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Determining the location of damage in electrical networks 35-10-6 kV by an analytical method based on matrix equations of the 3rd degree with respect to voltages

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Abstract. The article investigates an analytical method for determining the fault location in 35 kV, 10 kV and 6 kV networks based on third-degree matrix equations for voltages. The method is remote, with double-sided measurement, according to the emergency mode parameters, the mode parameters are voltages and currents at the beginning and at the end of the line. The case is considered when the errors in determining the location of the damage are calculated theoretical and, as shown by the calculations, are only 1% both for metal closures and for pair closures through the contact resistance. Actual errors will depend on the accuracy classes of current transformers, voltage transformers, voltmeters and ammeters, for example: 0.2 - 0.5 - 2.0 - 5.0. The case is considered with an error of ±5%. The annual economic effect per 1 feeder with a really possible error of 5% is 170 thousand rubles when replacing only the method and 230 thousand rubles when replacing both the method and the device. For 1000 feeders, the annual economic effect will be 170 million rubles and 230 million rubles, respectively. Thus, the considered analytical method for determining the location of damage is effective both from a technical and economic point of view.

1 Introduction

Determination of the damage site (DDS) is a complex, time-consuming, but very important task. For high-voltage networks with a voltage of 110 kV and above, it is solved due to the availability of effective devices and methods for determining the location of the fault.

For electrical networks of 6-10-35 kV, the solution of the problem of determining the location of the fault is complicated by the fact that distribution networks operate with an isolated neutral and the methods applicable to high-voltage networks of the 110 kV class and above are ineffective for these networks [1-4].

In high-voltage networks, the most commonly used device for fault location is SIRIUS-2-DDS [5]. However, its efficiency is low for networks with a voltage of 6-10-35 kV, where the most frequently occurring emergency modes (EM) are single-phase earth faults, which

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this device cannot determine. In addition, the cost of SIRIUS is quite high. From all this it follows that new methods and devices for determining the location of an accident for distribution networks are required, such as those described in [6-7].

Abroad, studies have been carried out on the following methods for determining the location of damage:

- In emergency modes, an arc often occurs, for its extinguishing in [8] an adjustable resistance is used, and voltages and currents in the coordinates of three symmetrical components are used to determine the fault location.
- The equipment is constantly wearing out and aging, therefore in [9] it is proposed to use an intelligent network, which, based on the analysis of previous events, reports on the possible place of the accident.
- Voltages in the network nodes can serve as an indicator of the occurrence of damage, therefore, in [10], it is proposed to periodically measure voltages, find a correlation between them and determine the nodes most likely to be damaged.
- Often short circuits in lines occur through high resistance, for example, when a wire falls on tree branches, therefore, work [11] is devoted to the study of short circuits through contact resistance and OMF.
- A description of new methods for determining the location of damage is devoted to the work [12], where 3 methods are analyzed: a method based on impedance measurement, a traveling wave method and a method using artificial intelligence.
- Methods for determining the location of damage should simulate the load, therefore, in [13], load models with resistance, current, power or static and dynamic characteristics are considered, and their effectiveness is also noted.

However, these methods do not allow to determine the place of occurrence of all possible emergency modes.

2 Materials and methods

In order to improve the efficiency of determining the location of damage in this article, an analytical method was developed based on matrix equations of the 3rd degree with respect to stresses.

The calculated equivalent circuit for a line with damage in its middle is shown in Figure 1.

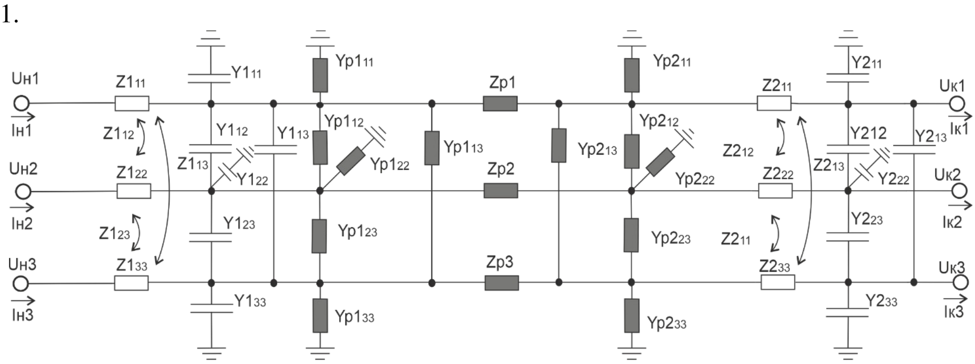

Fig. 1. Estimated equivalent circuit for a line with a fault location.

Figure 1 shows: *Z1, Z2, Y1, Y2* - square matrices of longitudinal resistances and transverse conductivities of two sections of the line; *Zp, Yp1, Yp2* - square matrices of damage resistances and conductivities; *Un, In, Uk, Ik* - column matrices of voltages and currents at the beginning and at the end of the line; *Ip, I2* - column matrices of currents through resistances *Zp* and *Z2*.

Let's write down the initial matrix equations:

$$\begin{gathered} U\textit{н} - U1 = Z1 \cdot I\textit{н} U\textit{н} - U1 = Z1 \cdot I\textit{н} \\ U1 - U2 = Zp \cdot Ip \\ U2 - U\textit{к} = Z2 \cdot I2 \\ IY1 = Y1 \cdot U1 \\ IY\,p1 = Yp1 \cdot U1 \\ IY\,p2 = Yp2 \cdot U2 \\ IY2 = Y2 \cdot U\textit{к} \\ I\textit{н} = IY1 + IYp1 + Ip \\ Ip = IYp2 + I2 \\ I2 = IY2 + I\textit{к} \end{gathered} \tag{1}$$

From (1) we obtain matrix equations for stresses at the beginning and at the end of the line:

$$U1 - Zp \cdot Ip - Z2 \cdot I2 - U\textit{к} = 0 \tag{2}$$

That is why the method is called "with respect to stresses".

For the first and second sections, the lines of the matrix of resistances and conductivities are equal to:

$$\begin{gathered} Z1 = R \cdot L + jX \cdot L \\ Y1 = G \cdot L + jB \cdot L \\ Z2 = R \cdot (LS - L) + jX \cdot (LS - L) \\ Y2 = G \cdot (LS - L) + jB \cdot (LS - L) \end{gathered} \tag{3}$$

Where: *L* is the length of the line before damage; *LS* is the length of the entire line; *R*, *X* – matrices of active and inductive line resistances; *G*, *B* are the active and capacitive conductance matrices of the line.

Transforming (2) taking into account (3) with respect to the powers of *L*, we obtain a matrix cubic equation:

$$AU \cdot L^3 + BU \cdot L^2 + CU \cdot L + DU = 0 \tag{4}$$

Let's single out the required line from (4): for phase A – 1; for phase B - 2; for phase C - 3. Then we obtain cubic equations for the distance L to the damage site:

- For phase A:

$$AU_1 \cdot L^3 + BU_1 \cdot L^2 + CU_1 \cdot L + DU_1 = 0 \tag{5}$$

- For phase B:

$$AU_2 \cdot L^3 + BU_2 \cdot L^2 + CU_2 \cdot L + DU_2 = 0 \tag{6}$$

- For phase C:

$$AU_3 \cdot L^3 + BU_3 \cdot L^2 + CU_3 \cdot L + DU_3 = 0 \tag{7}$$

By equation (5), it is possible to determine the distance *L* for all emergency modes with a damaged phase A. According to (6) - with a damaged phase B. According to (7) - with a damaged phase C.

In (5) - (7) the coefficients *AU, BU, CU, DU* depend on the line parameters, voltages and currents at the beginning and end of the line, as well as on the type of emergency mode. That is, the method under study is remote, with two-sided measurement, according to the parameters of the emergency mode, the mode parameters are voltages and currents at the beginning and at the end of the line. The expressions for the coefficients *AU, BU, CU, DU* are not given because they are cumbersome.

The emergency mode itself was calculated by the method of phase coordinates [14-16]. Previously, methods for determining the location of damage presented in [17-18] were studied. Analytical methods are presented in [19-20].

The developed analytical method for determining the location of damage is valid so far only for main feeders 6-10-35 kV without branches.

For measurements of vector diagrams of voltages and currents in a quasi-steady emergency mode, it is necessary to use devices implemented, for example, in the SIRIUS device. That is, both modules and phases of voltages and currents are measured.

3 Results and Discussion

The results of calculations for electrical networks of 35 kV, 10 kV and 6 kV are presented in Table 1 for a metal circuit and for a circuit through a contact resistance. The transition resistance is taken for a 35 kV line - 750 (Ohm), for a 10 kV line - 500 (Ohm), for a 6 kV line - 300 (Ohm). The line length is assumed: for a 35 kV line - 40 (km), for a 10 kV line - 20 (km), for a 6 kV line - 15 (km). Calculations are given only for damaged phase A. For phases B, C, the results are similar.

Table 1 shows the calculated theoretical mathematical errors in determining the location of damage. That is, the stresses at the end were not measured, but calculated exactly in order to evaluate the mathematical efficiency of the presented method.

Table 1. Mathematical fault location error (%) for 35 kV, 10 kV and 6 kV networks.

Mode	35 kV metal	35 kV through transitional	10 kV metal	10 kV through transitional	6 kV metal	6 kV through transitional
$Z^{(1)}$ Phase A	0-0.085	0-0.06	0-0.001	0-0.06	0-0.027	0-0.08
$K^{(2)}$ Phases A-B	0	0-0.01	0	0-0.02	0	0-0.027
$K^{(2)}$ Phases A-C	0	0-0.01	0	0	0	0
$K^{(3)}$ Phases A-B-C	0	0-0.05	0	0	0	0
$Z^{(1+1)}$ Phases A-B	0-0.01	0-0.2	0-0.01	0-0.38	0	0-0.187
$Z^{(1+1)}$ Phases A-C	0-0.003	0-0.18	0	0-0.12	0	0-0.053
$O^{(1)}$ Break A	0-0.25	0-0.04	0-0.28	0-0.28	0-0.587	0-0.587
$Z^{(1)}$ Phases A+ $O^{(1)}$ Break A	0-0.055	0-0.77	0-0.01	0-0.727	0-0.013	0-0.16
$O^{(1)}$ Break A+ $Z^{(1)}$ Phases A	0-0.04	0-0.04	0-0.31	0	0-0.427	0-0.32

From Table 1 it follows that for the considered 35-10-6 kV networks, the mathematical error in determining the fault location is less than 1%. This is true for modes with a metallic circuit and with a circuit through a contact resistance. It should be noted that this is a theoretical error.

Actual errors will depend on the accuracy classes of current transformers, voltage transformers, voltmeters and ammeters, for example: 0.2 - 0.5 - 2.0 - 5.0. Calculations show that errors in determining the location of damage are practically proportional to measurement errors. That is, if the measurement errors are ±2.5%, then the errors in determining the location of the damage are close to 2.5%, and if ±5%, then they are close to 5%.

So, with a line length of 20 km and a measurement error of ±2.5%, the damage search interval will be about 500 meters. The applied method can be used as a mathematical apparatus in new microprocessor devices for determining the location of damage. Recently, the error of measuring instruments has been greatly reduced. At new substations, devices of accuracy class 0.2 and even 0.1 are already used. In addition, even at old substations, instruments are being replaced with more accurate ones. That is, the application of the considered method in conjunction with new measuring instruments will allow obtaining sufficient accuracy in determining the location of damage. And now we need to focus on the future.

Thus, when using equations of the third degree with respect to stresses, the error of the analytical method for determining the fault location itself is less than 1%, and the real errors will depend on the errors of the measuring instruments.

In addition to technical efficiency, economic efficiency is calculated.

Networks 6 - 10 - 35 kV are very numerous and distributed over a large area. They mainly feed agricultural consumers. Therefore, in case of damage, damage occurs from the undersupply of electricity [21-22]. This, in turn, leads to a disruption of modern processes for processing agricultural products, as well as processes for caring for animals. The smaller the interruption in power supply, the less damage. The time of interruption in power supply is the sum of the time of detection of an accident and the time required to eliminate the accident. The more accurate the remote method for determining the location of damage, the shorter the break time. That is, increasing the accuracy in determining the location of damage leads to a decrease in damage and an increase in the obtained economic effect [21-22].

Calculations of the technical and economic effect are summarized in Table 2. Options for obtaining savings were considered when using only the considered method for determining the location of damage and when using both the method and the new device for determining the location of damage. In this case, the theoretical calculated error of the method ±1% and the real possible error ±5% were considered. As a device in the original version, the Sirius-2- DDS device was considered, costing 87 thousand rubles. It contains a measurement unit, a calculation unit, a display and a data transmission channel to a computer. The new device is a device divided into 2 parts. In the device itself, only the measurement unit and the unit for transmitting measurements to the computer remained. The program for determining the location of damage is located on the dispatcher's computer. The measured voltages and currents in each emergency mode are transferred to the computer, and the program determines the location before the fault from the beginning of the line. The cost of the converted device and program is 30,000 rubles.

Table 2. Annual economic effect per 1 feeder for 35 kV, 10 kV and 6 kV networks (thousand rubles).

Mains voltage	Method only. Measurement error ±1%	Method and device. Measurement error ±1%	Method only. Measurement error ±5%	Method and device. Measurement error ±5%
35 kV	254	315	211	273
10 kV	204	266	181	243

6 kV	140	201	127	188

The analysis of Table 2 showed that when using the analytical method for determining the location of damage according to the equations of the 3rd degree with respect to voltages, the following annual economic effect is achieved for 6-10-35 kV networks per 1 feeder:

- With a theoretical measurement error of ±1%, when replacing only the method for determining the location of damage, the effect is 140-254 thousand rubles.
- With a theoretical measurement error of ±1%, when replacing both the method for determining the location of damage and the device, the effect is 201-315 thousand rubles.
- With a really possible measurement error of ±5%, when replacing only the method for determining the location of damage, the effect is 127-211 thousand rubles.
- With a really possible measurement error of ±5%, when replacing both the method for determining the location of damage and the device, the effect is 188-273 thousand rubles.

At the same time, for all options, the payback period is about a year.

Let us round off the economic effect with a really possible error of ±5% to 170 thousand rubles when replacing only the method and up to 230 thousand rubles when replacing both the method and the device. Then the annual economic effect for 1000 feeders will be 170 million rubles and 230 million rubles, respectively, etc. with an increase in the number of feeders.

4 Conclusion

Thus, the considered analytical method for determining the location of damage based on matrix equations of the 3rd degree with respect to stresses is effective both from a technical and economic point of view.

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