Application of XLPE Cables in Electric Networks Supplying DC Traction Loads

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Abstract: The connection of railway traction substations (TS) to high-voltage networks of electric power systems relies on overhead power transmission lines. This approach has several downsides: considerable width of the protection zone; potential for damage during strong winds, and the accumulation of ice and frost deposits. Additionally, there is a risk of injury to both people and animals caused by step voltages resulting from wire breakage. The noted negative consequences can be forgotten when using 110 kV cable lines (CL) with cross-linked polyethylene (XLPE) insulation for connecting traction substations. The study presented in this paper aims to develop digital models for determining power flows in direct current traction power supply systems (DC TPSS) with power supply to converter substations via cable line. Multiphase modeling methods are used alongside the Fazonord software product, specifically version 5.3.5.0–2024. The obtained results allow us to draw the following conclusions: the use of cable lines leads to an increase in the minimum three-minute voltages of 2 to 3.5%, while active power losses in the main power transmission line decrease by 8 to 14%. DC traction substations do not create some noticeable levels of unbalance in the adjacent networks. However, any unbalance in a three-phase system has a negative effect on power consumers, especially on widely used induction electric motors. The use of XLPE cables allows reducing unbalance factors by 11-22 times. In the presence of overhead lines (OL), the levels of harmonic distortions on the 110 kV buses of traction substation (TS) 2 and TS 3 exceed the normally permissible values. Replacing the overhead lines with cable lines makes it possible to reduce the indicators by approximately 60%. The factors of certain harmonics are reduced by 37...100%. The developed digital models can be used to design and operate DC TPSS. The method for power flow determination is universal and can be used to make calculations for external power supply systems of any configuration and traction networks of various designs.

1 INTRODUCTION

Overhead power lines are traditionally used to connect railway traction substations (TS) to 110-220 kV networks. This approach has some disadvantages:

- a significant area of the protection zone;
- the potential for damage from strong winds and the accumulation of ice and frost deposits;
- the risk of injury to people and animals caused by step voltages when wires break.

These negative effects can be eliminated by using 110-220 kV cables with cross-linked polyethylene (XLPE) insulation in external systems of power

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supply to TS. Cable lines differ from overhead lines in a small area of the protection zones, protection from the effects of powerful winds and ice, a lower risk of electrical injuries, increased capacity with compensation for inductive loads, and others. In some cases, despite the high cost, CLs may be preferable to overhead lines.

The issues of energy efficiency, quality and reliability of equipment and power transmission lines have been considered in many studies by researchers (Asainov, 2024; Rzazade, 2023, Bulatov, 2020). Modern methods and mathematical models are used in the research (Rogalev, 2022; Klyuev, 2022; Monakov, 2023, Zlatov, 2014, Genbach, 2020, Bulatov 2017).

Many studies examine the problems of determining the power flows of DC TPSS, which underscores their significance. For example, algorithms for modeling the electrical interference of 24 kV DC traction network on adjacent lines are presented in (Marikin, 2019). The method for considering the conductivity of the earth when determining the power flows of DC TPSS is described in (Lesnikov, 2020). The specific features of traction network calculations are explored in (Gavrilin, 2012). The problem of enhancing the energy efficiency of TPSS by using storage devices located at sectioning points is solved in (Cheremisin, 2015). The method for assessing the effect of magnetic interference of 3 and 24 kV DC traction networks on adjacent communication lines is presented in (Mushkov, 2021). The results of fault analysis based on modeling the DC TPSS of the metro under various operating conditions are presented in (Luo, 2022). The characteristics of DC TPSS under short-circuit conditions are investigated in (Xia, 2020). An algorithm for determining the equivalent load of TPSS is implemented in (Lu, 2021). An AC/DC converter applicable in the DC TPSS and intended for high-speed trains is presented in (Sokol, 2019). The results of modeling the dynamic distribution of the earth fault current in the DC TPSS are given in (Yan, 2022). The reliability and service life of the DC TPSS are assessed considering load characteristics in (Chen, 2021). A new DC TPSS is described in (Chen, 2015). The influence of the metro DC TPSS on the harmonics of the power grid is studied in (Aoyang, 2017). A method for improving the efficiency of feeder protection in the DC TPSS is proposed in (Wei, 2019). The structural diagram and control strategy of the enhanced DC TPSS are considered in (Kang, 2022). A comprehensive strategy for improving the quality of electric power for the TPSS is developed in (Song, 2023). Modeling the DC TPSS for high-speed rail transport is explored in (Simiyu, 2021). The results of studying the new TPSS for a comprehensive improvement of the electric power quality are discussed in (Chen, 2015). A probabilistic method for calculating the metro traction load based on the Monte Carlo method is proposed in (Chang, 2020). The hardware emulator of the DC TPSS for determining the rail potential is described in (Wang, 2018). A new hybrid transformer for the metro TPSS is modeled and simulated in (Wang, 2022).

2 METHODOLOGY

The analysis of the publications indicates that they address numerous significant aspects of the DC TPSS modeling. However, the problem of determining the power flows of DC TPSS, which include cable lines with insulation made of cross-linked polyethylene, remains unsolved. TPSSs have a number of features that significantly distinguish them from general-purpose electrical networks. These include (Zakaryukin, 2005): a highly variable and nonlinear traction load; the structural diversity of subsystems resulting from single-phase DC traction networks and three-phase external power supplies in DC TPSS; notable spatial distribution; and mobility of electricity consumers such as electric locomotives. The listed factors complicate modeling the DC TPSS operating conditions characterized by significant harmonic distortions. This problem – significant for both theory and practice – can be solved using the methods, algorithms, and the Fazonord software described in (Zakaryukin, 2005; Zakaryukin, 2023; Suslov, 2023; Kryukov, 2024; Kryukov, 2024).

The constant EMF method used for modeling is described in detail in (Wang, 2018). The calculations of the DC TPSS power flows were carried out using diacoptic methods. In this case, the electromotive forces and their internal resistances were assumed to be constant and were determined by the idle parameters of the converter.

The TPSS power flows were determined using the commercial software Fazonord. The current 5.3.5.0–2024 version of this software implements the DC network modeling technology described in detail in (Zakaryukin, 2023).

3 RESULTS OF MODELING

Below are the calculation results for the power supply system of a DC railway section (Figure 1). The TPSS includes three substations and two inter-substation areas, 20 km long. Modeling is carried out for two options that differ in the design of the external network. The first option considers lines implemented on the basis of XLPE cables, and the second option employs overhead power transmission lines.

The power flows arising during the movement of trains weighing 3 884 tons were calculated. The coordinates of the location of the live parts are shown in Figure 2.

The modeling results are shown in Table 1 and Figures 3-12. Figures 3 and 4, along with Table 1 present data characterizing the voltage levels U on the current collectors of electric locomotives. As seen in the Figures, the use of cable lines leads to an increase in the minimum three-minute voltage of 2 to 3.5%. It is also seen that these parameters are stabilized, for example, the standard deviation U for the first down train decreases by 7%.

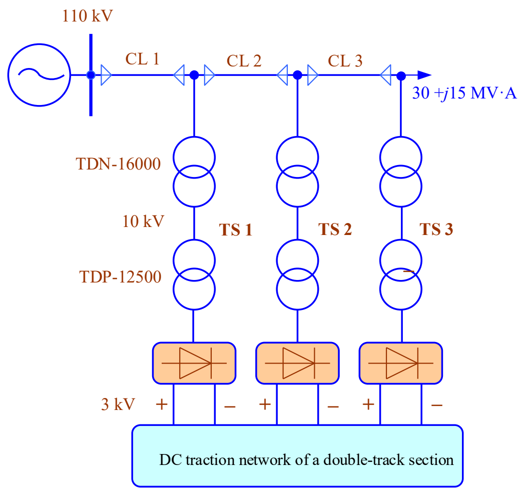
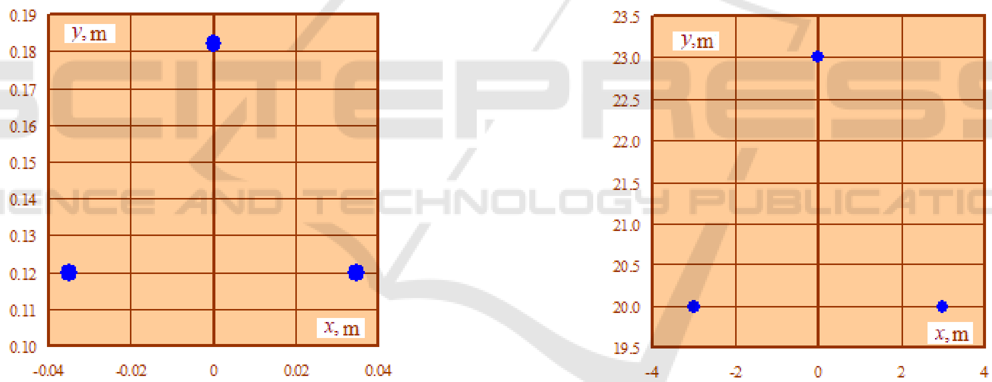


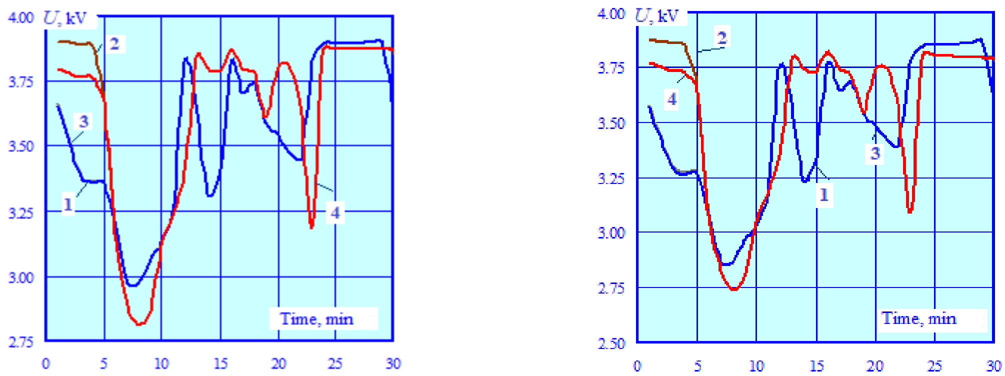
Figure 1: Electrical network diagram.

Figures 5 - 7 show graphs characterizing the energy efficiency of the external network of the TPSS. As seen in the Figures, power losses in the main power transmission line are reduced by 8 to 14% when cable lines are used.



a) b)

Figure 2: Coordinates of live parts: a – cable centers; b – overhead line wires.



a) b)

Figure 3: Voltage on pantographs of electric locomotives.

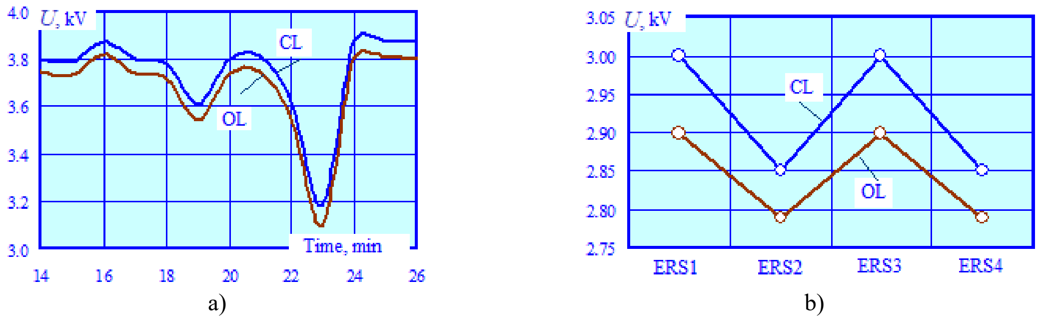


Figure 4: Comparison of cable lines and overhead lines: a – voltage changes for electric locomotive 2; b – minimum three-minute voltages; ERS – electric rolling stock.

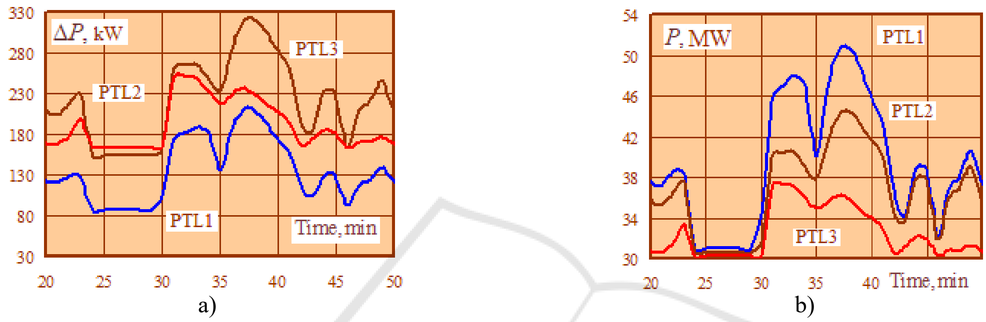


Figure 5: Power losses (a) and flows (b) for the case of cable lines.

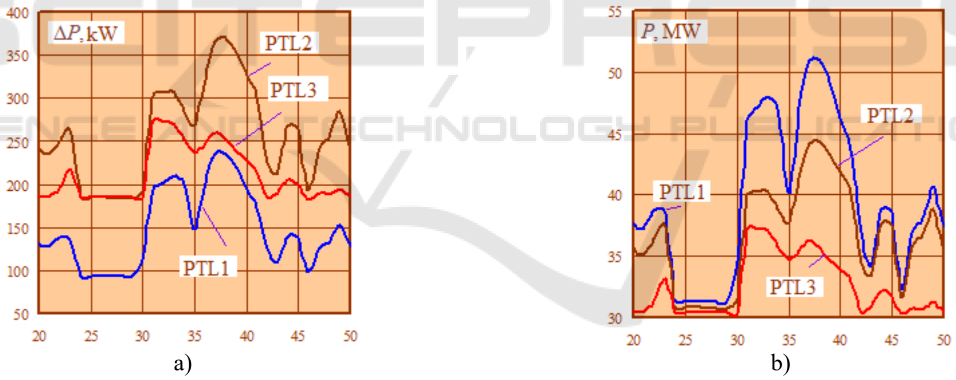


Figure 6: Power losses (a) and flows (b) for the case of overhead power lines.

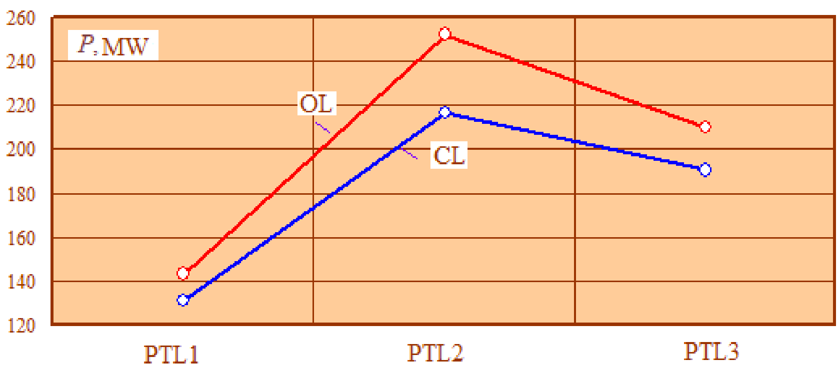


Figure 7: Comparison of power losses in transmission lines.

Table 1: Minimum three-minute voltage at the current collectors.

Power line types	Electric locomotive number			
	1	**2**	**3**	**4**
Cable line	3	2.85	3	2.85
Overhead line	2.9	2.79	2.9	2.79

Direct current traction substations do not create noticeable levels of unbalance in adjacent networks. However, any unbalance of a three-phase system affects negatively power consumers, especially widely used induction motors. The use of XLPE cables decreases the levels of unbalance by 11 to 22 times, as illustrated in Figure 8.

Figures 9-11 demonstrate the determined non-sinusoidal conditions generated by the converter units of the traction substation. They indicate that in the presence of an overhead line, the levels of harmonic distortion on the 110 kV buses of TS 2 and TS 3 exceed the normally permissible values. The replacement of an overhead line with a cable line diminishes the total harmonic factor by 60%. The indicators kU(n) for individual harmonics decrease by 37 to 100%, as shown in Figure 11.

Figure 12 illustrates the results of determining the magnetic field strengths along the railway axis at a height of 1.8 m. As seen in the Figure, the maximum values H_{max} of the amplitudes do not exceed the permissible values for the considered calculation options. For cable lines, however, the maximum value of H_{max} is 28% higher than this indicator for overhead lines.

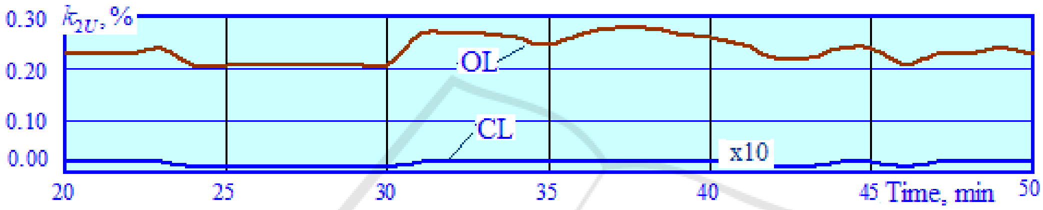
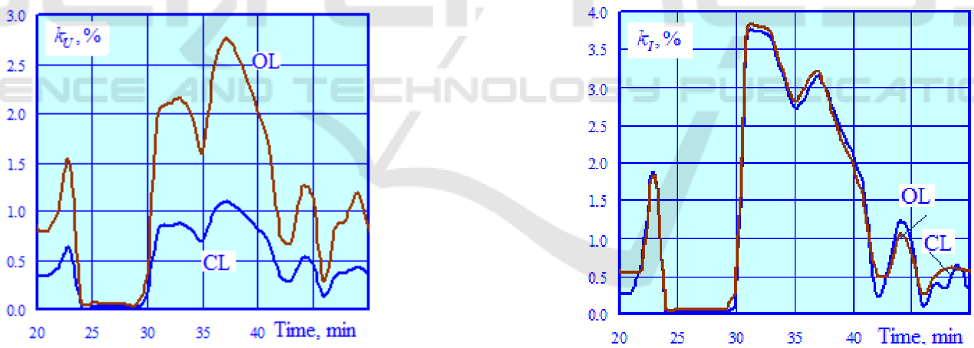
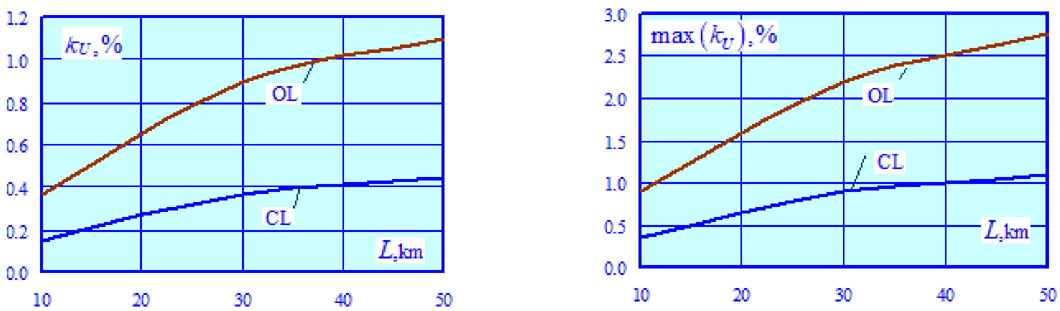


Figure 8: Unbalance on 110 kV buses of TS 3: for illustration purposes, the k2U values for the cable line are increased tenfold.



a) b)

Figure 9: Harmonic distortion factors for voltage (a) and current (b) on 110 kV TS3 buses of (phase A)



a) b)

Figure 10: Harmonic distortion factors for voltage on 110 kV TS buses (phase A): a – average values; b – maxima.

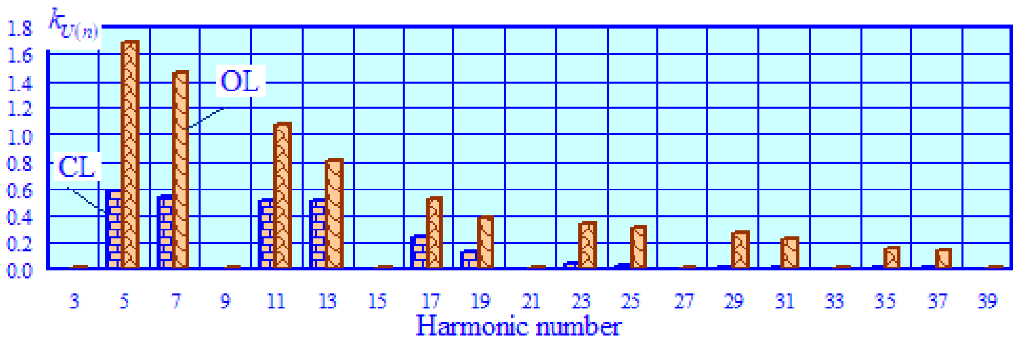


Figure 11: Harmonic spectra of voltage on 110 kV TS3 buses.

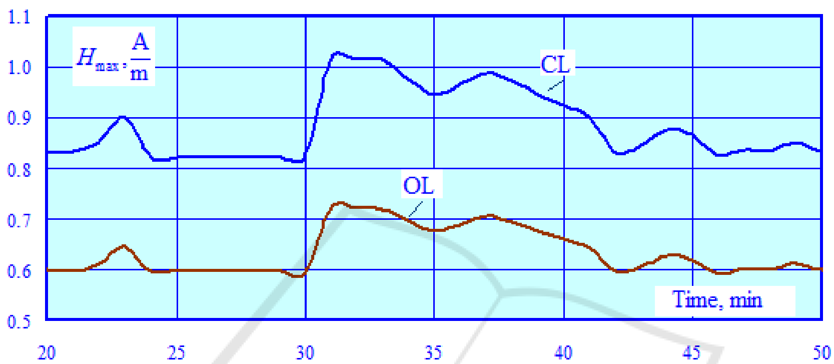


Figure 12: Amplitudes of magnetic field strengths along the power transmission line axis at a height of 1.8 m.

4 CONCLUSIONS

The use of XLPE cables in external power supply systems of DC railways provides the following positive outcomes: it substantially narrows the required protection zone; mitigates damage from severe winds, as well as the buildup of ice and frost; and reduces the risk of injury to people and animals caused by step potentials when wires break. In addition, the modeling results indicate that utilizing XLPE cables increases the minimum three-minute voltages by 2 to 3.5%, decreases active power losses in the main power transmission line by 8 to 14%, and brings down unbalance factors by 11 to 22 times. By replacing the overhead line with XLPE cables, we can achieve a reduction of approximately 60 % in harmonic distortions on the 110 kV buses of the traction substation.

The developed digital models can be used to design and operate DC TPSS. The methodology for determining the power flows is highly adaptable and can be used in calculating the power flows of external power supply systems of any configuration and traction networks of various designs.

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