Modeling of Power Supply Systems Equipped with Double Two Wires and Earth Transmission Lines

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Abstract: Power supply systems (PSS) of the agro-industrial complex, as well objects located in the areas remote from the networks of electric power systems, sometimes use electric transmission lines (ETLs) that exploit the ground as a conducting part. When currents flow in the ground, it causes electrical safety issues. To solve them, double two wires and earth (TWE) lines can be used. Such lines use special transformers, in which the voltage vectors of the grounded terminals have an angular shift of 180º. Due to this, there are no currents in the ground a symmetrical mode. In the context of digitalization of the electric power industry, creating computer models of such PSSes that adequately simulate stationary modes is of particular relevance. This paper presents the results of studies aimed at the implementation of computer models of power supply systems that incorporate double TWE lines. Constructive diagrams of ETLs with double TWE lines are proposed. Simulation was carried out by means of the Fazonord software package. The simulation results drew us to the following conclusions: in comparison with a double-circuit ETL, a double TWE line can significantly reduce the cost of non-ferrous metal; the asymmetrical design of this ETL causes a decrease in the quality indicators of electricity at its receiving end; in addition, higher power losses are observed; the double TWE line can be implemented on the basis of two or four single-phase shielded cables.

1 INTRODUCTION

In agricultural areas, distribution electrical networks are of considerable. In order to save non-ferrous metal, their implementation sometimes implies construction power lines that use ground as a conducting part. Such solutions can also be used to provide electrical energy to objects located in areas remote from the networks of electric power systems.

A number of works are devoted to solving the problems of researching power supply systems equipped with single-wire power lines with earth as a return wire (Single Wire Earth Return) (SWER).

The article (Helwig and Ahfock, 2013) discusses the issues of increasing the capacity of these lines. A solution to a similar problem for rural SWER networks is presented in (Wolfs, 2005) and (Wolfs et al., 2007). The paper (Kavi et al., 2016) describes methods for detecting faults in single-wire distribution networks. The paper (Brooking et al., 1992) is devoted to the problems of upgrading SWER networks. Models for selecting wires in networks with SWER lines are proposed in (Bakkabulindi et al., 2013). The results of studies of the influence of distributed generation on the modes of electrical networks with SWER lines are given in (Kashem and Ledwich, 2004) and (Ledwich, 2004).

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An article (Nkom et al., 2019) discusses the challenges of using SWER lines in rural Africa. The article (Nkom et. al., 2018) provides a solution to the problem of narrow-band modeling of single-wire power lines. When currents flow in the ground, electrical safety becomes an issue. To solve them, dual lines "two wires - ground" (TWE) can be built, which were first considered in the papers (Andreev, 1952) and (Filshtinsky, 1952). The development of this idea is given in (Buryanina et al., 2005). These lines use special transformers in which the voltage vectors of the grounded terminals have an angular shift of 180º. Due to this, there are no currents in the ground in a symmetrical mode.

In the context of the electric power industry digitalization (Vorotnitsky, 2019), the problems of creating digital models of PSS with double TWE lines to ensure adequate simulation of stationary modes acquire a special relevance. Such models can be formed on the basis of developments (Zakaryukin and Kryukov, 2005) implemented in the Fazonord software product. These developments are based on the ideas of building models of elements of electric power systems (EPS) based on phase coordinates; at the same time, the main power elements of the EPS, which include electric transmission line and transformers, are considered as multi-wire or multi-winding objects and are presented in the form of lattice equivalent circuits with a fully connected topology. Based on this approach, methods and computer technologies have been implemented, the distinctive features of which are as follows:

- *multi-phase,* which consists in the possibility of modeling multi-phase systems (single-phase, three-phase, four-phase, six-phase and their various combinations in one network);
- *multi-mode,* which allows modeling a wide range of EPS modes: normal and emergency, asymmetric, non-sinusoidal, limiting in terms of static aperiodic stability;
- *multitasking,* providing the possibility of solving additional problems relevant for practice: determination of induced voltages on adjacent transmission lines; calculation of the intensity of electromagnetic fields created by traction networks; parametric identification of transmission lines and transformers according to measurement data; accounting of active elements of the EPS; modeling of thermal processes during ice melting.

2 DOUBLE TWE LINE

To justify the use of double TWE lines and to determine their effectiveness, it is necessary to develop adequate computer models. Since the double TWE lines are characterized by an asymmetric structure, it appears reasonable to build their models on the basis of phase coordinates. Below are the results of simulating the modes and electromagnetic fields (Buyakova et al., 2018) of a double TWE line with a voltage of 35 kV with respect to the ground, Fig. 1.

The coordinates of the wires of this line with a length of 5 km with 95 mm^2 aluminium conductor steel reinforced cables are shown in Fig. 2. To assess energy efficiency, power quality and electromagnetic safety conditions, the corresponding indicators were compared with the results of simulating the modes and electromagnetic fields (EMF) of a three-phase power trans-mission line with 95 mm^2 aluminium conductor steel reinforced cables, non-standard voltage of 35 kV with respect to the ground and a line voltage of 60 kV.

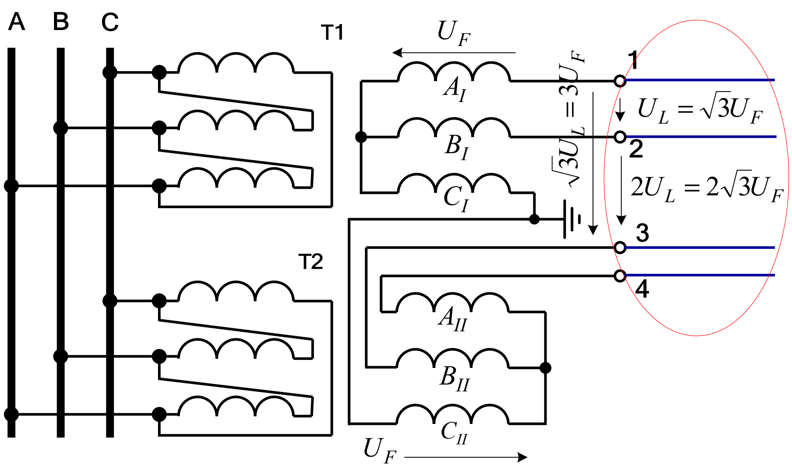


Figure 1: Schematic diagram of the overhead TWE lines.

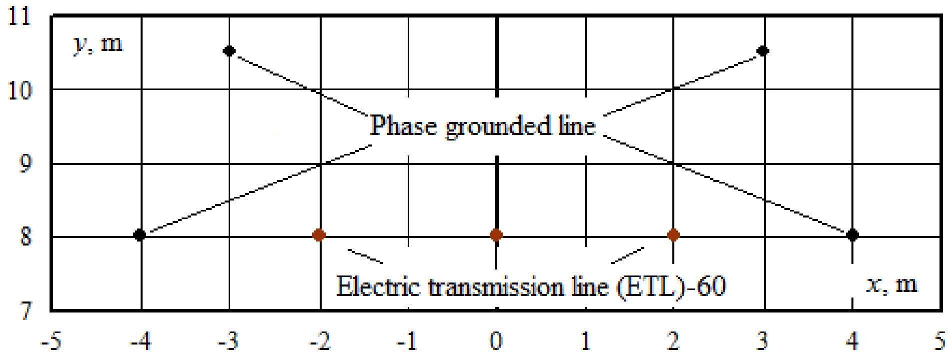


Figure 2: Wires location coordinates.

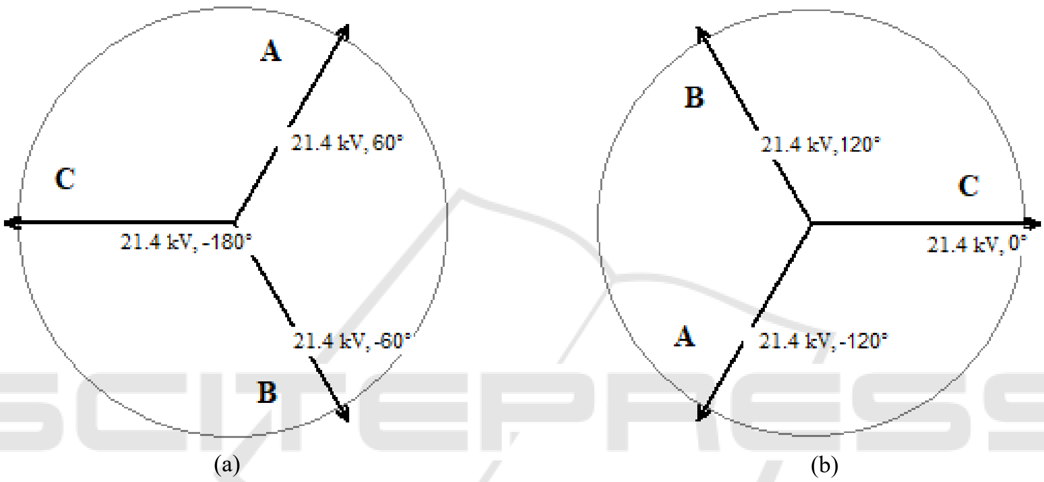


Figure 3: Vector voltage diagrams of the phases of the secondary winding of transformers: (a) – T1, the fifth group of connections; (b) – T2, the eleventh group of connections.

The lack of current in the ground can be illustrated using vector diagrams of voltages on the secondary windings of transformers (Fig. 3). These diagrams were obtained as a result of determining the mode of the double TWE line without the grounding of phase C. The mode calculation was carried out with loads of $4 + j3$ MV·A per phase at the receiving end. Figure 3 shows that for the groups of transformers 5 and 11, the voltage vectors of the grounded terminals are in antiphase. This ensures that there are no ground currents in symmetrical modes.

The results of determining the PSS modes by the double TWE line show that on the 10 kV side of the consumer substation, connected at its receiving end and at the loads indicated above, the voltage asymmetry factor in the return sequence is 0.8%, and the total current flowing into the ground is 0.16 A. Dependences of losses and asymmetry in the electric transmission line (ETL)-60 and a double TWE line on the transmitted active power are shown in Figs. 4 and 5. They were obtained with a power factor of 0.89. The analysis of these dependences implies that the double TWE line is characterized by higher losses in comparison with the ETL-60 (Fig. 4). At the receiving end of this ETL, a significantly greater asymmetry is observed. Figures 6 and 7 show the dependences of the EMF strengths of the double TWE line on the x coordinate, which is measured from the center of the line.

Figure 8 shows three-dimensional diagrams of the strengths of the electric (a) and magnetic (b) fields created by the double TWE line.

The simulation results draw us to the following conclusions:

1. In comparison with the ETL of traditional design, the TWE line has higher losses and voltage asymmetry at the receiving end;
2. The strengths of the electric field directly under the wires of the TWE ETL is 33% higher than the same indicator for the 60 kV ETL;
3. The maximum amplitude of the magnetic field of the TWE ETL is twice as high as that one of the 60 kV ETL.

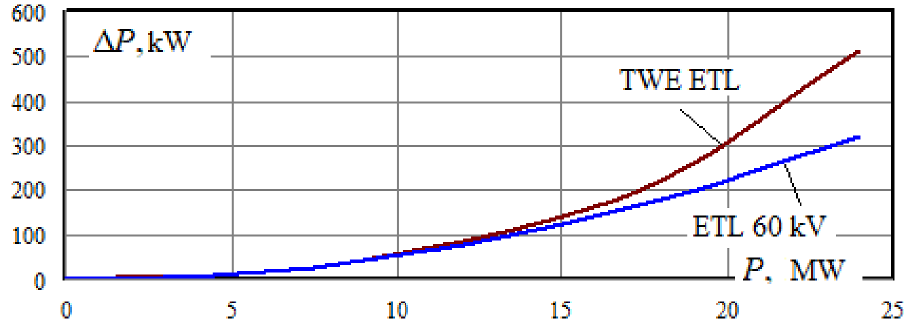


Figure 4: Dependences of active losses in the line on the transmitted power.

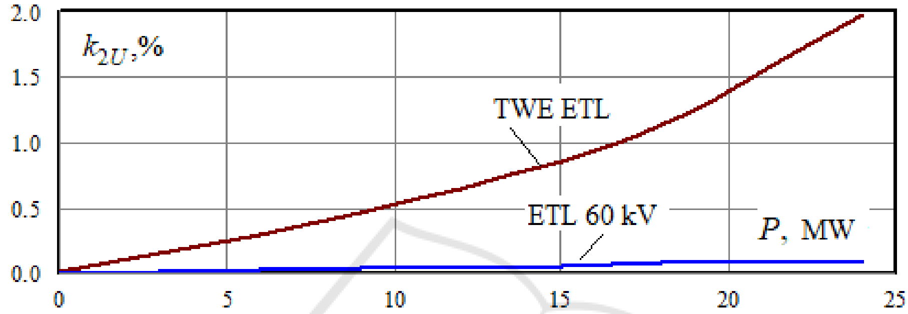


Figure 5: Dependencies of the asymmetry coefficient on the transmitted power.

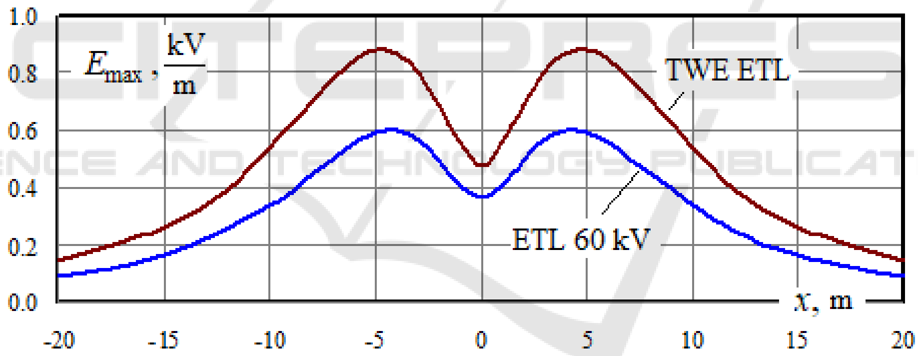


Figure 6: Dependences of the amplitudes of the electric field strengths at the height of 1.8 m on the x coordinate.

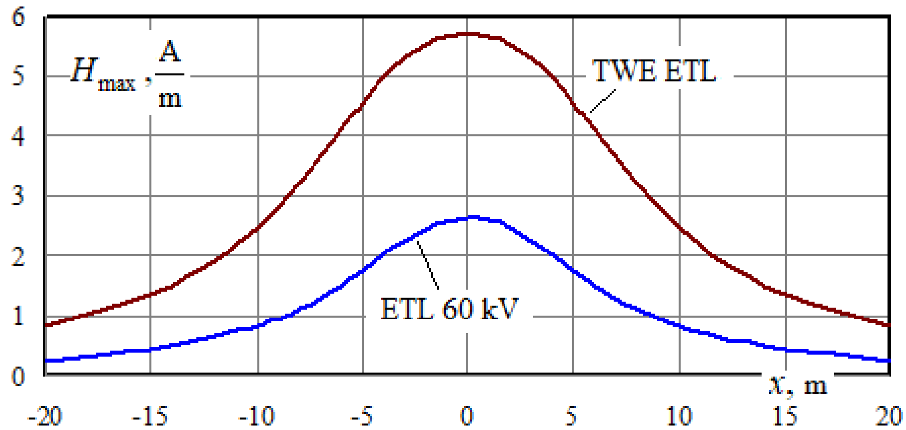
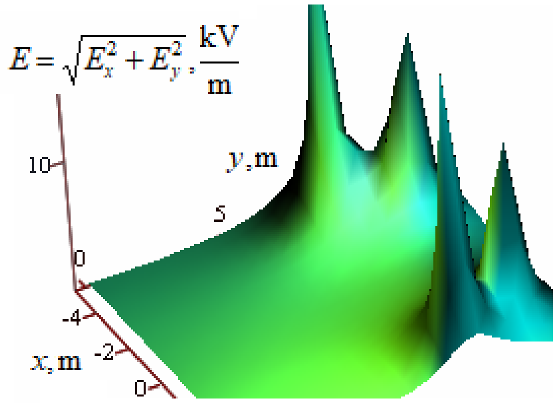
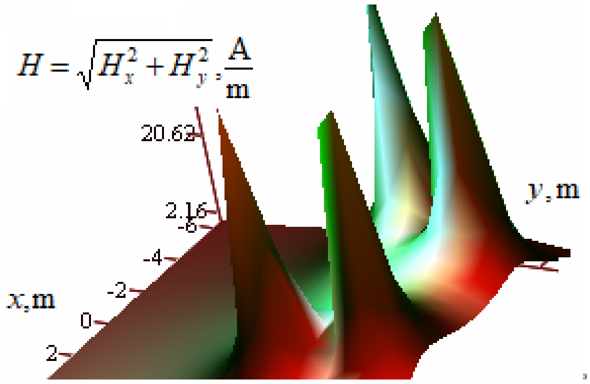


Figure 7: Dependences of the amplitudes of the magnetic field strengths at the height of 1.8 m on the x coordinate.





(a) (b)

Figure 8: Volumetric diagrams of electric (a) and magnetic (b) field strengths of the double TWE line.

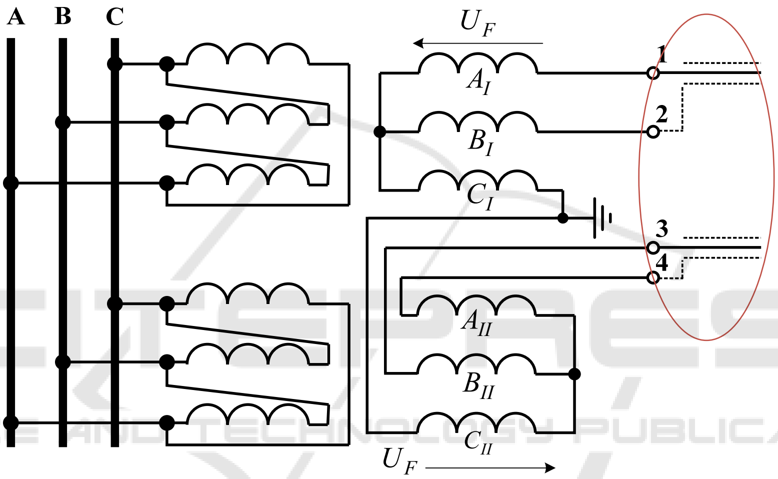


Figure 9: Schematic diagram of the two-cable TWE line connection.

3 THE TWE LINE BUILD WITH TWO SPECIAL DESIGN CABLES

In some cases, when forming a PSS, the use of overhead electric transmission lines is limited. Such situations are typical for some settlements, sites of industrial enterprises, as well as for areas with high wind loads. In addition, the use of cable TWE lines can be expedient for the transmission of electricity by submarine cables to facilities located on the islands of rivers, lakes, and seas.

Implementation of a double TWE cable line may use the proposed in (Buyakova et al., 2019) constructive scheme based on two single-core shielded cables with molecular cross-linked polyethylene insulation.

In contrast to the widely used designs, cable shields for this ETL should ensure that the flow of currents are proportionate to the currents of the conductors. In addition, they must have the same insulation class as the conductors. Such cable lines can be placed in galleries, overpasses and on other structures of a similar type. The cable line diagram (Fig. 9) corresponds to Fig. 1; operating currents of the cable line flow through the shields. The location coordinates of the conducting parts of a double cable line are given in Fig 10. The electrical parameters of the conductors and shields are the same as in the above-discussed overhead TWE ETL.

The diagram showing the currents distribution through the wires of overhead and cable lines is given in Fig. 11. We can observe some differences in the currents of conductors and shields of the cable TWE ETL which is associated with its asymmetric design.

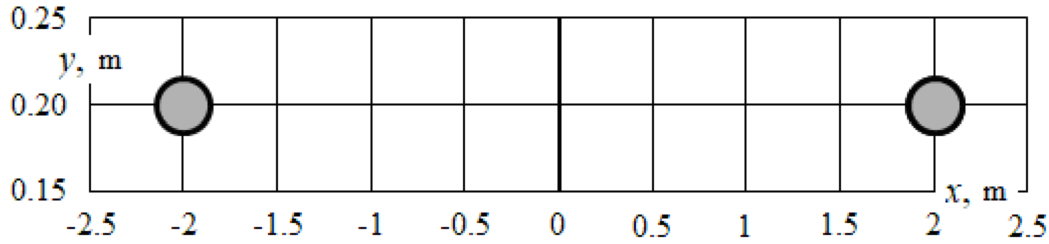


Figure 10: Coordinates of conducting parts.

Vector diagrams characterizing currents and voltages at the receiving and outgoing ends of the cable TWE line are shown in Figs. 12 and 13. The input voltages and currents of cable lines are far from a symmetrical four-phase system, but the voltages and load currents on busbars of the 10 kV transformers are symmetrical with a return sequence voltage asymmetry coefficient equal to 0.5%.

Figures 14-16 show comparative graphs characterizing energy efficiency, power quality indicators for asymmetry and electromagnetic safety of the considered cable line design in comparison with a four-wire overhead line.

Compared with the overhead line, the cable TWE line is characterized by a significantly lower level of asymmetry (Fig. 15). However, higher magnetic field strengths are created near the cables. With the same cross-section of the conducting parts, the active power losses for overhead lines and cable TWE lines differ insignificantly (Fig. 14).

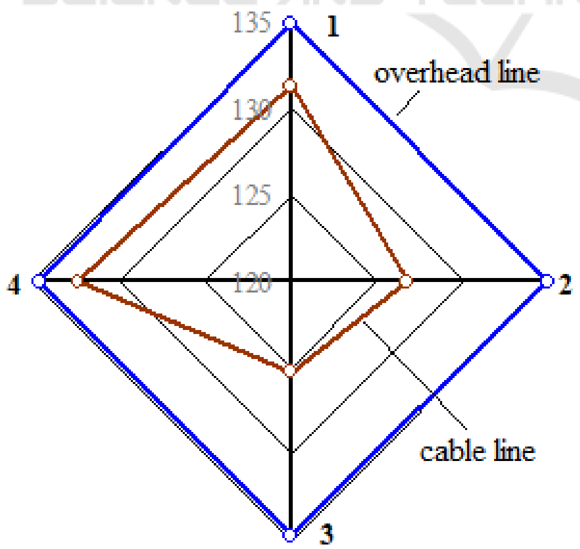


Figure 11: Currents in the wires of the overhead line and cables at the starting ends of the ETL.

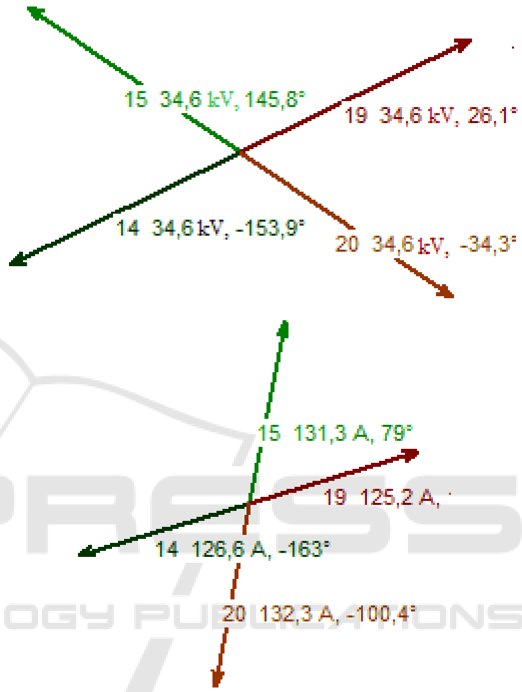


Figure 12: Vector diagrams of at the outgoing end of the cable TWE line.

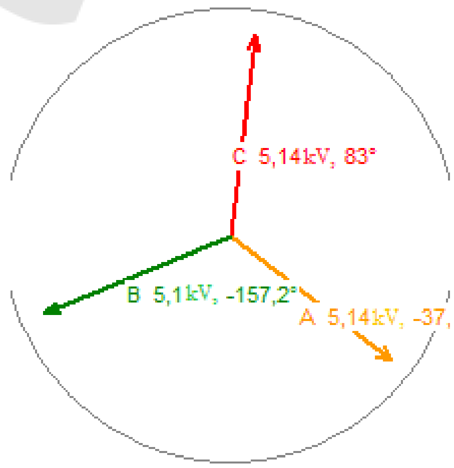


Figure 13: Vector diagrams of voltages on 10 kV busbars.

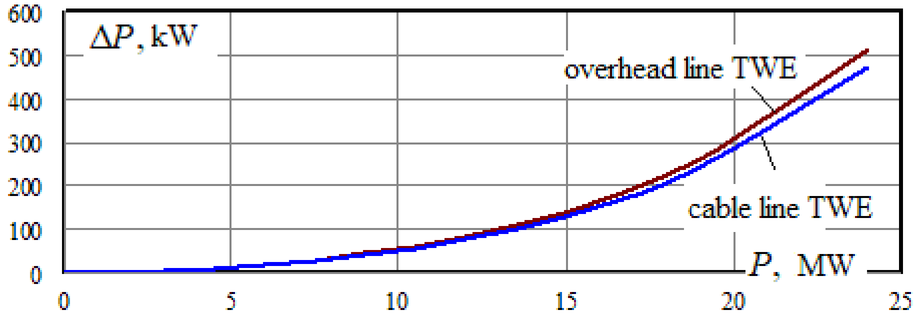


Figure 14: Dependences of losses on the transmitted active power.

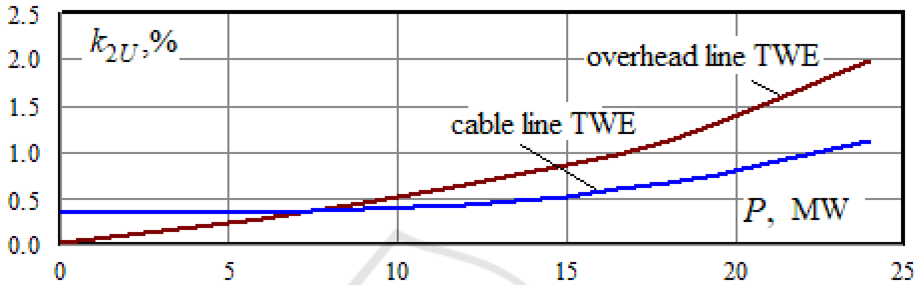


Figure 15: Dependences of the return sequence asymmetry coefficient on transmitted power.

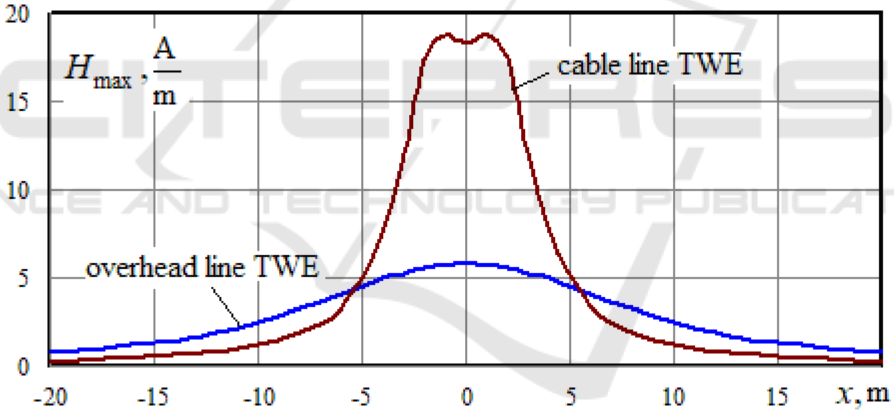


Figure 16: Dependences of the amplitudes of the magnetic field strengths at the height of 1.8 m on the *x* coordinate.

4 THE TWE STRUCTURE BASED ON FOUR CABLES OF A STANDARD STRUCTURE

It is possible to consider a scheme of the TWE line which implementation requires four typical molecular cross-linked polyethylene cables, Fig. 17. Its cross-section is shown in Fig. 18.

In simulation, it was assumed that the cable shields are grounded on one side. At shield currents of 8.2 A, the total current did not flow through the ground electrode. Dependences of losses on the transmitted active power at are shown in Fig. 19 for the following types of TWE lines: overhead, two-cable, and four-cable lines. For all types of TWE lines, the losses are almost the same (Fig. 19). Asymmetry at high transmitted powers prevails in the double overhead TWE line. However, at low powers, asymmetry is greater in the four-cable line, although the asymmetry coefficient does not exceed 0.5%. The dependences of the amplitudes of the magnetic field strengths on the *x* coordinate are shown in Fig. 21.

Analysis of the simulation results allows us to conclude that the four-cable TWE line, when compared to the two-cable one, is characterized by a higher level of asymmetry and creates a magnetic field of the same order.

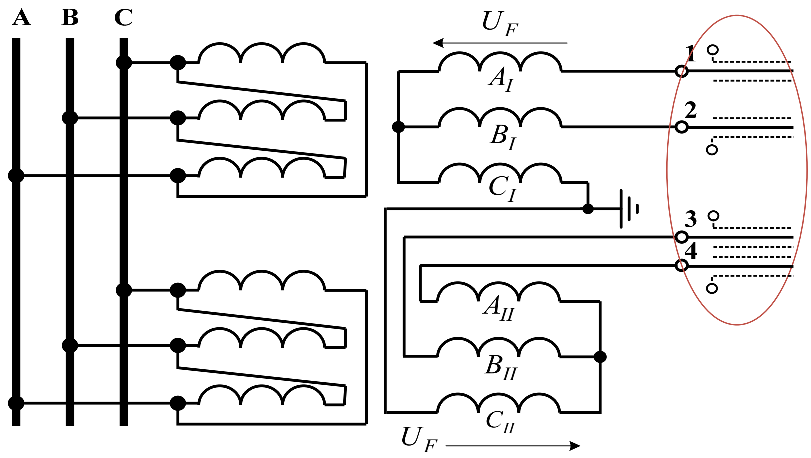


Figure 17: Schematic diagram of the four-cable TWE line connection.

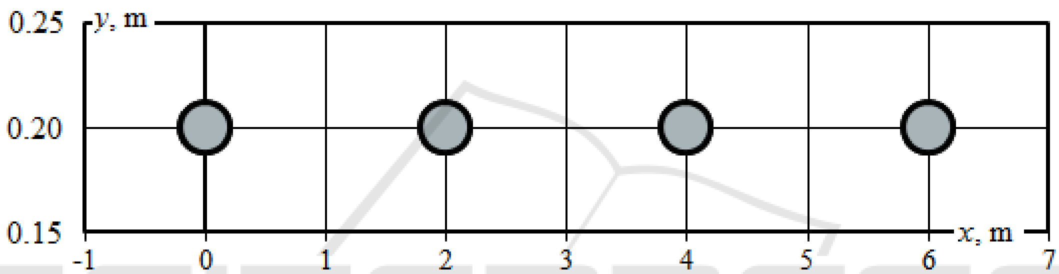


Figure 18: Coordinates of cable locations.

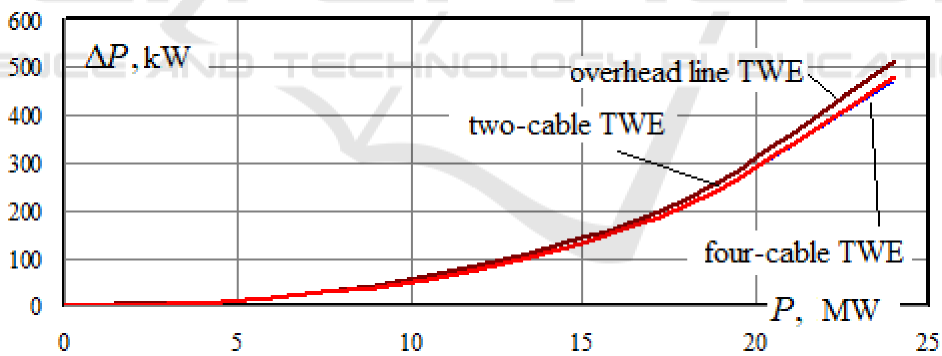


Figure 19: Dependences of losses on transmitted power.

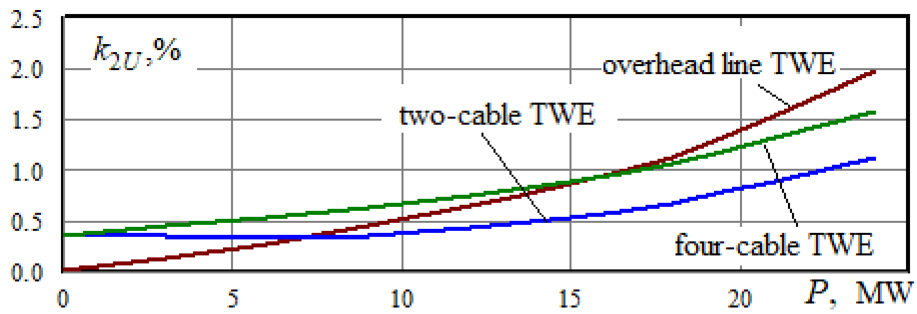


Figure 20: Dependences of the asymmetry coefficient on transmitted power.

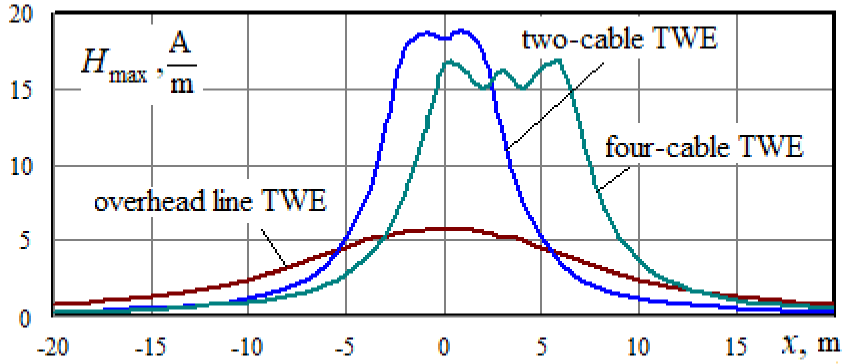


Figure 21: Dependence of the amplitude of the magnetic field strength on the *x* coordinate.

5 CONCLUSIONS

We proposed a technique that helps adequately model and simulate double electric two wires and earth lines. We considered the original designs of TWE cable lines that can be implemented when the use of overhead ETLs is limited. Such situations are typical for some settlements, sites of industrial enterprises, as well as for areas with high wind loads. In addition, the use of cable TWE lines may be appropriate for the transmission of electricity by submarine cables to facilities located on the islands of rivers, lakes, and seas.

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