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Development of a method for determining the location of a single line-to-ground fault of an overhead power line with voltage of 6(10) kV considering climatic factors

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Abstract. One of the main causes of the high accidents and outages rate in 6(10)-kV distributed power supply systems of oil well clusters is damage to overhead power lines due to single line-to-ground faults. Widely conducted studies to locate a single line-to-ground fault have established a correlation between the accuracy of determination and a large number of changing factors, such as operating mode parameters, overhead power line parameters, type of damage, transition resistance, soil resistance, and others. Rationing of technical means for determining the location of a single line-to-ground fault by instrumental errors without taking into account the methodological component translates into the error in locating the damage up to 30%. Thus, relevant research is aimed at determining the primary parameters of power lines and minimizing the methodological error in determining the location of damaged power lines, considering climatic factors. The study takes into account the basic physical processes of propagation of an electromagnetic wave in the power line. The main principles of the theory of electrical circuits and the electromagnetic field and MATLAB Simulink package algorithms are used. As part of the study, a technique has been developed that allows determining the distance from 6(10)/0.4-kV substations to a single line-to-ground fault location in distribution networks of oil well clusters taking into account climatic factors. A simulation model of a 10-kV distribution network supplying oil well clusters was developed in MATLAB Simulink, taking into account the dependence of the primary power line parameters on climatic factors and soil resistivity.

1 Introduction

Overhead power lines (PL) are the basis of the electrical network which largely determines the uninterrupted power supply. According to statistics on the distribution of failures by type of equipment in the distribution networks of oil and gas companies in Western Siberia, presented in Figure 1, the share of faults of 6(10)-kV overhead power lines amounts to 43% [1-4].

Widely conducted studies to locate a single line-to-ground fault have established a correlation between the accuracy of determination and a large number of changing factors, such as operating mode parameters, overhead power line parameters, type of damage, transition resistance, soil resistance, and others [5-8]. To date, a fairly large number of remote sensing methods and technical means for locating damage to a power line have been developed [2, 9-13]. Rationing of these technical means by instrumental errors without taking into account the methodological component translates

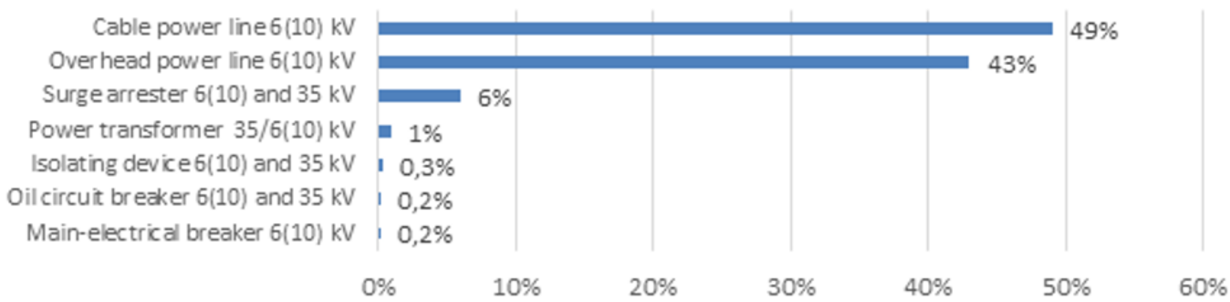

Fig. 1. Chart of failure distribution by type of equipment.

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into the error in locating the damage up to 30%. Thus, relevant research is aimed at determining the primary parameters of power lines and minimizing the methodological error in determining the location of damaged power lines, considering climatic factors. The purpose of the study is to improve the accuracy of determining the place of occurrence of a single line-to-ground fault of a 6(10)-kV power line by developing a methodology that takes into account the influence of climatic factors.

2 Analysis of climatic factors

The research objective includes the analysis of climatic factors affecting the primary parameters of an overhead power line, elaboration of the methodology for the location of damage to power lines, and testing the developed methodology on a simulation model of a 6(10)-kV distribution network.

As a rule, the existing remote sensing methods for damage location use the structural and geometric parameters of power lines, the characteristics of the installed line equipment, fault impedance, and soil conductivity, taking their average values regardless of changes in climatic conditions [6, 8-13].

According to the method of electrical images, the design scheme of a three-phase power line is shown in Figure 2. The distances between the wires and the earth surface are determined by the parameters of the support.

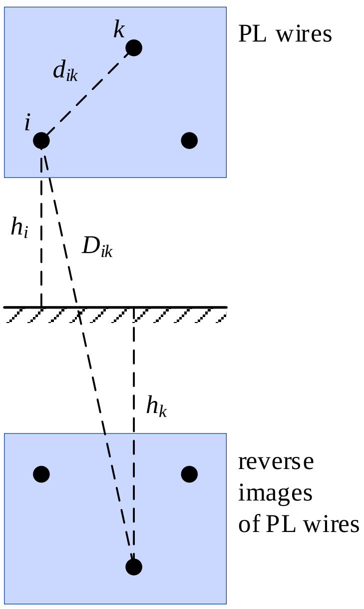

Fig. 2. Design scheme of power lines: h_i, h_k – height of wires *i*, *k* above the ground; d_{ik} – distance between wires *i* and *k*; D_{ik} – distance between the wire *i* and the reverse image of the wire *k*.

The parameters of the power line substitution scheme are determined as follows:

1. Own and mutual partial resistances (Ω/km):

$$R_{ii} = R_i + \Delta R_{ii}\,;\ R_{ik} = \Delta R_{ik}\,. \tag{1}$$

2. Own and mutual partial inductances (H/km):

$$L_{ii} = L_i + \frac{\mu_0}{2\pi}\cdot \lg\frac{2h_i}{r_i} + \Delta L_{ii}\,; L_{ik} = \frac{\mu_0}{2\pi}\cdot \lg\frac{D_{ik}}{d_{ik}} + \Delta L_{ik}\,. \tag{3}$$

3. Own and mutual partial potential coefficients (km/F) and capacities (F/km):

$$P_{ii} = \frac{1}{2\pi\varepsilon_0}\cdot \lg\frac{2h_i}{r_i}\,;\ P_{ik} = \frac{1}{2\pi\varepsilon_0}\cdot \lg\frac{D_{ik}}{d_{ik}}\,; [C]=[P]^{-1}\,. \tag{3}$$

In formulas (1) – (3), the effect of soil resistivity is taken into account by the Carson correction integrals of 1926 ΔR_{ii}, ΔR_{ik}, ΔL_{ii}, ΔL_{ik} [14]. The application of the Carson integrals to the calculation of the electromagnetic state of power lines is described in detail in the works of V.G. Goldstein [15-16].

The specific active resistance of the wire is determined by its cross section and the specific resistance of the material. Data provided in reference books are designed for a temperature of 20 °C and do not take into account seasonal changes in ambient temperature. The specific inductance and specific capacitance of the wire are determined by the cross section of the wire and the geometrical arrangement of the power lines relative to each other and the surface of the earth.

Graphs of dependences of the relative errors of the PL primary parameters on the ambient temperature and humidity, atmospheric pressure and soil resistivity are shown in Figure 3.

Depending on the composition, porosity, humidity, temperature, the presence of chemical pollutants, the resistivity of soils varies within very wide limits. In this case, the relative error in determining the inductance of a PL wire can reach 26% with a change in the value of soil resistivity from 100 to 1000 Ω·m.

The dependence of the specific capacitance of power lines from atmospheric pressure and ambient humidity is not significant and does not exceed 91 and 60 ppm, respectively.

Temperature has a significant impact on the magnitude of the active resistance of power lines; not taking into account this factor contributes a relative error of up to 32% to the calculation of resistance. Temperature does not significantly affect the inductance and capacitance of power lines, and the relative error does not exceed 0.13% and 0.012%, respectively.

3 Object and research methods

Let us consider the effect of the dependences built in Figure 3 on the calculation of the primary parameters of a 10-kV distribution network section of oil well clusters, a simplified single-line power supply diagram of which is shown in Figure 4.

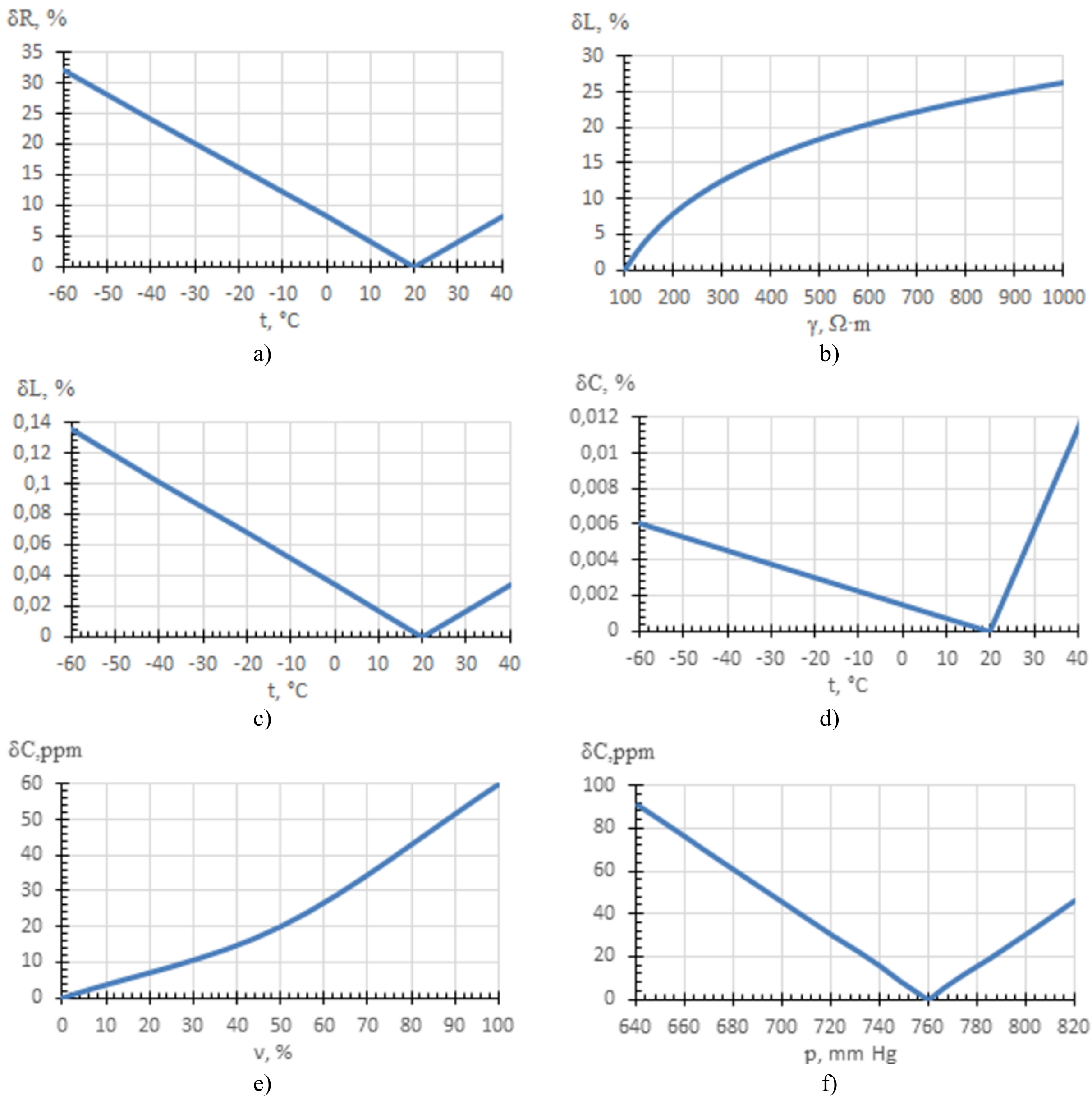

Fig. 3. Graphs of dependences of relative errors of PL wire active resistance on ambient temperature (a); PL inductance on soil resistivity (b) and ambient temperature (c); PL capacitance on temperature (d), ambient humidity (e) and atmospheric pressure (f).

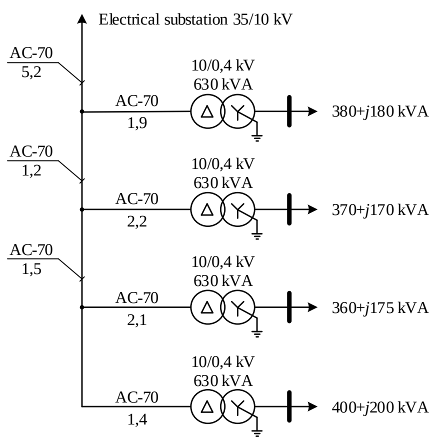

Fig. 4. Simplified 10-kV distribution network of oil well clusters.

According to the power supply diagram, a simulation model was developed in MATLAB Simulink for a section of a 10-kV distribution network of oil well clusters shown in Figure 5.

Model parameters are calculated taking into account the structural and geometric parameters of the line. Then they are refined taking into account the significant climatic factors and soil resistivity.

The calculation results of the primary parameters of the 10-kV distribution network model with and without consideration of climatic factors are summarized in Table 1.

Data analysis of Table 1 showed that climatic factors contribute to the results of calculations of the active resistance matrix a relative error within 8%, and to the results of calculations of the inductance matrix - within

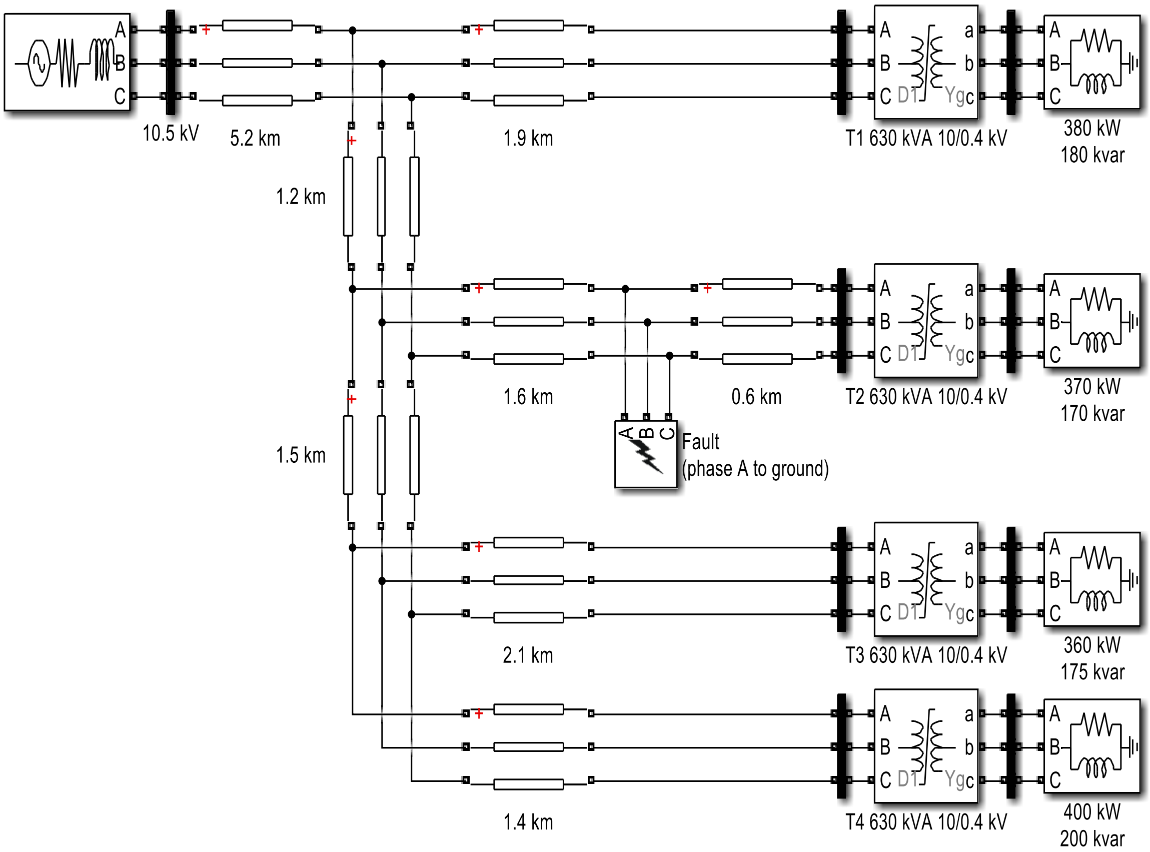

Fig. 5. Diagram of a simulation model of a 10-kV distribution network of oil well clusters in MATLAB Simulink.

26%. A relative error in the calculation of the capacitance matrix does not exceed 2%.

According to the results of the calculations given in Table 2, when calculating the parameters of a direct-sequence power line equivalent circuit, the largest relative error in the calculation of the active resistance is 2.11%; when calculating the parameters of a zero-sequence power line equivalent circuit, the maximum relative error in calculating the inductance is 15.52%.

Obtained in the process of research, the values of the relative errors in the calculation of the primary parameters of power lines (Tables 1, 2) lead to a distortion of the results of remote-sensing methods for locating damage to the overhead line.

As a result of single line-to-ground faults of an overhead power line, voltages containing “resonant” harmonics arise on electrical equipment of the power supply system. The parameters of the "resonant" harmonics depend on the matrices of active resistance, inductance and capacitance of the line, which allows one to determine the correlation function of the distance to the damage.

It is assumed that the use of technical tools that implement the proposed method for determining the location of damage to an overhead power line will increase the technical and economic performance of electricity supply, increase the reliability of the operation of overhead lines, and reduce resources for searching for a place of damage. In order to improve the accuracy of determining the place of occurrence of a single line-to-ground fault of power lines, a method has been developed that takes into account the influence of climatic factors.

The method of determining the location of damage in a single line-to-ground fault taking into account climatic factors includes the following components:

1. On the low-voltage side of each 6(10)/0.4-kV transformer substation of a 6(10)-kV distribution network, installation of a technical means of recording phase voltage signals of each phase and converting them to a digital form with subsequent transfer to the microprocessor-based fault location system (MFLS).
2. The MFLS performs spectral analysis of received digital signals using the fast Fourier transform. The appearance of higher harmonic components exceeding the values prior to the emergency operation of power lines in signals from several transformer substations means the occurrence of damage.
3. When a single line-to-ground fault occurs, the MFLS calculates the fault location using the programmed algorithm based on the spectral analysis data of the phase voltage signals and the built-in mathematical PL model whose parameters are adjusted in accordance with the input signals of the technical equipment for monitoring the temperature and soil resistivity.

The results of modeling the operation of a 10-kV distribution network of oil well clusters with and without consideration of the influence of climatic factors are shown in Figure 6.

Table 1. Calculation results of the primary parameters of the simulation model.

Considering climatic factors			Not considering climatic factors			Relative calculation error		
Active resistance matrix. Ω/km						Resistance. %		
0.4861	0.0490	0.0501	0.4700	0.0482	0.0482	3.42%	1.63%	3.91%
0.0490	0.4861	0.0521	0.0482	0.4702	0.0483	1.63%	3.37%	7.80%
0.0501	0.0521	0.4861	0.0482	0.0483	0.4702	3.91%	7.80%	3.37%
Inductance matrix. mH/km						Inductance. %		
2.7423	1.4499	1.5101	2.4460	1.1533	1.2135	12.11%	25.72%	24.44%
1.4499	2.7421	1.5291	1.1533	2.4452	1.2322	25.72%	12.14%	24.09%
1.5101	1.5291	2.7421	1.2135	1.2322	2.4452	24.44%	24.09%	12.14%
Capacitance matrix. nF/km						Capacitance. %		
7.5015	-1.2971	-1.6760	7.4822	-1.3207	-1.6994	0.26%	-1.79%	-1.38%
-1.2971	7.7262	-1.7127	-1.3207	7.6934	-1.7425	-1.79%	0.43%	-1.71%
-1.6760	-1.7127	7.8764	-1.6994	-1.7425	7.8463	-1.38%	-1.71%	0.38%

Table 2. Results of the calculation of the parameters of direct-sequence (DS) and zero-sequence (ZS) power line equivalent circuits.

	Considering climatic factors		Not considering climatic factors		Relative calculation error	
	DS	ZS	DS	ZS	DS	ZS
R. Ω/km	0.4310	0.5891	0.4219	0.5667	2.11%	3.81%
L. mH/km	1.2458	5.7348	1.2458	4.8448	0.00%	15.52%
C. nF/km	9.2633	4.5775	9.2615	4.4989	0.02%	1.72%

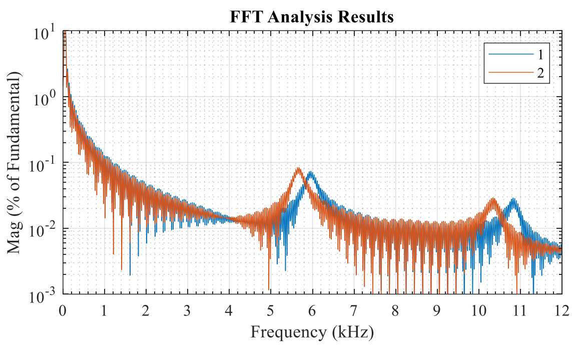

Fig. 6. The amplitude-frequency characteristic of the voltage on the low-voltage side of a transformer substation with a damaged line (phase a) not considering (1) and considering (2) climatic factors.

A 9% reduction of the methodical error of calculating the "resonant" harmonics which allow establishing the distance to the damage leads to an increase in the accuracy of determining the damage location by 12%.

4 Conclusion

1. It has been established that the ambient temperature has a significant effect on the magnitude of the active resistance R of the PL wire; the relative error in calculating R can reach 32%. The values of inductance and capacitance of PL wires with respect to each other and the earth's surface is almost independent of temperature (the relative error is not more than 0.13% and 0.012%, respectively), ambient humidity and atmospheric pressure.

2. It has been established that soil resistivity, which varies depending on the ambient temperature and humidity, has a significant effect on the magnitude of the inductance L of the PL wire, the relative error in calculating L can reach 26%.

3. A simulation model of a 6(10)-kV oil field distribution network has been developed. As a result of modeling, amplitude-frequency characteristics of phase voltages on the low-voltage side of 6(10)-kV transformer substations have been obtained. The showed the presence of “resonant” harmonics determining the location of power line damage.

4. A method is proposed for determining the location of a single line-to-ground fault of overhead power line wires from the secondary voltage of transformer substations, taking into account climatic factors, which increases the accuracy of determining the location of damage by 12%.

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