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Development of a Method of Fault Location in a 6 kV Network for a Digital Platform of Intelligent Services of an Electric Grid Company

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ABSTRACT

The article proposes a modern method of fault location for 6 kV networks according to empirical criteria for different types of emergency modes. When developing the criteria, the modules of phase voltages and currents at the beginning of the line, at the end of the line, and both at the beginning and at the end of the 6 kV line were used. It has shown that the error of the fault location method with one-sided measurement is below 6.71 %, except for the fault modes “ground fault with subsequent breakage” and “two-phase short-circuit”. However, while using double-sided metering at the beginning and end of the line, all of the emergency modes considered are identified, with a method error of below 4%.

A modern hierarchical structure of the automated process control system of an electric grid company is proposed, according to which at each control level an intelligent module is provided, allowing to integrate the local system into a common trusted software environment for the purpose of operational management in current and emergency situations. The model of information flows of the digital integration platform as a common trusted software environment for the automated control systems of the electric grid company was developed. In the MathCad environment the method of fault location using empirical criteria is implemented, designed to support the decision of the grid control centre dispatcher in current and emergency situations.

Keywords: *Fault location, Electrical network, Digital platform, Intelligent service.*

1. INTRODUCTION

For high-voltage networks of 110 kV and above with a deaf neutral the problem of fault location (FL) is sufficiently elaborated [1–3]. For medium voltage networks between 6-10-35 kV it is necessary to develop their own new methods of fault localization, since in these networks the length of lines and the breaking capacity are small. The existing devices [4–6] determine in these networks only emergency modes (EM) with two-phase and three-phase short circuits. 6-10-35 kV networks operate with isolated neutral, so ground faults in these networks are not short circuits. However, in medium-voltage networks ground faults account for about 70 % of all possible faults.

The concept “Digital Transformation 2030” developed by ROSSETI [7] indicates the need for large-scale transformations in the energy sector and, as a consequence, the overall development of our country's industry. One of the most important transformations necessary to implement the concept is to create a common digital platform for energy [8].

The goal of this article is to develop the modern method for remote fault location in 6 kV networks using empirical criteria. The proposed criteria depend on voltage and current changes at the beginning of the line (single-sided measurement), at the end of the line (single-sided measurement), at both the beginning and the end of the line (double-sided measurement). It is also required to develop a service for the developed method of fault location in 6 kV networks for its integration into the digital platform of intelligent services of the electric grid company.

2. DEVELOPMENT OF THE REMOTE METHOD FOR FAULT LOCATION FOR 6 KV NETWORKS

FL devices are divided into remote and topographic [9]. The remote ones allow you to locate the fault without bypassing the line, while the topographic ones require bypassing the line. There are no effective remote devices for 6-10-35 kV networks. Topographic devices are mainly used. One type of remote devices are devices based on fault mode parameters. They mainly use the parameters of the electrical network, as well as voltages and currents at certain points of the network. For example, in [4] the following formulas for determining the distance to three-phase, two-phase and single-phase short-circuit (SC) are used:

$$\mathrm{Lkzs}^{(3)} = \frac{U}{\sqrt{3}\cdot \mathrm{Ikz}^{(3)}\cdot \mathrm{Zpr}} \cdot \sin\phi 3 \quad (1)$$

$$\mathrm{Lkzs}^{(2)} = \frac{U}{2\cdot \mathrm{Ikz}^{(2)}\cdot \mathrm{Zpr}} \cdot \sin\phi 2 \quad (2)$$

$$\mathrm{Lkzs}^{(1)} = \frac{\sqrt{3}\cdot U}{\mathrm{Ikz}^{(1)}\cdot (2\cdot \mathrm{Zpr}+\mathrm{Znul})} \cdot \sin\phi 1 \quad (3)$$

In these formulas are denoted: U – voltages of the corresponding line phases; Zpr, Znul – modules of specific impedances of direct and zero sequence; Ikz – currents of the corresponding line phases; φ1, φ2, φ3 – angles between the applied voltages and currents for the corresponding faults.

Thus, the existing FL devices detect only SC and do not detect EM with single-phase ground faults and with phase failures. To eliminate this disadvantage, individual empirical criteria for each type of EM were developed in [10, 11], and in [12] a method for determining the type of fault was proposed. The works [10–12] are devoted to the methods of determining the type and place of EM in 6 kV networks, based on the application of empirical criteria. The criteria are formulas individual for each type of EM. In the numerator of the formula are placed voltages and currents, increasing when moving the point of failure along the line length, and in the denominator – decreasing. Parameters that do not change are not taken into account. This makes it possible to always get a criterion graph with a large steepness and to determine the fault location with sufficient accuracy. In [10], criteria based on voltages and currents only at the beginning of the line are considered. It is of interest to research the effectiveness of FL when using the criteria based on voltages and currents at the end of the line, as well as at the beginning and at the end both at the same time.

For comparison, Tables 1 and 2 present empirical criteria obtained for voltages and currents at the beginning of the 6 kV line and at the end of the line. The criteria are presented for modes with a damaged phase A, B and C. The criteria depend on the phase voltages and currents Ua, Ub, Uc, Ia, Ib, Ic.

Tables 1 and 2 show that the obtained criteria "at the beginning" and "at the end" of the line are different. The "at the beginning" criteria use voltages and currents before the fault, and the "at the end" criteria use voltages and currents after the fault.

Table 1. Formulas for empirical criteria when using voltages and currents at the beginning of the line

Type of EM	For the damaged phase A	For the damaged phase B	For the damaged phase C
Single-phase ground fault	$Kao = \frac{Ua}{Ub \cdot Uc}$	$Kbo = \frac{Ub}{Ua \cdot Uc}$	$Kco = \frac{Uc}{Ua \cdot Ub}$
Two-phase short circuits.	$Kab = \frac{Ua \cdot Ub}{Ia \cdot Ib}$	$Kbc = \frac{Ub \cdot Uc}{Ib \cdot Ic}$	$Kac = \frac{Ua \cdot Uc}{Ia \cdot Ic}$
Three-phase short circuit.	$Kabc = \frac{Ua \cdot Ub \cdot Uc}{Ia \cdot Ib \cdot Ic}$		
Double ground faults	$Kaobo = \frac{Ua \cdot Ub}{Ia \cdot Ib}$	$Kboco = \frac{Ub \cdot Uc}{Ib \cdot Ic}$	$Kaoco = \frac{Ua \cdot Uc}{Ia \cdot Ic}$
Phase failures	$KbrA = \frac{Ub \cdot Uc}{Ua} \cdot Ia$	$KbrB = \frac{Ua \cdot Uc}{Ub} \cdot Ib$	$KbrC = \frac{Ua \cdot Ub}{Uc} \cdot Ic$
Concurrent ground faults with breaks afterwards	$KaobrA = Ua$	$KbobrB = Ub$	$KcobrC = Uc$
Concurrent breaks with ground faults after	$KbrAao = Ia$	$KbrBbo = Ib$	$KbrCco = Ic$

Table 2. Formulas for empirical criteria when using voltages and currents at the end of the line

Type of EM	For the damaged phase A	For the damaged phase B	For the damaged phase C
Single-phase ground fault	$Kao = \frac{1}{Ua \cdot Ub \cdot Uc}$	$Kbo = \frac{1}{Ua \cdot Ub \cdot Uc}$	$Kco = \frac{1}{Ua \cdot Ub \cdot Uc}$
Two-phase short circuits.	$Kab = \frac{Ub \cdot Ib}{Ua \cdot Ia}$	$Kbc = \frac{Uc \cdot Ic}{Ub \cdot Ib}$	$Kac = \frac{Ua \cdot Ia}{Uc \cdot Ic}$
Three-phase short circuit.	$Kabc = \frac{1}{Ua \cdot Ub \cdot Uc \cdot Ia \cdot Ib \cdot Ic}$		
Double ground faults	$Kaobo = \frac{Ib}{Ia \cdot Ub}$	$Kboco = \frac{Ic}{Ib \cdot Ub}$	$Kaoco = \frac{Ia}{Ic \cdot Uc}$
Phase failures	$KbrA = Ua \cdot Ub \cdot Uc$	$KbrB = Ua \cdot Ub \cdot Uc$	$KbrC = Ua \cdot Ub \cdot Uc$
Concurrent ground faults with breaks afterwards	$KaobrA = \frac{1}{Ua \cdot Ia}$	$KbobrB = \frac{1}{Ub \cdot Ib}$	$KcobrC = \frac{Uc}{Ic}$
Concurrent breaks with ground faults after	$KbrAao = \frac{Ia}{Ua}$	$KbrBbo = \frac{Ib}{Ub}$	$KbrAao = \frac{Ic}{Uc}$

For example, for a single-phase ground fault of phase A, the following criteria for the beginning (Kao1) and end (Kao2) as well as the generalized criterion (Kao3) are obtained:

$$Kao1 = \frac{Ua1}{Ub1 \cdot Uc1} \quad (4)$$

$$Kao2 = \frac{1}{Ua2 \cdot Ub2 \cdot Uc2} \quad (5)$$

$$Kao3 = Kao1 \cdot Kao2 \quad (6)$$

The generalized criteria are the multiplication of the criteria at the beginning and at the end of the line, and voltages and currents were calculated by the phase coordinate method [13]. Interpolation polynomials based on the Vandermonde matrix [13] were obtained from the calculated data of the criteria at four points with a line length of 15 km and at three points with a line length of 5 km, by which the fault location was determined.

The results of the calculation of the error FL for the line length of 15 km and 5 km are shown in Table 3.

Table 3. Error FL method for line lengths of 15 km and 5 km

Type of EM		Line length 15 km			Line length 5 km		
		Criterion at the beginning	Criterion at the end	Criterion at the beginning and at the end	Criterion at the beginning	Criterion at the end	Criterion at the beginning and at the end
Single-phase ground fault	A	6.37	0.1	0.1	4.94	0.1	0.1
	B	6.40	0.1	0.1	4.94	0.1	0.1
	C	6.41	0.1	0.1	4.96	0.1	0.1
Short circuits	AB	3.49	-	3.43	3.08	-	2.86
	BC	3.46	-	3.37	2.94	-	2.74
	AC	3.48	-	3.38	3.06	-	2.82
	ABC	2.23	5.42	2.29	1.28	1.38	0.1
Phase failures	A	3.38	4.14	1.54	2.66	4.1	1.04
	B	3.38	4.18	1.56	2.64	3.9	0.98
	C	3.39	3.94	1.49	2.68	3.92	1
Concurrent ground faults with breaks afterwards	A	-	5.05	3.38	-	3.22	2
	B	-	5.34	3.79	-	4.28	2.92
	C	-	5.0	3.36	-	4.6	3.26
Concurrent breaks with ground faults after	A	6.71	1.22	0.78	5.02	2.72	1.2
	B	6.08	1.44	0.86	4.98	3.26	1.34
	C	6.63	1.25	0.8	5	2.88	1.24
Double faults to ground	AB	6.56	0.1	0.1	5.38	0.1	0.1
	BC	6.63	1.1	0.73	5.42	0.8	0.38
	AC	6.61	0.1	0.1	5.52	0.1	0.1

Errors are given for a fault occurring in the middle of the line (i.e., at points 7.5 km and 2.5 km, correspondingly). Errors are calculated for measurements at the beginning of the line (criterion by the beginning), at the end of the line (criterion by the end), and at the beginning and end of the line simultaneously (criterion by the beginning and end).

It follows from Table 3 that the FL method error for a line length of 15 km:

• for the criteria "at the beginning" is in the range from 2.23 to 6.71 % (modes with concurrent ground faults and breaks are not detected);

• for the criteria "at the end" is in the range from 0.1 to 5.42 % (modes with two-phase short circuits are not detected);

• for the criteria "at the beginning and at the end" is in the range from 0.1 to 3.79 % (all modes are detected).

Table 3 shows that the FL method error for the line length of 5 km:

• for "at the beginning" is in the range of 1.28 to 5.52 % (modes with concurrent ground faults and breaks are not detected);

• for the criteria “at the end” is in the range from 0.1 to 4.6 % (modes with two-phase short circuits are not detected);

• for the criteria “at the beginning and at the end” is in the range from 0.1 to 3.26 % (all modes are detected).

The research shows that the error of the fault location method with one-sided measurement is below 6.71 %, except for the fault modes “ground fault with subsequent breakage” and “two-phase short-circuit”. However, when using double-sided metering at the beginning and end of the line, all of the emergency modes considered are identified, with a method error of below 4 %.

3. DEVELOPMENT OF A FAULT LOCATION SERVICE INTO THE DIGITAL PLATFORM OF AN ELECTRIC GRID COMPANY

At the moment, the automated process control system (APCS) of the electric grid company is a corporate information system (CIS), which provides automation of the main types of business processes related to the activities of electricity transmission and distribution [14]. In accordance with this structure, APCS of the electric grid company is a set of control systems of various types of operational dispatch, technological, financial and economic activities. CIS is the main source of information in the formation of the basic services of the digital integration platform. It also follows from the APCS structure that the emergence of a digital integration platform is impossible without the formation of an automated information and management environment at electric grid facilities. In this case, the development of automation tools should be carried out in the direction of integration of both automated dispatcher control systems and automated process control systems.

Let's consider the scenario of integration of intelligent services of the electric grid company into a digital platform on the example of a hardware-software fault location complex (FLC). In this integration scenario, the initial stage of development of the information and control environment of electric distribution grids should be considered the introduction of the simplest FL devices. The next stage involves the formation of a hierarchical FLC. Then it is necessary to move to the next level of development – the creation of an intelligent FL system through the use of a forecasting subsystem and the implementation on this basis of a proactive control system for different time intervals [15–17]. A further direction of development is the outgrowth of automated control systems into the Internet of Things, which in the future will allow the full automation of dispatching and technological control.

The multilevel structure allows the formation of information systems of the required scale, to integrate them with other subsystems of the APCS network company. In the block diagram proposed in Figure 1, at each level of control there is an intelligent module that allows to quickly assess the state of the network in current and emergency situations, to issue the information of interest to the trusted network, which forms the basis for the formation of intelligent services digital platform [18].

Necessary conditions for the modern development of the digital infrastructure of the control system in the electric grid companies is the formation of a concentrator of intelligent services. Its basis should be a digital integration platform that combines such analytical modules as fault location, power consumption forecasting, power loss monitoring, assessment of the state of active network devices, decision making support for operational management, strategic planning, etc.

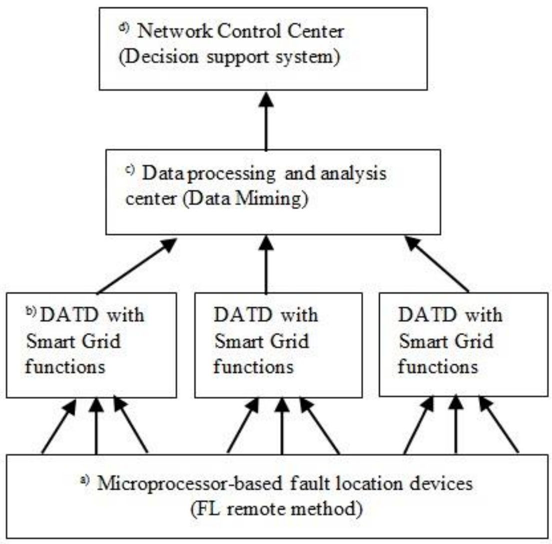

Figure 1 Perspective block diagram of the development of electric grid company FL service: a – the level of measurement and information complex; b – the level of information-computer complex of the power object (DATD – data acquisition and transmission device); c – the level of information-computer complex of the data processing centre; d – the level of automated workplace.

The model of information flows for the digital platform of intelligent services of the electric grid company is shown in Figure 2.

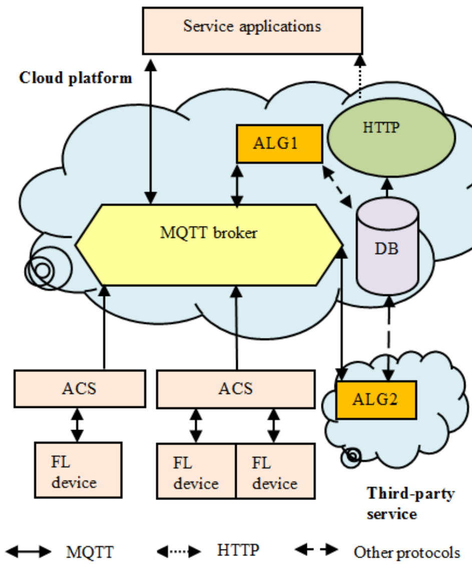

Figure 2 Model of information flows of electric grid company digital platform of intelligent services: ALG – algorithms; ACS – local automated control systems at facilities; DB – database; MQTT (Message Queue Telemetry Transport) – simplified network protocol used to exchange messages between devices according to the "publisher-subscriber" principle.

Digital platform services can be oriented to be used by all kinds of functional customer services (power supply and power grid companies, housing and utility companies, household consumers) as a decision support system for the current situation and for the strategic perspective. Examples of basic services are: determining the location and type of fault; forecasting energy consumption (short-term, medium-term, long-term); tasks to upgrade or repair active devices of grid infrastructure (meters, measuring current and voltage transformers, data acquisition and transmission facilities); prospective development of power grid areas (technological connections); interaction with consumers on energy saving issues.

4. PRACTICAL IMPLEMENTATION OF THE FL SERVICE IN AN ELECTRIC GRID COMPANY

When implementing in practice the FL service, the existing multifunctional current and voltage transducers [17] at the level of the measurement and information complex of the power facility were used. The programmable logic controller (PLC) OVEN PLC154 [21, 22] was used as a device for acquisition, processing and transmitting information at the level of the information-computer complex. For it in the CoDeSys software environment, the program code for primary data preparation by the fault location method in 6 kV electric networks with the use of empirical criteria was implemented.

Primary data processing is performed directly on the PLC, then the information via communication channels of the power facility comes to the data processing centre. At the level of servers of information-computer complex of data processing centre in MathCad environment the method of fault location with the use of empirical criteria by voltage and current at the beginning, at the end and simultaneously at the beginning and at the end of 6 kV line was developed, investigated and tested. In accordance with the proposed information model of the digital platform, the calculated information on fault location is transmitted to the grid control centre, where it is used by the dispatcher as input data when making managerial decisions in current and emergency situations on 6 kV electric networks.

4. CONCLUSION

The method of fault location in 6 kV electric grids using empirical criteria has been developed. The criteria are obtained for three cases of measuring voltages and currents: at the beginning of the line, at the end of the line, simultaneously at the beginning and at the end of the line. Line lengths of 15 km and 5 km are considered. It is shown that error of the method at one-side measurement is less than 6.71 % and at two-side measurement less than 4 %.

An updated structure of the automated process control system of an electric grid company is proposed, which includes an intelligent module on each level of control, allowing to combine information from disparate corporate and technical systems into a common trusted software environment. The model of information flows for the digital platform of intelligent services of the electric grid company was developed. Practical implementation of the fault location method at the electric grid facility is based on the existing information and measurement systems of the electric grid facility and the addition of a PLC with updated firmware at the level of the information and computing complex. For the PLC in the software environment CoDeSys, the program code for the primary preparation of data on the fault location method in 6 kV electrical networks using empirical criteria was implemented. On the level of data analysis and processing centre in MathCad environment the method of fault location with the use of empirical criteria by voltage and current at the beginning, at the end and simultaneously at the beginning and at the end of the 6 kV line was realized.

The possibility of phased implementation of the grid company's digital platform of intelligent services creates a methodological basis and determines the sequence of development of the system of direct digital management of the electric grid complex in accordance with the Russian Energy Strategy.

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