Distributed automated control and protection system for power lines with any degree of longitudinal compensation

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Abstract. With longitudinal compensation of the reactance of the line, the problem of its protection against overcurrents arises from the point of view of relay protection. The problem is relevant with a greater degree of compensation. When compensating more than 50% of the reactance of the line, the protection of the power transmission line becomes practically impossible due to the failure or false operation of all existing types and forms of protection [1, 2]. Therefore, at present, the compensation of the line reactance is, as a rule, no more than 50% [3, 4], which does not allow the full potential of the line in terms of its transmission capacity to be revealed. The purpose of this study was to develop and test a new relay protection algorithm to be able to solve the above problem. The studies were carried out using modeling techniques in the PS CAD package, where a power transmission line with longitudinal compensation and an algorithm to protect it from internal damage were built. When carrying out the research, the work was carried out on the protection algorithm of the power transmission line with longitudinal compensation in the static mode without transferring electricity between substations and without the transmission mode along the active power line in both directions. It is shown that in order to determine the location of the damage, it is possible to use the criterion of the angle of the active component of the short-circuit current, which depends exclusively on the voltage angle and does not depend on the reactive parameters of the electrical network. The simulation result showed correct operation in all investigated modes. The algorithm described in the article showed quite satisfactory results, which makes it possible to protect the power transmission line with any degree of longitudinal compensation.

1 Theoretical information on the transmission capacity of power lines

In the power generating industry, there are several ways to increase the capacity of electric power transmission lines. One of the ways is to install a line of capacitors in sequence to compensate the reactive resistance of electrical power transmission lines [5, 6]. This technical solution, in addition to advantages, also has disadvantages: with a compensation coefficient of more than 50% of the line reactance, such phenomena are observed as: current inversion during a short circuit, voltage inversion during a short circuit, low-frequency oscillations after a short circuit clearance, etc. [7, 8]. These (and other) events lead to the impossibility of protecting the electrical power transmission line, since they lead to false operation or non-operation of relay protection in case of damage on the protected line [9, 10]. In particular, current inversion at a short circuit on the line leads to the fact that the currents are not directed to the place of the short circuit (see Figure 1), but as though in transit past it (see Figure 2), as a result, the differential and phase-differential protection perceives this damage as external and does not work [11, 12]. For this reason, at present, the degree of compensation for the reactance of the power transmission line does not exceed 50% [13].

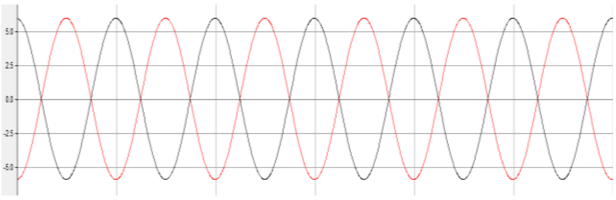

Fig. 1. Oscillogram of currents at a three-phase short circuit in the middle of a line with two-way power supply without longitudinal compensation (currents from different ends of the line are shown in different colours).

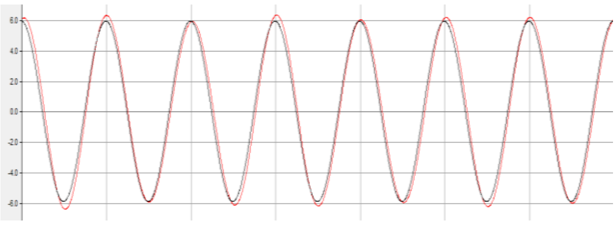

Fig. 2. Oscillogram of currents at a three-phase short circuit in the middle of a line with two-way power supply with longitudinal compensation (currents from different ends of the line are shown in different colours).

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The purpose of this research is to improve the algorithms of differential relay protection aimed at ensuring the efficiency of functioning under the conditions of the introduction of a longitudinal compensation device into the protected object (electric power transmission line). The objective of the research is to develop a model of an electric power system containing an electrical power transmission line with a longitudinal compensation device; study of transient and steady-state processes in case of damage in the line and outside; development of an algorithm for differential relay protection, which allows to protect the electrical power transmission line with any degree of longitudinal compensation.

2 Methods

In the PSCAD software environment, a model of the electrical network was assembled, the equivalent network of which is shown in Figure 3. It consists of: two substations - substation 1, substation 2; two electric power systems: system 1, system 2; four identical segments of electrical power transmission line, longitudinal compensation devices *C*. Each system is represented by an ideal three-phase voltage source with a series-connected active resistance (0,01 Ohm). Segments of the electrical power transmission line represent a U-shaped equivalent circuit with mutual capacity couplings between the wires (see Figure 4 and Table 1). The length of each section is 50 km. An ideal capacitor was used as a longitudinal compensation device. Substation 1 and substation 2 in this model are a kind of interface separating the electrical power transmission line from the system. In this model, the substations do not contain switching equipment because it is not used in the research. An ideal ammeter and voltmeter are located at the substations in order to measure currents and voltages for the needs of relay protection. Since only symmetrical short circuits were simulated in the model, measurements are made only for one phase. The short-circuit resistance between the phase and the ground at points *K1-K4* had a purely active character and was taken equal to 0,01 Ohm.

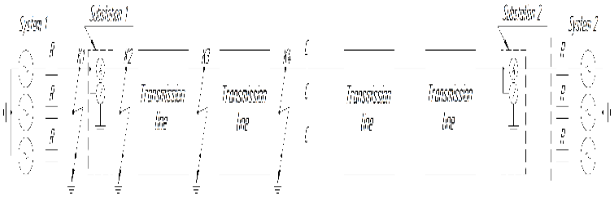

Fig. 3. Equivalent circuit of a longitudinal compensated line connecting two electric energy systems.

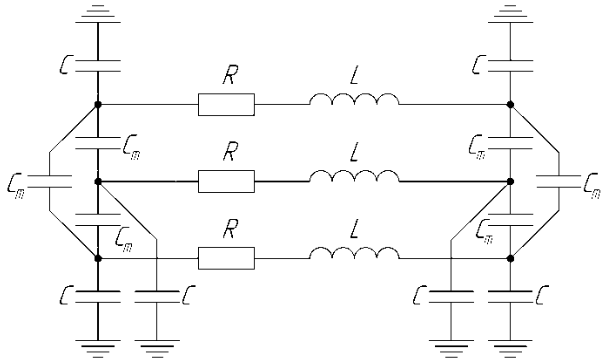

Fig. 4. Equivalent circuit of a electrical power transmission line.

Table 1. List of elements used in the equivalent circuit and their technical characteristics.

Designation in the scheme	Name	Technical data
R	Active resistance of a wire	Positive sequence: $0,1781598\times10^{-4}$ Ohm/m. Zero sequence: $0,2952201\times10^{-3}$ Ohm/m.
L	Inductive resistance of a wire	Positive sequence: $0,31388\times10^{-3}$ Ohm/m. Zero sequence: $0,1039898\times10^{-2}$ Ohm/m.
C	Capacitive resistance between the wire and the ground	414,1642 MOhm/m
C_m	Capacitive resistance between the wires	273,5448 MOhm/m

In order to solve the problem described in the introduction, an algorithm was developed to protect the power transmission line at any degree of longitudinal compensation (fig. 5).

It is known that during a short circuit both components of the current (active and reactive) are directed to the point of the short circuit [14, 15]. The angle of the reactive component (plus 90° or minus 90°) depends on which resistance prevails - inductive or capacitive [16, 17]. The angle of the active component of the current does not depend on this and is always equal to the voltage angle [18, 19] - this is a property of the law of electrophysics and it is proposed to use it to determine the damage inside the line. To implement this algorithm, continuous data collection is carried out on the instantaneous voltage values on the substation buses and the values of the total currents from both ends of the line. Further, according to the known formulas [20], the absolute value of the active current from each end of the line and its sign are calculated (the direction of the current from left to right is taken as the positive direction of currents in this algorithm).

It is assumed that digital terminals of relay protection installed at each end of the line will be used to implement the algorithms. The connection between the terminals will be carried out via fiber-optic

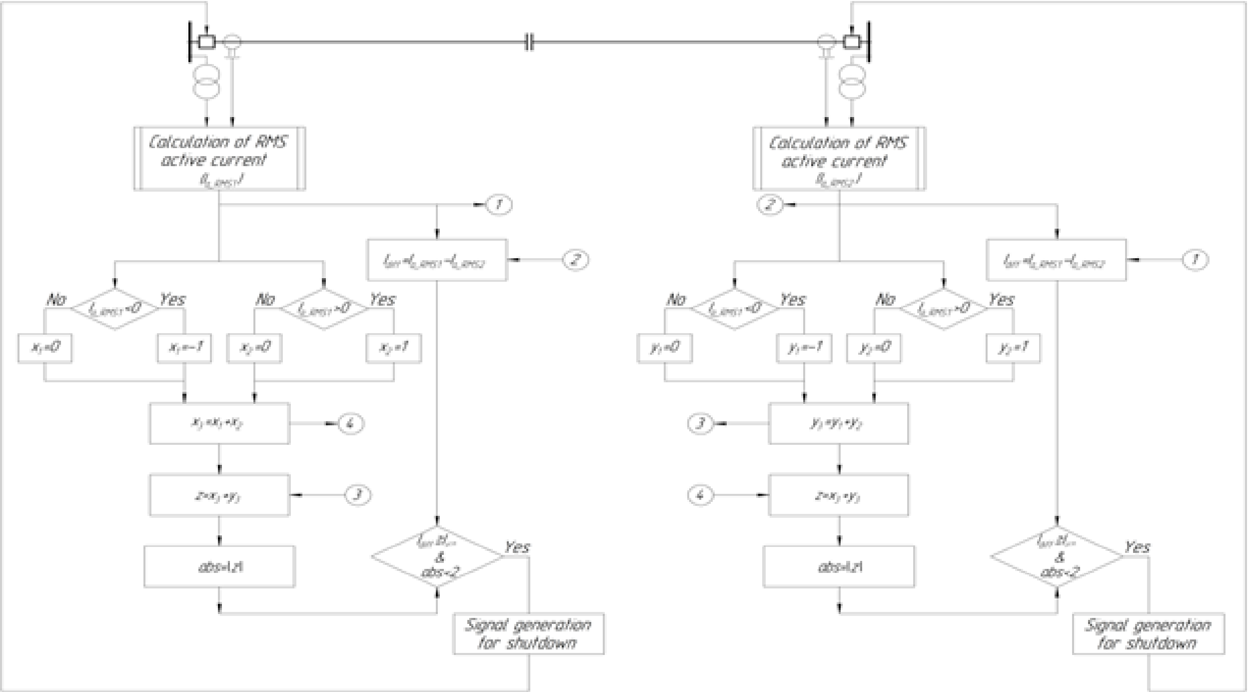

Fig. 5. Algorithm of protection of the power transmission line in case of internal damage.

communication. For clarity, in the figure, these connections are indicated not by solid lines, but in the form of connector blocks ①, ②, ③, ④.

After calculating the rms active current, the algorithm branches with two parallel branches. In one of them, the differential value of the currents at the ends of the line is calculated. In another branch, an algorithm is organized, aimed at determining the difference in the signs of the compared currents for subsequent blocking, if the signs are the same. To determine the sign, two branching blocks are used, where the root-mean-square value of the current is compared with zero and two variable flags x1 and x2 (y1 and y2 for the algorithm at the other end of the line) which are assigned a positive or negative value depending on what sign the current has.

Next, the sum of the flags at both ends of the line is calculated (*z*-value). Then the absolute value of this sum is determined (*abs* value). Then the values of the differential current and the absolute sum of the flags are fed to the inputs of the comparator, where the differential current is compared with the setting and the trip signal is blocked if the currents at the ends of the line have the same signs. This blocking is necessary to prevent false operation of protection during transient processes in electric power systems, for example, when an external short circuit is disconnected (fig. 6).

3 Checking the operation of the circuit according to the proposed algorithm

In order to check the operation of the algorithm, three-phase short circuits to the ground were emitted at points *K1* - *K4* (see Figure 3). The tests were carried out in 2 stages. At the first stage, tests were carried out in a static mode without power transmission between substations (no load operation of the line). At the second stage, tests were carried out with active power transmission in both directions.

At the first stage, in order to balance the power sources, their voltages were the same - 515 kV. A short circuit at point *K1* lasted for a time interval of 0.5 s - 1 s (fig. 6). As you can see, during all this time, no false operation of the algorithm was registered. Also, I would like to draw attention to the transient process at the moment of the disappearance of the short circuit, which causes uneven damping of the active current at different ends of the line, which causes differential current surge, which can affect the false operation of the protection at this moment. In this case, the proposed algorithm provides a block system (fig. 5).

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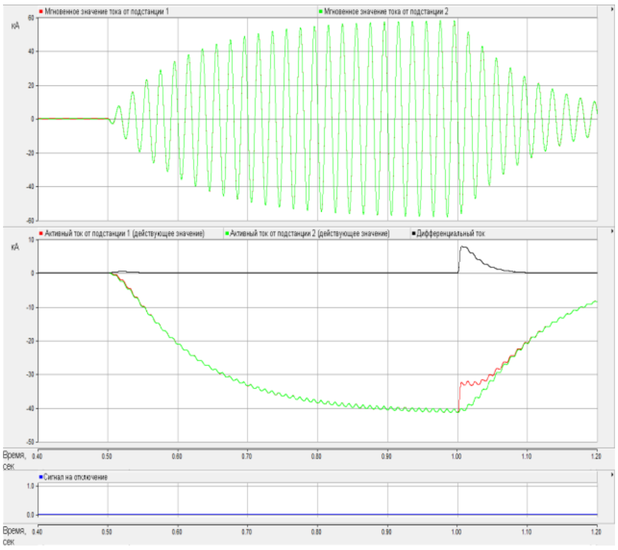

Fig. 6. Oscillograms of instantaneous and effective values of currents during a short circuit at point *K1* and the behavior of the relay protection algorithm.

A short circuit at point *K2* lasted for a time interval of 1.5 s - 2 s (fig. 7). When closing at this point, the short-circuit current is mainly determined by the current from substation 1, since despite 100% compensation of reactive resistance of the line, uncompensated (active) resistance is large enough to limit the current several times. For this reason, the differential current is mainly determined by the current from substation 1. A noticeable smooth-exponential increase and decrease in the effective value of the active current is associated with time averaging when calculating the root-mean-square value. Despite this, the protection is actuated almost instantly - in 0,446 ms after the start of the short circuit.

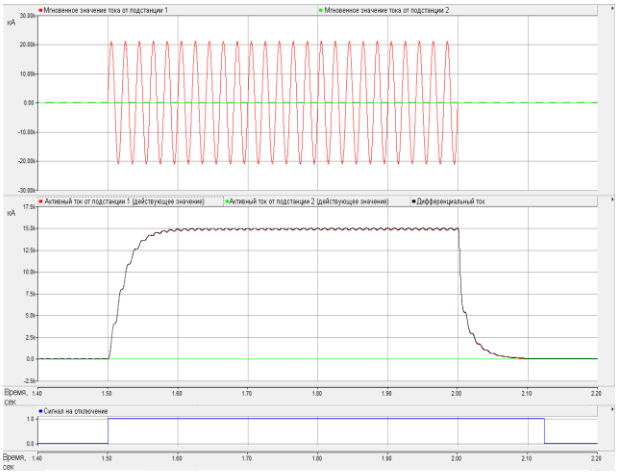

Fig. 7. Oscillograms of instantaneous and effective values of currents during a short circuit at point *K2* and the behavior of the relay protection algorithm.

A short circuit at point *K3* lasted for a time interval of 2,5 s - 3 s (see Figure 8). As you can see from the oscillograms of instantaneous currents, in the steady state of short circuit mode, the currents are directed, somewhat, in one direction. In this case, the effective values of the active currents are opposite in direction. The protection is actuated in 3,48 ms after the start of the short circuit. In this case, the shutdown signal resembles a "fence" due to the fact that blocking is actuated by the graphic of the active current (see the algorithm in Figure 5).

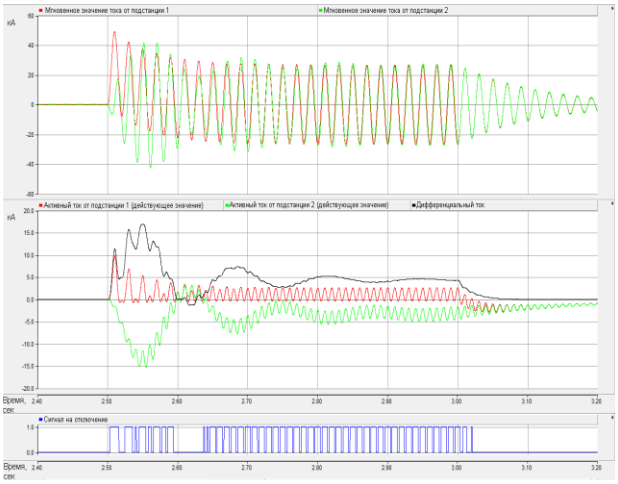

Fig. 8. Oscillograms of instantaneous and effective values of currents during a short circuit at point *K3* and the behavior of the relay protection algorithm.

A short circuit at point *K4* lasted for a time interval of 3,5 s - 4 s (see Figure 9). The protection is actuated in 3,9 ms after the start of the short circuit. The activation of the algorithm generates pulse bursts during the burning of the short circuit. This is, firstly, due to the work of blocking by the graphic of the active current and, secondly, due to the boundary value of the differential current fluctuating around the 1000 A setting.

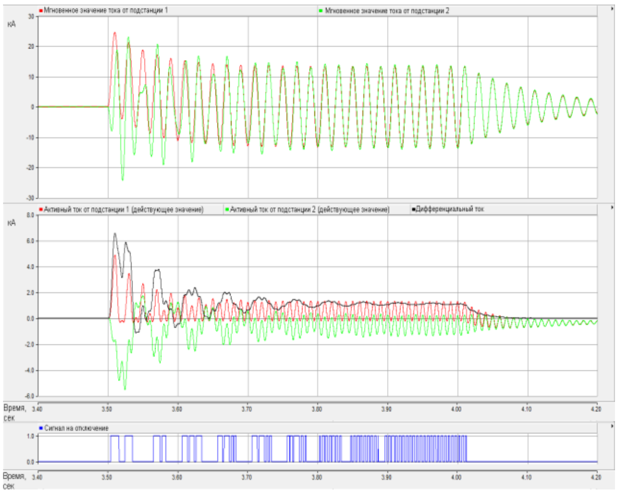

Fig. 9. Oscillograms of instantaneous and effective values of currents during a short circuit at point *K4* and the behavior of the relay protection algorithm.

At the second stage, research was carried out on the behavior of the relay protection algorithm during the transmission of electrical energy along the line in both directions at a nominal current of the line in the amount of 2835 A (see Figures 10 - 17).

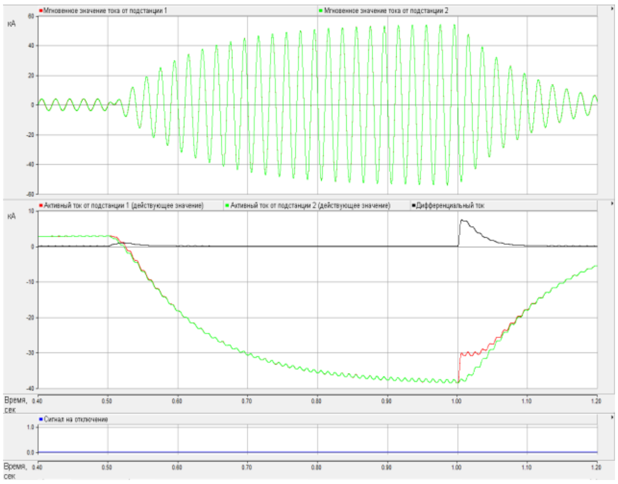

Fig. 10. Oscillograms of instantaneous and effective values of currents during a short circuit at point *K1* and the behavior of the relay protection algorithm in that event (power transmission from substation 1).

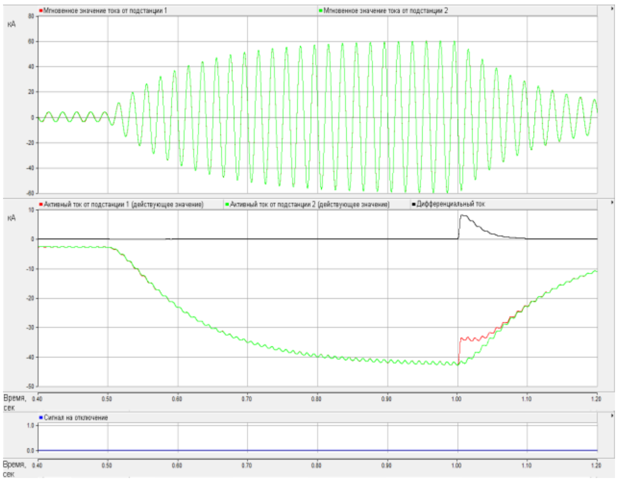

Fig. 11. Oscillograms of instantaneous and effective values of currents during a short circuit at point K1 and the behavior of the relay protection algorithm (transmission of electricity from substation 2).

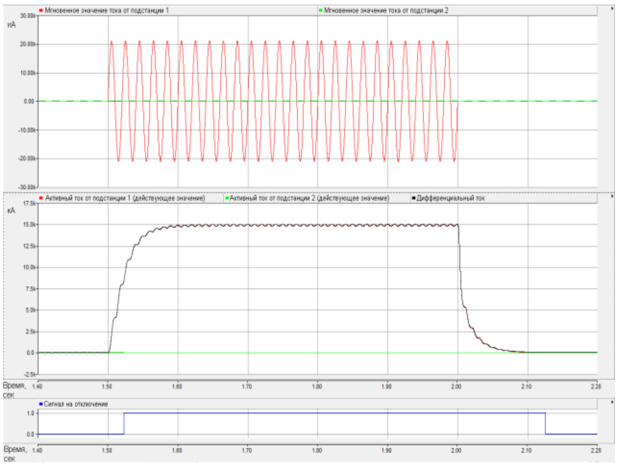

Fig. 12. Oscillograms of instantaneous and effective values of currents during a short circuit at point *K2* and the behavior of the relay protection algorithm in that event (power transmission from substation 1).

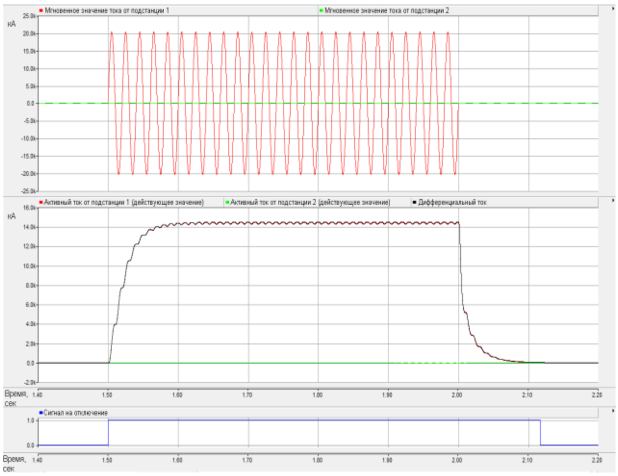

Fig. 13. Oscillograms of instantaneous and effective values of currents during a short circuit at point *K2* and the behavior of the relay protection algorithm in that event (power transmission from substation 2).

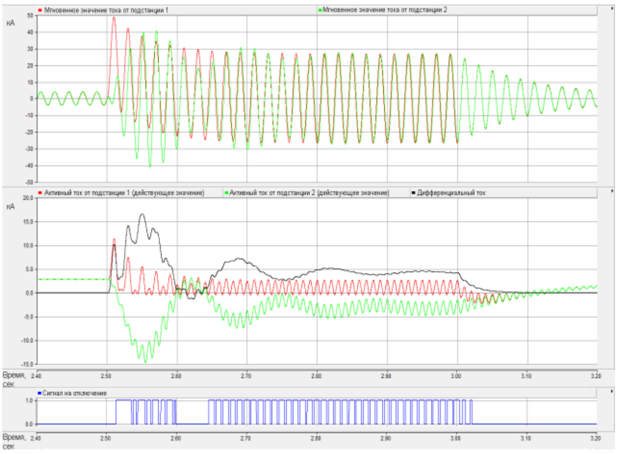

Fig. 14. Oscillograms of instantaneous and effective values of currents during a short circuit at point *K3* and the behavior of the relay protection algorithm in that event (power transmission from substation 1).

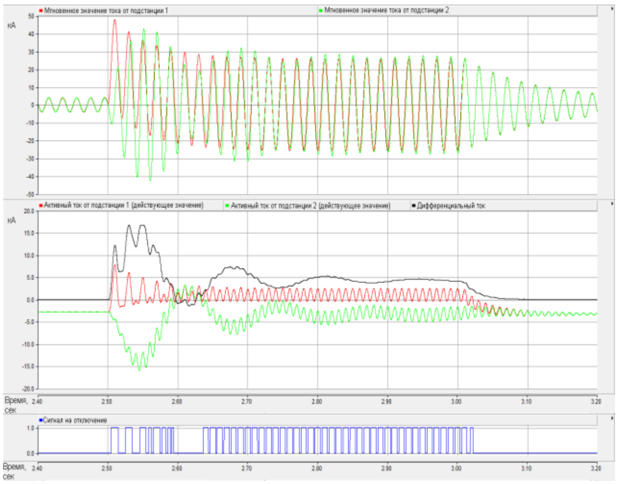

Fig. 15. Oscillograms of instantaneous and effective values of currents during a short circuit at point *K3* and the behavior of the relay protection algorithm in that event (power transmission from substation 2).

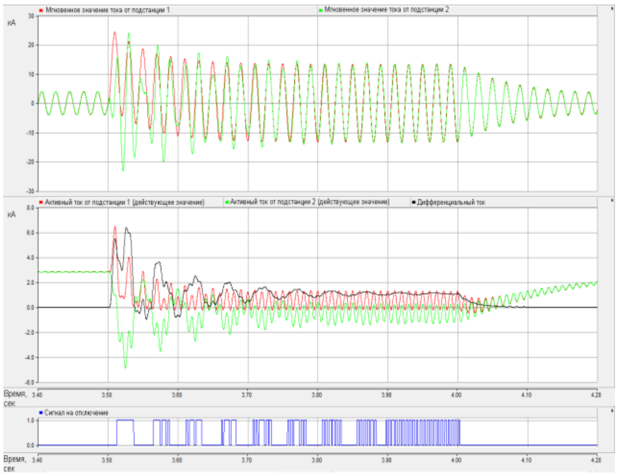

Fig. 16. Oscillograms of instantaneous and effective values of currents during a short circuit at point *K4* and the behavior of the relay protection algorithm in that event (power transmission from substation 1).

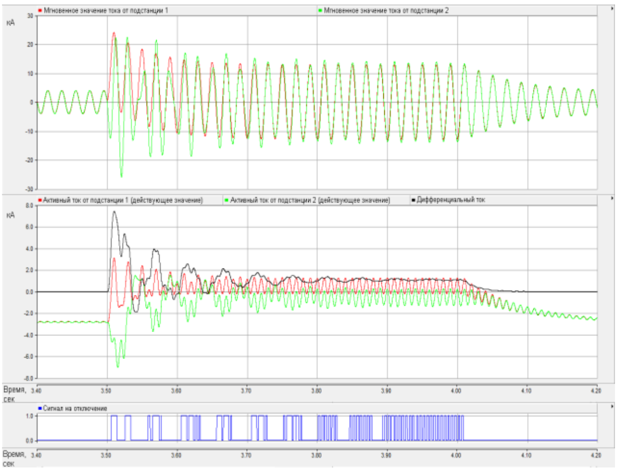

Fig. 17. Oscillograms of instantaneous and effective values of currents during a short circuit at point *K4* and the behavior of the relay protection algorithm in that event (power transmission from substation 2).

From the given diagrams (Figures 10 - 17), it can be seen that when the load current appears, the protection behavior does not change significantly except for the cases when the direction of the current flowing through the capacitor changes due to a short circuit (see Figures 12, 14, 16). In this case, the appearance of an additional pickup time delay is due to the inertia of the transient process in the inductance-capacitance circuit and the actuation of blocking by the graphic of the active current.

4 Conclusions

The conducted research fully confirmed the theoretical idea of the author in regard to the possibility of using the properties of Electrophysics in determining the location of a short circuit through the active component of the current. In this research, only symmetrical short circuits and, basically, steady state operation modes of the line without external disturbances were considered. Therefore, a more in-depth approbation is required in all possible modes, for example, during active power swing, generator rotors swing, etc. Nevertheless, for the studies carried out, the algorithm proposed by the author showed satisfactory results, but as some test modes have shown, for these modes the algorithm needs to be improved (modes presented in Figures 12, 14 and 16, when there is an active power flow and due to a short circuit, there is a change in the direction of the active current flowing through the capacitor). If this algorithm is refined and passes all stages of testing (two-phase short circuits in the zone and outside the zone of protection, two-phase short circuits to the ground in the zone and outside the zone of protection, operation of devices shunting capacitors during a short circuit, etc.), then it will be possible to use it on real power transmission lines with longitudinal compensation.

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References

1. N.V. Chernobrovov, *Relay protection* (Moscow: Publishing house “Energiya”, 680, 1974)
2. A.M. Fedoseev, *Relay protection of electrical systems* (Moscow: Publishing house “Energiya”, 560, 1976)
3. I.A. Moskvin, *Stability of an electric power system with adjustable longitudinal compensation: author. dis. for the degree of Cand. those. sciences* (Ivanovo, 20, 2014)
4. S.L. Kuzhekov, Construction of algorithms for programmable relay protection of electric motors, Bulletin of higher educational institutions, Electromechanics, **1-2**, 28-31 (1997)
5. A.A. Martirosyan, M.V. Zotova, D.N. Kormilitsyn, The choice of the installation site and the laws of regulation of longitudinal capacitive compensation devices for increasing the stability of the electric power system, **4**, 30-36 (2017)
6. A.N. Andreev, A.N. Sadovnikov, Algorithms of centralized complexes of relay protection and automation, Bulletin of the South Ural State University, Series: Energy, **11**, 25-28 (2008)
7. E.N. Kolobrodov, G.S. Nudelman, Increasing the efficiency of ultra-high voltage overhead line protection systems with controlled longitudinal compensation, IV international scientific and technical conference “Modern trends in the development of relay protection systems and automation of power systems”, Yekaterinburg, 1-8 (2013)
8. H.M. Joshi, N.H. Kothari, A review on Series Compensation of Transmission Lines and Its Impact on Performance of Transmission Lines,

International journal of engineering development and research, 72-76 (2014)

9. V.R. Ivanova, I.Y. Ivanov, V.V. Novokreshchenov, Structural and parametric synthesis of anti-average control algorithms for realizing adaptive frequency operating automaticselectrotechnical systems, Power engineering: research, equipment, technology, **21 (4)**, 66-76 (2019) (in Russian) DOI: 10.30724/1998-9903-2019-21-4-66-76
10. I.N. Lizunov, R.Sh. Misbakhov, V.V. Fedotov, V.M. Dragney, I.Z. Bagautdinov, Centralized system of relay protection and automation with adaptive intelligent algorithms of relay protection, Electrical equipment: operation and repair, **9**, 24-27 (2016)
11. D.V. Moiseev, N.A. Galanina, N.N. Ivanova, Development of algorithms for analyzing the operation of relay protection and automation functions using data on the location of damage, Bulletin of the Chuvash University, **1**, 97-112 (2020)
12. F. Chen, G. Qian, F. Wang, Study on Traveling-wave Differential Protection for Series Compensated Line, Journal of International Council on Electrical Engineering, **1 (3)**, 359-366 (2011)
13. V.R. Ivanova, I.Yu. Ivanov, Development of criteria for assessing the decisions made in the design, creation and operation of active-adaptive electric power systems, Materials of the international scientific conference “High technologies and innovations in science”, SPb., 112-116 (2018)
14. V.R. Ivanova, L.V. Fetisov, Development of training bench for effective and safe operation of backup power at industrial enterprises, Power engineering: research, equipment, technology, **20 (9-10)**, 120-128. (2018) (in Russian) DOI : 10.30724/1998-9903-2018-20-9-10-120-128
15. I.N. Lizunov, E.F. Khakimzyanov, R.G. Mustafin, R.S. Misbakhov, I.F. Immamutdinov, O.E. Naumov, A.M. Touitiyrov, Algorithm development for fault location in power transmission lines of branched medium voltage circuits, Journal of engineering and applied sciences, **12 (S1)**, 5731-5734 (2017)
16. V.R. Ivanova, L.V. Fetisov, O.A. Bulatov, The Analysis of Measurements of Indicators of Quality of the Electric Power and Calculation of Economic Efficiency After Installation of the Booster Transformer, 2018 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon), Vladivostok, 1-4 (2018)
17. A.S. Shalimov, Testing of special algorithms of relay protection devices using the IEC 61850-9-2LE process bus, Protection and automation, **3**, 39-42 (2017)
18. V.R. Ivanova, I.Y. Ivanov, N.V. Rozhentcova, Justification of the set of technical and technological criteria when designing a combined power supply system for multi-story residential buildings, International Conference on Electrotechnical Complexes and Systems (ICOECS), 26-30 (2019)
19. Phase Angle (AC) [Electronic resource], vCalc (2020) Available at: https://www.vcalc.com/wiki/MichaelBartmess/Phase+Angle+(AC) (accessed: 02.08.2020)
20. V.R. Ivanova, V.V. Novokreschenov, O.D. Semenova, Analysis of the main elements of an intelligent electric power system with an active-adaptive network, Materials of the I All-Russian Scientific and Practical Conference “Problems and Prospects for the Development of Electric Power and Electrical Engineering”, 12-17 (2019)
21. D.A. Ivanov, M.F. Sadykov, A.V. Golenischev-Kutuzov, D.A. Yaroslavsky, T.G. Galieva, A. Arslanov, The application of the technology of sensor networks for the intellectualization of the overhead power transmission lines, E3S Web Conf., Sustainable Energy Systems: Innovative Perspectives (SES-2020), **220**, **5** (2020) DOI: 10.1051/e3sconf/202022001071
22. D.A. Ivanov, T.G. Galieva, M.F. Sadykov, A.V. Golenischev-Kutuzov, A.A. Naumov, Method for the diagnosis of high-voltage dielectric elements during operation based on dynamic registration of electromagnetic radiation, Rudenko International Conference “Methodological problems in reliability study of large energy systems” (RSES 2020), E3S Web Conf., **216** **(3)** (2020) DOI: 10.1051/e3sconf/202021601061