Remote determining the location of a single-phase earth fault in 6-10 kV networks based on voltage sensors

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Abstract. The article considers a method for determining the location of a single-phase earth fault by voltage values measured in steady state on the damaged phase. A voltage sensor based on a capacitive voltage divider is presented.

1. Introduction
Overhead power lines are the least reliable elements of the power system, damage to which leads to difficult searches for damage and poses a great danger to the lives of people who are nearby [1]. Networks with an isolated neutral have a highly branched tree topology, and the most common type of damage is the single-phase earth fault, in which the phase-to-phase voltage triangle is not distorted, and therefore does not affect the power supply of consumers [2].

Meanwhile, long-term searches for the single-phase earth faults in these networks often cause the transition of single-phase damage to more complex types of damage that require immediate shutdown of the line. To eliminate the consequences caused by the single-phase earth fault, it is necessary to quickly localize the damage site. The issue of determining the location of damage is considered in many works, for example, in [3-8].

According to the Regulations of PJSC "Rosseti" [9] "clause 2.5 The main directions of technical policy in ... the operation of overhead power lines are ... the use of systems for diagnosing the technical condition of overhead lines under operating voltage without decommissioning”.

Nowadays, three methods for determining the location of damage are used: topographic, remote, and the network division method.

The topographic method consists in the use of special instruments, such as Poisk 1 (OJSC Mytishchi Electromechanical Plant), Kvant-K (LLC Kvazar), Vector (LLC Elektrobezopasnost-Vyatka), which measure the parameters of the power line and indicate the direction to the place of the single-phase earth fault. These devices are the most cost-effective, but do not meet the conditions of performance.

Among the remote devices for determining the location of the single-phase earth fault, the most popular are microprocessor protection units with the determining the location of damage function, such as IMF-10, Sirius-2-OMP. They detect the single-phase earth fault and determine the damaged feeder with the ability to work both on a signal and on a shutdown.

The method of sequential division of the network allows you to select only the damaged section of the network. This class includes such devices as IKZ-V31, IKZ-V34L, IKZ-V33L (LLC Small Scientific and Production Enterprise Antraks) and IPVL FI-3A2F/W (LLC Relematika), which
measure the fault current. In practical applications, these devices operate only 50% of the time due to the low earth fault current.

Based on the above, at the moment, the development of remote determination of the fault location under voltage and without disconnecting the line is an urgent task.

2. Materials and methods

Calculation of line parameters by the method of phase coordinates.

In this study, the phase coordinate method and the MatLab Simulink software package were used. During studying the method of symmetrical components for a line with an isolated neutral, it is generally accepted that at a single-phase earth fault on a damaged phase, it is zero volts [10]. Among workers, this process is called "ground in the network".

The work [11] presents the method of phase coordinates for determining the location of damage. The presented method can be used to obtain analytical relationships between the parameters of the power lines, however, for a visual demonstration, we will use the Matlab Simulink software package to simulate the process.

In order to make sure that the calculations are unambiguous, we calculate the parameters of the overhead power line by the method of phase coordinates and compare the obtained values with those calculated in Matlab Simulink.

Figure 1 shows a simulated 10 kV line with a delta phase arrangement.

![Figure 1. Schematic arrangement of phases of the overhead power lines.](image)

The brand of the wire is accepted AC 35/6.2: resist. direct current $R_0 = 0.7774$ Ohm/km, outer diameter $d=0.0084$ m, distance between phases $m=1$m, support height $H=10$m, wire radius $r_0=0.0042$m, wire sag $f_{pr}=1.5$m.

The phases will have the following coordinates: $A (0; 8.366)$, $B (0.5; 7.5)$, $C (-0.5; 7.5)$.

Let's find the matrix of linear active resistances of the line $[R]$:

$$ R_{ii} = R_0 + R_z = 0.827 \tag{1} $$

Where $R_z$ is ground resistance, Ohm/km:

$$ R_z = R_0 = 0.049 \tag{2} $$

Substitute the found values (1) and (2) into the matrix (3):
Find the inductive longitudinal resistance of the power line conductors [X]:

\[ X_{ii} = 4 \cdot \pi \cdot 10^{-4} \cdot f \cdot \ln(D_z / r_{oi}) = 0.774 \]  \hspace{1cm} (4)

\[ X_{ij} = 4 \cdot \pi \cdot 10^{-4} \cdot f \cdot \ln\left(D_z / \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}\right) = 0.43 \]  \hspace{1cm} (5)

Let's find own and mutual potential coefficients and average them (6 and 7):

\[ \alpha_{c1} = \frac{1}{3} (\alpha_{11} + \alpha_{22} + \alpha_{33}) = 8.217 \]  \hspace{1cm} (6)

\[ \alpha_{b1} = \frac{1}{3} (\alpha_{12} + \alpha_{13} + \alpha_{23}) = 2.765 \]  \hspace{1cm} (7)

The capacitance matrix after matrix inversion (\(\alpha\)) will look like (8):

\[ C = \frac{1}{q} \begin{bmatrix} \alpha_c & \alpha_b & \alpha_b \\ \alpha_b & \alpha_c & \alpha_b \\ \alpha_b & \alpha_b & \alpha_c \end{bmatrix} \]  \hspace{1cm} (8)

Where \(\alpha_c = \alpha_{c1} + \alpha_{b1} = 10.963\), \(\alpha_b = -\alpha_{b1} = -2.746\), \(q = \alpha_{c1} \cdot \alpha_{b1} - 2 \cdot \alpha_{b1}^2 + \alpha_{c1}^2 = 75.003\).

The conductivity matrix, considering (6)-(8), will take the following form (F/km):

\[ Y = i \cdot 2\pi \varepsilon_0 \cdot 10^3 \cdot \frac{1}{q} \begin{bmatrix} \alpha_c & \alpha_b & \alpha_b \\ \alpha_b & \alpha_c & \alpha_b \\ \alpha_b & \alpha_b & \alpha_c \end{bmatrix} = i \begin{bmatrix} 8.128 \cdot 10^{-9} & 2.036 \cdot 10^{-9} & 2.036 \cdot 10^{-9} \\ 2.036 \cdot 10^{-9} & 8.128 \cdot 10^{-9} & 2.036 \cdot 10^{-9} \\ 2.036 \cdot 10^{-9} & 2.036 \cdot 10^{-9} & 8.128 \cdot 10^{-9} \end{bmatrix} \]  \hspace{1cm} (9)

Let’s compare the obtained data (3) and (9) with those obtained in the Matlab Simulink program.

Resistance matrix (Ohm/km):

\[ R = \begin{bmatrix} 0.82204 & 0.048047 & 0.048047 \\ 0.048047 & 0.82217 & 0.048112 \\ 0.048047 & 0.048112 & 0.82217 \end{bmatrix} \]  \hspace{1cm} (10)

Capacitance matrix (F/km):
The data error between calculations by the method of phase coordinates and the Matlab Simulink program (3) and (10), (9) and (11) is no more than 0.7%, which allows using the program to consider the proposed method.

Modeling a line with two taps.

In [12], a study was carried out on the dependence between the voltage values on the damaged phase, measured at the beginning and at the ends of the power line for a line with two taps (figure 2).

![Figure 2. Structural diagram of a power line.](image)

According to the results of studies [12], the use of the differential method (the difference between the values of a pair of triggered devices) makes it possible not to consider the source of alternating voltage, the load at consumers, the contact resistance at the accident site and the earth resistance.

Figure 3 shows the dependence of the damaged phase voltage difference at the beginning and at the ends of the power line on the distance to the single-phase earth fault for the figure 2.

![Figure 3. Dependence of the damaged phase voltage difference at the beginning (U1) and at the ends of the power line (U2, U3, U4) on the distance to the single-phase earth fault.](image)
According to figure 3, it can be seen that during modeling a line with two taps, it is possible to determine the location of the damage, knowing the voltage difference between the beginning and the end of the power line.

3. Results
Methodology of the differential method for determining the location of damage.
To determine the damage location for a single-phase earth fault, the following steps must be taken:

- Measure the phase voltage of the damaged phase during the single-phase earth fault (from 0 to 1000 V) at the beginning of U1 and at the ends of the line U2, U3, U4.
- Send the measured voltage values to the dispatcher's server.
- Apply the differential method (calculation of the difference between the beginning and the ends of the power lines U1-U2, U1-U3, U1-U4).
- Determine the location of damage according to the presented dependencies $L = f(U1-U2)$.

Items 3 and 4 must be processed on the dispatcher's server in a pre-written program for each power line. The program allows you to determine at what distance from the beginning of the line a single-phase earth fault occurred and at what tap.

The question remains, what device can measure the phase voltage of a damaged line in a steady state of industrial frequency?
Voltage sensor based on capacitive voltage divider.
Nowadays, the most common device for measuring voltage is a voltage transformer, however, for our task, it is not suitable, because it is large-sized, expensive and has a large error during measuring voltage up to 1000 V.
Therefore, it is necessary to develop a device that will be small-sized, electrically safe, able to measure within the specified limits and transmit information remotely.
According to the research, a method for measuring voltage is possible "in the form of a capacitive voltage divider (figure 4).

![Figure 4. Structural diagram of a capacitive voltage divider.](image)

The first plate is the phase of the power line, the second is a metal insulated rod parallel to the conductor, suspended at an insulation distance from the first plate, in this case the measured value of the potential difference between the plates allows you to calculate the voltage on the phase wire of the line using the formula (12):

$$U_f = \Delta U / K$$  \hspace{1cm} (12)

Where $\Delta U$ is the measured potential difference between the phase of the power line and the metal insulated rod, and $K$ is the formula (13).
\[ K = \frac{C_2}{(C_1 + C_2)} \]  

(13)

Where \( C_1 \) is the capacitance between the power line phase and the metal insulated rod, \( C_2 \) is the capacitance between the metal insulated rod and the ground.

4. Discussion

The given calculations showed that during modeling power lines using the method of the phase coordinates and in the Matlab Simulink software package, they differ by no more than 0.7%.

Using the technique given in chapter 3.1, you can remotely determine the location of the damage.

The development of a device based on a capacitive voltage divider will make it possible to create an autonomous voltage sensor, without electrical connection with the ground and with remote transmission of information.

5. Conclusion

Thus, using voltage sensors that will measure the voltage value in the steady state, it is possible to unambiguously determine the location of the fault in the single-phase earth fault, regardless of the transient resistance values at the accident site, the parameters of the source and load of consumers, as well as the number of taps. Further research prospects are to develop and test the performance of a device for measuring voltage, writing and testing a program for remote fault location for a real 10 kV overhead power line.

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