additional traction substations;
- application of distributed power supply units;
- complete replacement of six-pulse rectifiers on twelve-pulse ones;
- design of rectifiers with the optimal scale of nominal capacities;
- expansion of the sphere of recuperative braking and operational development of twelve-pulse rectifier-inverter;
- operational development of effective schemes of filters on DC traction substations;
- installation on the feeder zone of the booster devices with voltage regulation;
- using of the transformer with voltage regulation under load.

The basic concepts and principles of strengthening the system of DC traction 3,0 kV are described already in 60 - 80 years of the last century [4]. Modern strengthening of the TPSS 3.0 kV did not undergo significant structural changes, and only the element base changed due to the development of science and technology. In [5] comparative calculations of different systems of traction power supply have been carried out. The offered methods of reinforcement of DC TPSS are based on modern achievements, their advantages and disadvantages are fully explained, results of operational experience are given.

However, the effect of the application of individual measures is different and, as a rule, is insufficient [3, 10, 11]. In order to achieve the required specific power output, a range of measures is required to ensure the high-speed transportation. Therefore, more and more researchers propose distributed power supply systems for electrified railways. Under the distributed power supply scheme of the contact line, one understands the way in which trains in the most loaded zones receive power not only from the nearest but also from a range of remote substations [6]. The participation of such points in the supply of adjacent sections leads to lower power of traction units installed on one substation (Fig. 1).

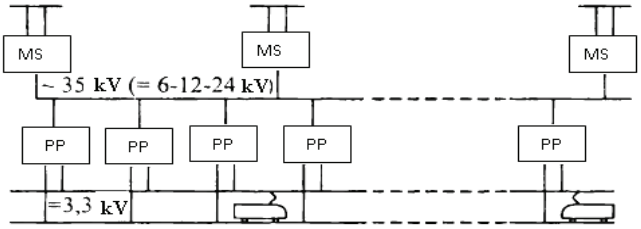

Fig. 1 Block diagram of the distributed power supply system: MS – main substation, PP –power point

3. Comparison of the Efficiency of Centralized and Distributed Traction Power Supply Systems

The calculations were made to evaluate the modes of voltage and power in the case of the eventual introduction of high-speed transportation for DC electrified 50.8 km long section Б –С of Pridnieprovskaya railway. The system receives power from the three traction substations in a nodal scheme. The data for calculation are shown on Fig. 1 and in the Table 1. For comparative analysis, the existing centralized traction power supply system (CTPSS) was transformed into a distributed TPSS (DTPSS) (Fig. 2).

The estimation of the economic efficiency of DC distributed power supply system with power differentiation along the length of the intersubstation zone, which scientific principles are described above, can be accomplished by comparing this system with a centralized traction power supply system, by comparing the difference between capital costs and the difference in operating costs of both options. To do this, it was determined the capital investments and operating costs only in that part, which in different options is not the same. For the above systems, capital costs in the traction substation equipment will differ. The difference in capital costs for traction substation equipment in the analyzed cases occurred because of a different number of traction substations and different installed capacity. Operating costs will be different due to different depreciation charges of the traction substations, due to different factors for contact network will be the same for the two options, so we will not take them into account. Only capital investments in loading of transformers, converters, different losses in the traction line and in the traction substation' equipment, different losses from higher harmonic components. Initial data for the technical and economic calculation was described in [7]. To make the overall assessment of the economic efficiency of the given systems, we will continue to operate averaged data and values.

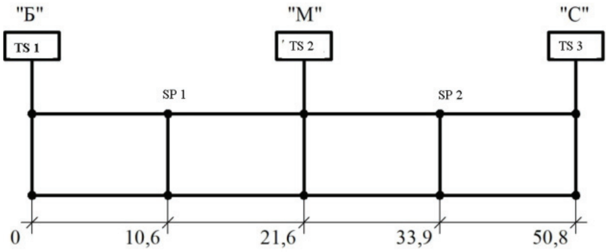

Fig. 2 Scheme of the section of CTPSS

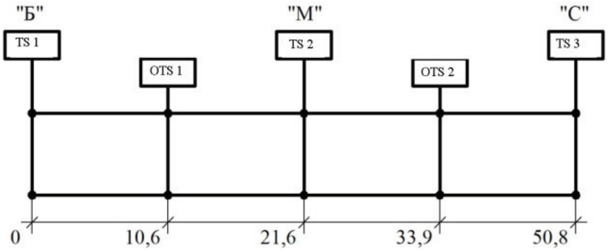

Fig. 3 Scheme of the section of DTPSS with one-unit substations

3.1. Capital Costs

For a given section with a length of L km, capital costs can be calculated as follows:

$$K = K_{TS}\, n_{TS} + K_{OTS} n_{OTS} + K_{CL}\, L\ , \tag{1}$$

where K_{TS} – the cost of the traction substation, K_{OTS} – the cost of one-unit substations (is applied only when calculating capital costs for a distributed power system); n_{TS} – number of traction substations on a line with length L; n_{OTS} – number of one-unit substations per line with length L; K_{CL} – cost per km of contact line.

In the case of a uniform location of traction substations, their number on the section will be equal to:

$$n = \frac{L}{l} + 1\ , \tag{2}$$

where l - the length of one intersubstation zone.

Further in the text we will make the descriptions as follows - index 1 will be for components related to the classical system of centralized electricity supply; index 2 will be for the proposed distributed supply system.

The average cost of traction substations is taken as follows: K_{TS1} = 70.5 million UAH, K_{TS2} = UAH 50.2 million, $K_{.OTS1}$ = 0 million UAH (in the CTPSS there is no OTS), K_{OAP2}= 35.7 million UAH. (obtained by averaging tenders' data for similar equipment in 2018). Capital costs for options are calculated according to the (1) without taking into account the cost of the traction line since in both options these costs are the same. The results of the calculations are shown in Table 1.

3.2. Operational Expenses

Depreciation charges of traction substations

Traction substation depreciation charges are equal to:

$$Z_a = \frac{\alpha_{TS}}{100}\left(K_{TS} n_{TS} + K_{OTS} n_{OTS}\right)\ , \tag{3}$$

where α_{TS} - annual rate of depreciation of traction substations' equipment, %

The annual depreciation rate is calculated in accordance with [8]. Calculations of depreciation charges are given in Table 1.

Table 1

Capital costs and depreciation deductions for traction substations

Indicator	Unit	Value
Capital costs on CTPSS, $K_{.1}$	mln. UAH	211,5
Capital costs for DTPSS, $K_{.2}$	mln. UAH	222,0
The annual rate of depreciation charge of traction substation equipment, α	%	4,4
Average annual amount of depreciation deductions CTPSS, Z_{a1}	mln. UAH	9,31
The average annual amount of depreciation deductions, $Z_{.a2}$	mln. UAH	9,77

The cost of covering electrical power losses in the traction network and in the equipment of traction substations

Power losses in the traction network of the given section were obtained for both options by simulation in the iSET software environment, and the power losses in the substation equipment were calculated in accordance with [9]. When calculating the losses of power energy in the equipment of traction substations one considers only losses in power transformers, traction transformers and traction converters. Other losses were not taken into account due to their small value.

According to [9] were calculated the losses of power energy in transformers ΔW_{PT} and in traction transformers ΔW_{TT}. Power losses in converters can be calculated in accordance with [9] depending on their type in the following way

$$\Delta W_{BA} = 0,0007 \cdot WP_F \,, \tag{4}$$

where ΔW_{BA} - losses in converters; WP_F.- actual consumption of active electric power for traction in the calculated period.

The cost of electric energy losses in the traction substation and traction line is equal to:

$$Z_e = C_e\left(\Delta WP_{PT} + \Delta WP_{TT} + \Delta WP_{BA} + \Delta WP_{TL}\right)T_P \,, \tag{5}$$

where ΔWP_{TL} – losses of active power in the traction line; Tp – the number of operating hours of transformer under load in the accounting period.

The results of calculating the cost of losses of power energy are given in Table 2.

Table 2

Cost of power losses by options

Indicator	Unit of measurement	Value
Tariff for electricity	UAH / kWh	1, 61887
The cost of electricity losses in the CTPSS, Ze_1	mln UAH	8,948
Cost of power losses in DTPSS, Ze_2	mln. UAH	6,070
Cost of reduction of electric power losses, $Z2$-$Z1$	mln. UAH	2,879

3.3. Annual Life-Cycle Costs

The annual life-cycle costs for CTPSS and DTPSS can be calculated as follows:

$$Z = K \cdot E_n + Z_{\mathrm{a}} + Z_{\mathrm{e}} \,, \tag{6}$$

where E_n – the economic efficiency rate.

The results of calculation of annual life-cycle costs are given in Table 3.

Table 3

Results of calculation of the annual life-cycle costs

№	Indicator	Identificator	Indicator' value	
			CTPSS	DTPSS
1	Capital costs, mln. UAH	K	211,5	222
2.	Depreciation charges, UAH	Z_a	9,31	9,77
3	Cost of electric energy losses on given section, mln. UAH .	Z_e	8,948	6,070
4	The annual life-cycle costs, mln. UAH.	Z	44.70	43,59

4. Conclusions

The paper is devoted to the solving of the actual scientific and applied task of increasing the energy efficiency of DC power traction systems by developing scientific principles for the design of the distributed power systems that fit into the existing infrastructure to provide high-speed traffic, which is essential for electric transport.

The feasibility study shows that the proposed energy-efficient power supply system for the DC traction with distributed power supply, which as much as possible fits into the existing infrastructure, allows effective use of the capital investments and has a minimum annual operating costs. Implementation of the distributed power system allows to save annually on the experimental section 2,879 million UAH by reducing the cost of power losses in the power supply system.

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