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Investigation of the Effect of Current Protections in Conditions of Single-Phase Ground Fault through Transient Resistance in the Electrical Networks of Mining Enterprises

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Abstract: The efficiency of electrical complexes depends directly on the level of power supply system reliability, which comprises extensive and branched distribution networks. A complex of single-phase ground fault (SPGF) relay protection and automation devices (RPA) is used to reduce the economic losses from the failure of the electrical receivers' distribution networks. This paper presents a study of the protection sensitivity factor, taking into account the influence of the network capacity and the resistance during a fault. The results of this study determined the minimum permissible values of the sensitivity factor that ensures the stable operation of the protection device. This was achieved by taking into account the influence of the transient resistance at the point of short circuit. The practical significance of the study is as follows: the obtained characteristics will allow for the development of new functional logic circuits for SPGF protection. The practical implementation of the obtained results will allow for the following: to increase the sensitivity and selectivity of current non-directional protections in conditions of incomplete short circuits; to ensure the reliable functioning of technological equipment and responsible consumers; to reduce the level of electrical injuries of service personnel; and to reduce economic losses associated with the repair of damaged electrical receivers.

Keywords: distribution network; transient resistance; sensitivity factor; zero-sequence current; relay protection and automation; incomplete single-phase ground fault

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1. Introduction

The efficient operation of mining enterprises of the mineral resource complex (MRC) is determined by the safety and continuity of technological processes [1–3]. Motorized loads comprise the main part of MRC loads. Their operation depends on the reliability of the power supply system, which comprises long and branched networks with constantly changing parameters [4–6]. In such networks, on the medium-voltage level of 6–35 kV, 81% of failure incidents are caused by SPGF [7–9].

Subsequently, due to this high failure rate, and in order to reduce the resulting economic losses and improve the safety of production in mining enterprises, it is necessary to use modern and reliable RPA devices. As a consequence, this will allow workers to selectively determine the damaged sections of the electrical network and eliminate the emergency modes.

However, the introduction of RPAs into the mining electrical grid is met with the following problems:

- The increase in the length and branching of medium-voltage air-cable and cable lines and the complexity of the MV grid with respect to the technological cycle application requires a timely update of the operation settings in order to preserve sufficient sensitivity in the protection behavior of the SPGF mode;

- The variety of SPGF modes and the places of their occurrence in the electrical network must be considered. For example, the arc SPGF (ASPGF) in the power supply system leads to overvoltage, exceeding the nominal value by 3–4 times. This causes deterioration of the insulation properties of electrical installations, accelerates the aging process, and, as a result, contributes to the premature failure of electrical equipment and increases the risk of electrical injuries of service personnel, unauthorized persons, and animals accidentally caught at the accident site [10];
- The calculation of the protection settings is straightforward in the case of a metallic SPGF mode. The incomplete ground fault (GF) mode is often accompanied by the presence of transient resistance at the point of fault, reaching values of several kilo-ohms [11]. The constant changing of the values of the zero-sequence current during the operation of 6–35 kV electrical networks (the conductivity of line phases relative to the ground, the parameters of neutral circuit grounding) causes additional difficulties in solving the problem of ensuring the stable functioning of protections in incomplete single-phase short circuit modes (through transient resistance).

According to the operational data, the incomplete line-to-ground short circuit was found to be the main reason for the low action selectivity and the stability disruption of the SPGF's functioning, based on the zero-sequence steady-state current control [12]. The incomplete SPGF mode happens due to the occurrence of a transient resistance at the point of short circuit. As it is a parameter of the zero-sequence circuit, this drops the value of the zero-sequence voltage and, as a consequence, the signals of zero-sequence currents of protected connections controlled for protection purposes. Considering that the operation of non-directional protections is set under the condition of metal short circuits (in the absence of a transient resistance at the site of the SPGF), the incompleteness of the phase short circuit to the ground will cause these protections to be inoperable under operating conditions.

The value of the transient resistance is random and depends on many factors: the resistance of the element through which the line phase touches the ground (a layer of snow, ice, fallen leaves, etc.), the resistance of the "reverse" current flow circuit of a single-phase short circuit along the ground from the point of the SPGF to the neutral of the network, the hemisphere of the "spreading current" in the place of contact with the ground, etc. According to [13], the value of the transient resistance can reach 5–7 kOhm, and according to [14], the transient resistance can reach 10 kOhm. The transient resistance is the cause of the failure not only of non-directional current protections from the SPGF, but also of the protection devices that respond to higher harmonic components in the steady-state earth fault current. The conducted studies on the analysis of the effect of the incompleteness of the phase-to-ground short circuit on the operational stability of these protections have shown that in an SPGF experiencing a transient resistance of several ohms, the level of higher harmonics decreases sharply, which reduces the selectivity and sensitivity of the action of these protections.

Directional protections that determine the direction of the zero-sequence power flow in the steady-state mode of a single-phase circuit have better characteristics in comparison with non-directional current protections from an SPGF. However, the performed analysis of the operational data of the ZZP-1 protection device indicates a low selectivity in the detection of a damaged connection in the event of an incomplete SPGF through transient resistances of 600–700 Ohms with a maximum capacitance of the distribution network of 6.5 μF.

It should be noted that the task of conducting a study of the incomplete SPGF regime effect on the stability of current protections, as well as identifying the ways to ensure the necessary selectivity and sensitivity of its action in such conditions, seems relevant today due to the prevalence of this type of SPGF in the electrical networks of mining enterprises, and due to the negative consequences associated with its untimely liquidation [15].

In addition, the existing method of calculating the protection settings does not allow for the adjustment of protection, ensuring its effective operation in conditions of incomplete earth faults, which also requires its improvement.

2. Problem Statement

The analysis of the number of SPGF and the corresponding effect of protections in Kemerovo region, Russia, in the 6–35 kV network at MRC enterprises for 2019 are shown in Figure 1. It follows from Figure 1 that in 30% of the emergency cases, if an SPGF is not resolved by time, it will lead to phase to phase short circuit (SC) [16].

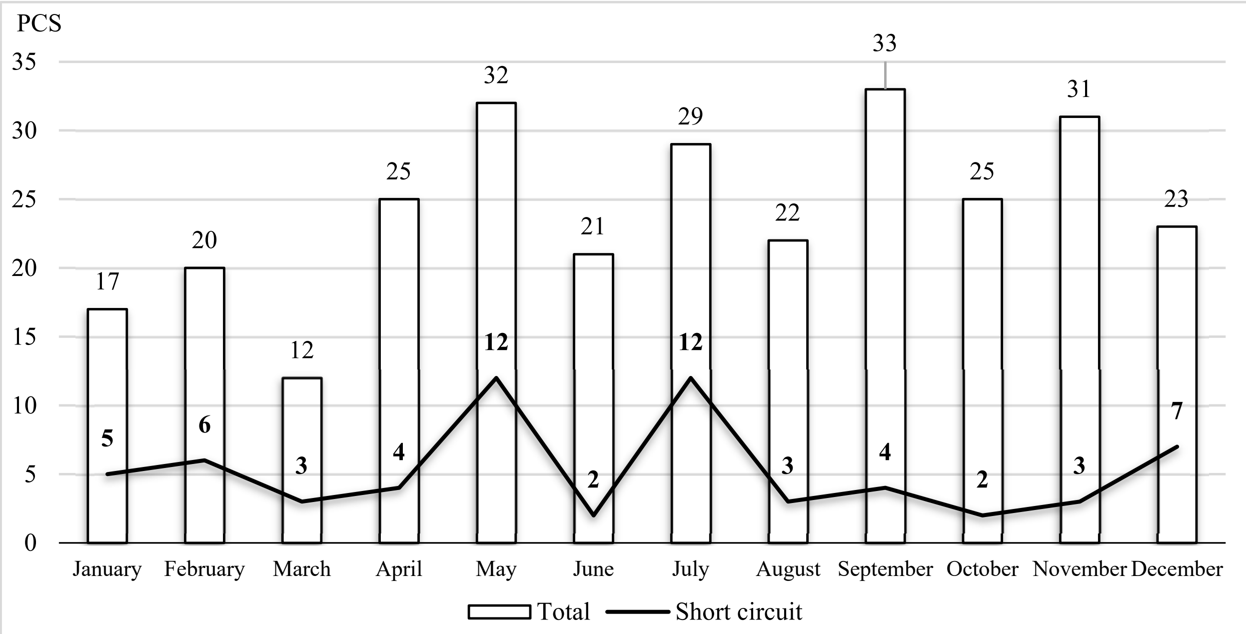


Figure 1. The total number of SPGF and the number of ground faults not eliminated in a timely manner that have passed into an inter-phase short circuit (SC) in 6–35 kV networks.

Combining heat and the high sensitivity of the SPGF protection devices, along with the desire of the MRC enterprises operating at 6–35 kV networks to maintain the power supply to their consumers under the conditions of SPGF mode until the damage location is reliably determined, create the conditions for the development of an accident. Despite the immutability of linear voltages values in SPGF mode with electric receivers switched on in medium-voltage networks, the long-existing single-phase short circuit mode increases the probability of intact phases insulation damage due to overvoltage and contributes to the transition to more serious damage—phase-to-phase short circuit, followed by immediate disconnection of the damaged line, shutdown of the technological process and an increase in economic losses [17–19].

The fulfillment of the requirements for a safe and reliable operation of the power supply system [20,21] directly depends on the state of the insulation of electrical installations. Timely detection of damage in 6–35 kV distribution networks and selective disconnection (selective protection) of damaged connections allow us not only to prevent the transition of SPGF to phase-to-phase short circuit, but also to significantly reduce the likelihood of electrical injuries to personnel.

The problem of organizing a reliable, selective and sensitive protection is associated with the transient processes complexity of unstable arc faults [22] in the following cases: (1) initial phase of damage; (2) interruption of the single-phase fault current in the process of its development; and (3) the isolated neutral mode of 6–35 kV networks [23–25]. In addition, as noted earlier, the calculation of the current setpoints of the directional and non-directional ground fault protections of 6–35 kV networks considers the mode of stable metal ground fault, where in most cases single-phase GF occurs through a resistance [26,27].

Figure 2 shows the characteristics of the change in phase voltages with incomplete SPGF. The analysis of the above characteristics allows us to conclude that the presence of a resistance at the location of the SPGF is the reason for the decrease in the operating signals necessary for the stable operation of the RPA device. From Figure 2 it can be seen that up to 0.22 s, the emergency mode is reflecting a stable voltage behavior during the SPGF. After the 0.22 s, the non-cleared damage switched to ASPGF mode resulting in an overvoltage up to 2.15–2.18 U_{ph} and subsequently in a disconnection of electrical installations. It should be noted that during arc SPGF mode in a network with isolated neutral, overvoltage at the undamaged phases can reach values of 3.1 to 3.4 U_{ph}, and in some unfavorable cases even higher values.

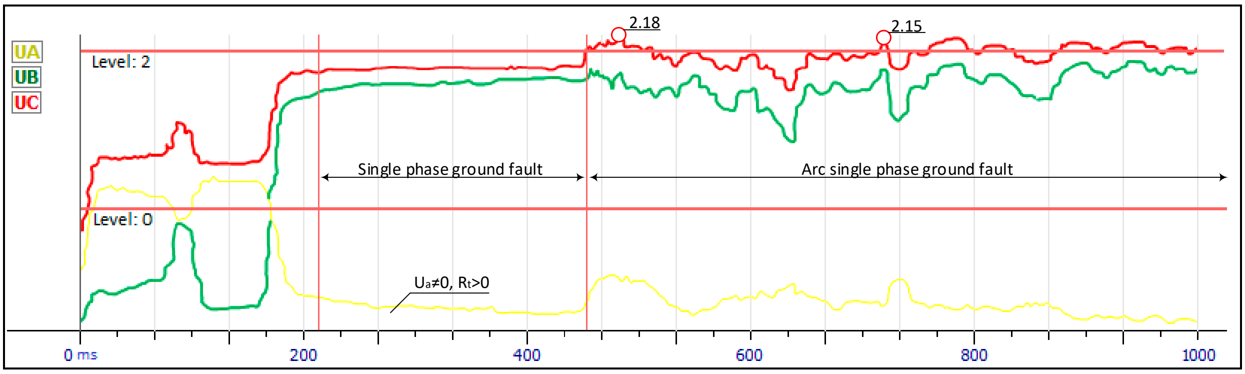


Figure 2. Dependences reflecting the nature of the change in time of voltage values of damaged phase (U_a), intact phases (U_b, U_c), at SPGF through the transient resistance (R_p).

3. Materials and Methods

The sensitivity analysis of the SPGF protection was performed on the section of 6 kV distribution network of the JSC "Polosukhinskaya Mine", and its one-line diagram is shown in Figure 3. The section of distribution network contains (Figure 3): a power transformer: TDTN-40000/115/38.5/6.6; six outgoing cable lines feeding: a central step-down substation (CSS); two and four sections of a closed switchgear (CS-6) and a packaged switchgear (CSW-2-10); a distribution substation (DS-6) and mechanical workshop for the mining installations repair (MW).

The experiment was carried out on the outgoing connection No. 6 by connecting a set of resistances to the neutral through a magnetic starter. Non-directional current protections are used as single-phase GF protections in the section under consideration. Its operating signal is the zero-sequence current $3I_0$, as well as non-selective protection of the zero-sequence voltage $3U_0$.

The characteristics of the load graph are presented in Table 1.

Table 1. Parameters of cable lines of the 6 kV distribution network of JSC "Polosukhinskaya Mine".

Cable Line	Cable Cross Section S_{cl}, mm^2	Cable Length l_i, km	Capacity C_i, µF/km	Resistance R, ohm/km	Inductance L, mH/km
1	120	6	0.418	0.196	0.268
2	120	3.217	0.418	0.196	0.268
3	50	0.056	0.292	0.494	0.313
4	95	0.163	0.380	0.247	0.278
5	120	7.755	0.418	0.196	0.268
6	50	0.07	0.292	0.494	0.313

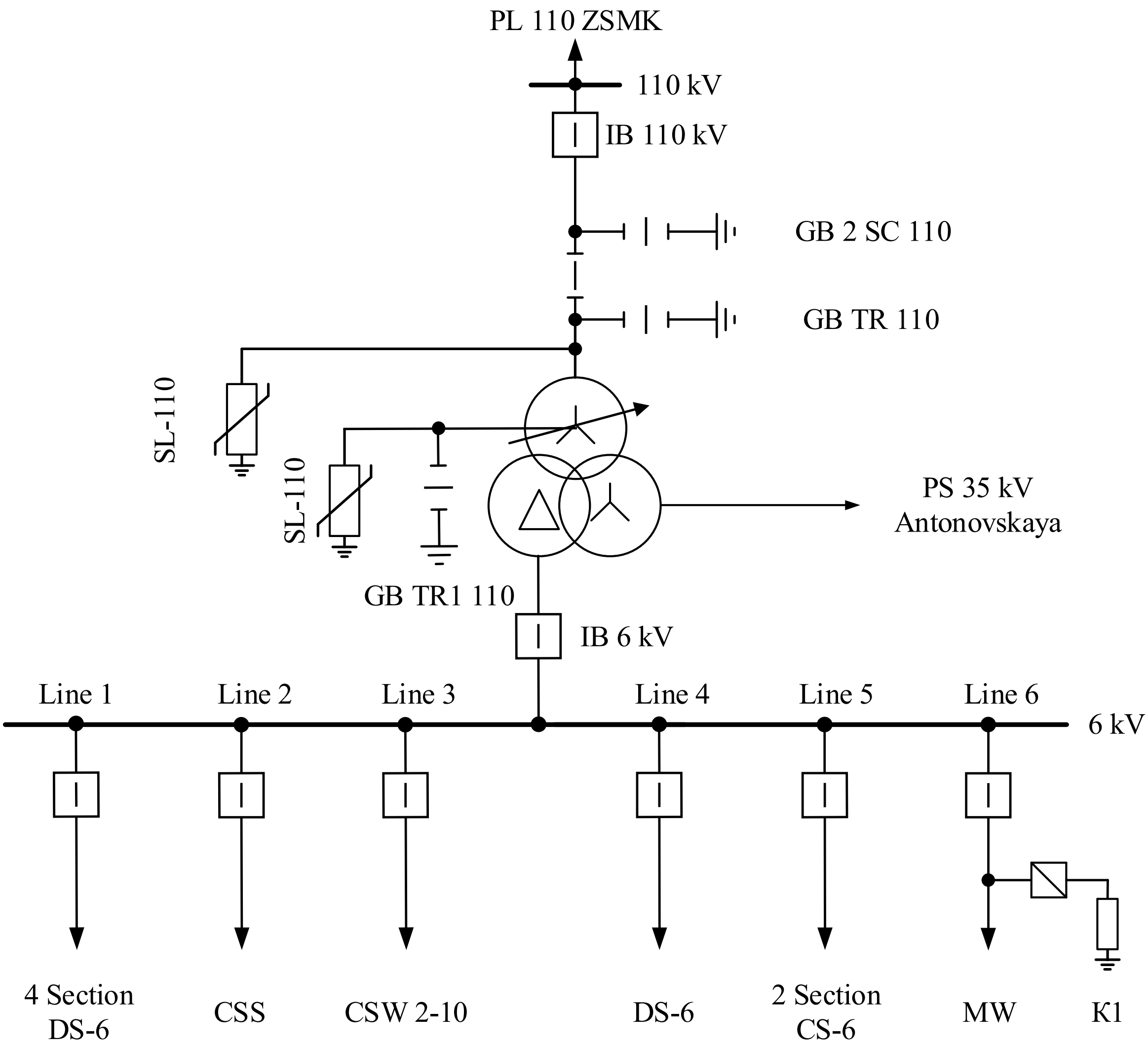


Figure 3. One-line power supply diagram of the step-down substation of the mining enterprise JSC "Polosukhinskaya Mine".

To perform a sensitivity analysis for the action of current protection against SPGFs used on the outgoing cable lines of the 6 kV distribution network, it is necessary to estimate the value of the current passing at the fault location, which in turn is determined by the Expression (1):

$$I_f = \beta \cdot I_{C_\Sigma} \cdot \sqrt{{d_n}^2 + 1} \tag{1}$$

where d_n is the factor of relative conductivity of neutral grounding system; $I_{c\Sigma}$ is the ground fault current, taking into account the value of all intact galvanically connected lines, with its value determined by the Expression (2):

$$I_{C_\Sigma} = \sum_{1}^{i} I_{cci} \tag{2}$$

where I_{cci} is the intrinsic capacitive current of the line [28] equal to (3):

$$I_{cci} = 0.6 \cdot l_i \cdot \sqrt{\frac{S_{cli.}}{50}} \tag{3}$$

where S_{cli}. is the cross-sectional area of the i-th outgoing cable line, mm^2; l_i is the length of the i-th cable line with a voltage of 6 kV, km.

In the incomplete SPGF mode, the current will decrease proportionally to the decrease in the protection sensitivity factor, taking into account the effect of resistance at the fault location on the current of the SPGF—β [29]. Based on [30,31], its value is determined by the following Equation (4):

$$\beta = \frac{1}{\sqrt{\left(\frac{C_\Sigma}{g_f} + \frac{d_n \cdot C_\Sigma}{g_f} + 1\right)^2 + \left(\frac{C_\Sigma}{g_f}\right)^2}} \tag{4}$$

where C_Σ (in μF) is the capacitance of the phases of galvanically connected network lines relative to the ground; g_f is the active conductivity at the point of fault. The value of ground fault completeness factor is in the range $0 \leq \beta \leq 1$, where 0 corresponds to an infinitely large resistance at the fault location, and 1 corresponds to the mode of metallic phase fault to ground.

The method of calculating the values of cable line intrinsic capacitive current was chosen based on previous studies of the accuracy of existing methods for calculating the SPGF current at the coal mining enterprise of the JSC "Polosukhinskaya Mine". The calculation is done by taking into account the length and cross-section of the laid lines (underground cables) [32].

The choice of the operation set point of the RPA from the SPGF I_{set} must be based on the following Condition (5):

$$I_f \geq I_{set} \geq I_{cci} \cdot K_{pd} \tag{5}$$

where $K_{pd} = K_r \cdot K_{cc}$ is the protection detuning factor [33], which includes K_r = 1.2–1.3, the reliability factor, taking into account the relay and calculation errors of I_{cci};

K_{cc} = 1.5–1.8 is the capacitive current kick factor [34], which takes into account the inrush capacitive current at the moment of fault occurrence, as well as the response of the SPGF protection devices.

By considering the given boundary values of K_r and K_{cc}, the values of the detuning factor will be K_{pd_min} = 1.8 and K_{pd_max} = 2.34, respectively.

The value of the sensitivity factor of K_s determines the operability of the SPGF protection [35] and is calculated by Equation (6):

$$K_s = \frac{1 - m}{K_{pd} \cdot m} \geq 1.25 \tag{6}$$

where m is a fractional participation factor of the line's own capacitive current in the total current of SPGF, equal to (7):

$$m = \frac{I_{cci}}{I_{C_\Sigma}} \tag{7}$$

On the basis of Expression (7) and the values given in Table 1, the dependences of the K_s on the value of fractional participation factor for one of the outgoing cable lines from the 6 kV busbar section (Figure 3) were determined, and shown in Figure 4.

It follows from Figure 4 that the SPGF protection will be stable when part of the damaged line current in the total current of GF will not be more than 25.4% and 30.7%, having the factors of detuning K_{pd_max} = 2.34 and K_{pd_min} = 1.8, respectively. This circumstance imposes certain restrictions on the operating conditions of the non-directional protections reacting to the zero-sequence current in distribution networks with a significant level of inhomogeneity of transverse parameters relative to the ground.

Taking into account the above expressions, the formula for determining the K_s single-phase GF protection, using the parameters considered above, will take the following form (8):

$$K_s = \frac{I_{C_\Sigma} \cdot \sqrt{{d_n}^2 + 1}}{K_{pd} \cdot I_{cci} \cdot \sqrt{\left(\frac{C_\Sigma}{g_f} + \frac{d_n \cdot C_\Sigma}{g_f} + 1\right)^2 + \left(\frac{C_\Sigma}{g_f}\right)^2}} \geq 1.25 \quad (8)$$

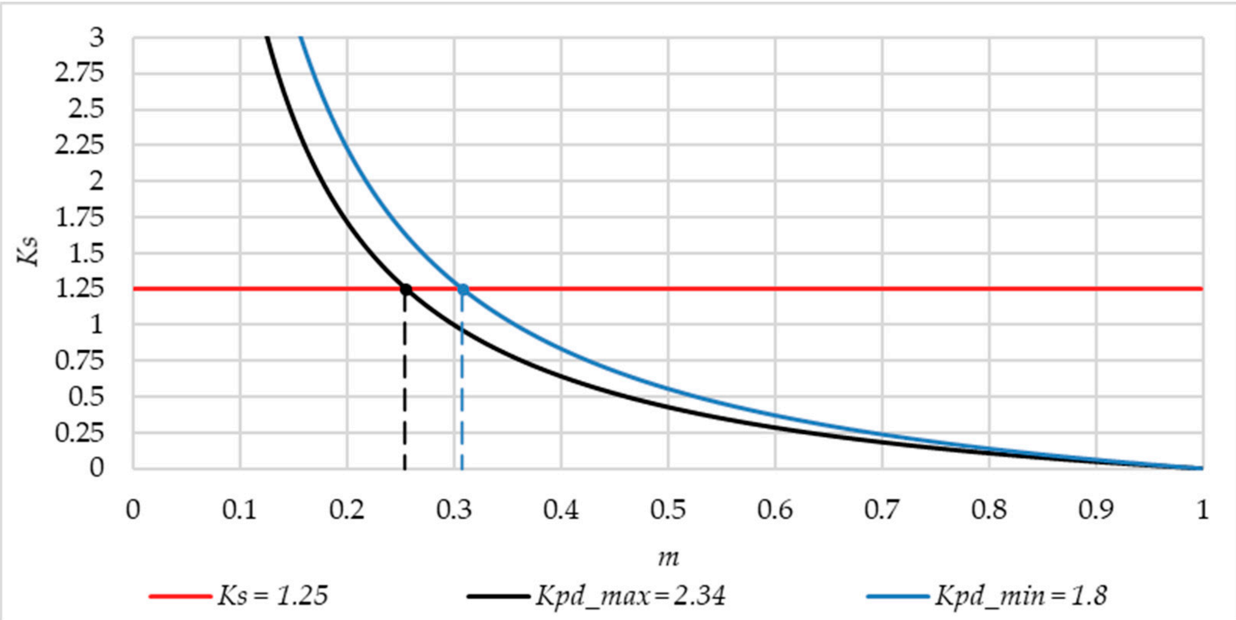


Figure 4. Experimental setup for creating a single-phase ground fault through a transient resistance on a section of a 6 kV distribution network of JSC "Polosukhinskaya Mine".

The factor of relative conductivity of the neutral grounding system d_n allows us to investigate the effect of changing the neutral grounding mode, from isolated to resistive-grounded, on the sensitivity of the SPGF protection. This is done by taking into account the selection of the resistor's active current in the neutral with respect to the total capacitive current of the network. So, for example, with an isolated neutral of the network, the value of the d_n factor will be 0, but when a resistor is switched on in the neutral, the relative conductivity can range from 2 to 4 d_n [36,37].

To assess the effect of the phase-to-ground fault completeness factor on the sensitivity of protection, an experimental study of a single-phase short circuit was carried out on a section of the 6 kV distribution network of the mining enterprise JSC "Polosukhinskaya Mine"; the experimental installation is shown in Figure 5.

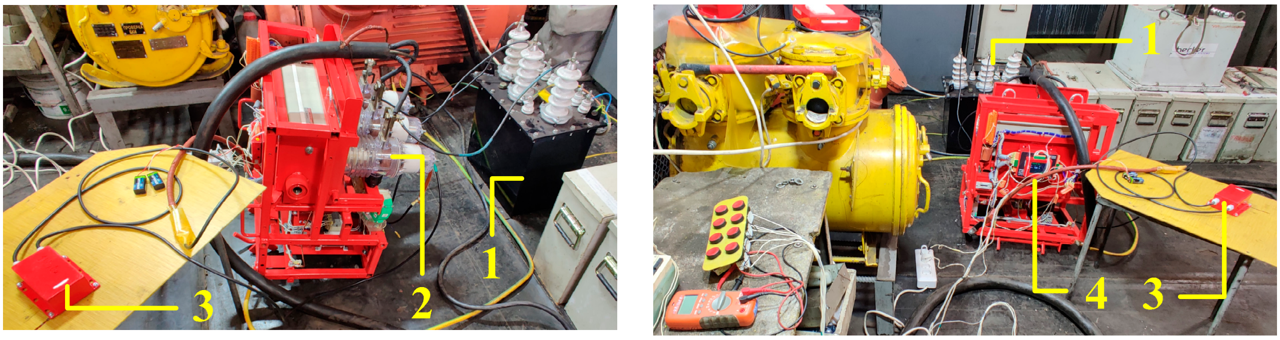


Figure 5. Experimental setup for creating a single-phase ground fault through a transient resistance on a section of a 6 kV distribution network of JSC "Polosukhinskaya Mine".

The experimental setup contains: (1) measuring voltage transformer NTMI-6, used to remove the voltage of the zero-sequence $3U_0$; (2) switch line No. 6; (3) a set of resistances; (4) calibrated microcontroller "HV" manufactured by LLC "Service Coal Company", providing measurement of the zero-sequence current $3I_0$ in the ranges of 0–5000 mA with an accuracy of 2%; RIGOL DS1052E digital oscilloscope (Figure 6), recording the value of the zero-sequence voltage; and the remote control of the cable line switch.

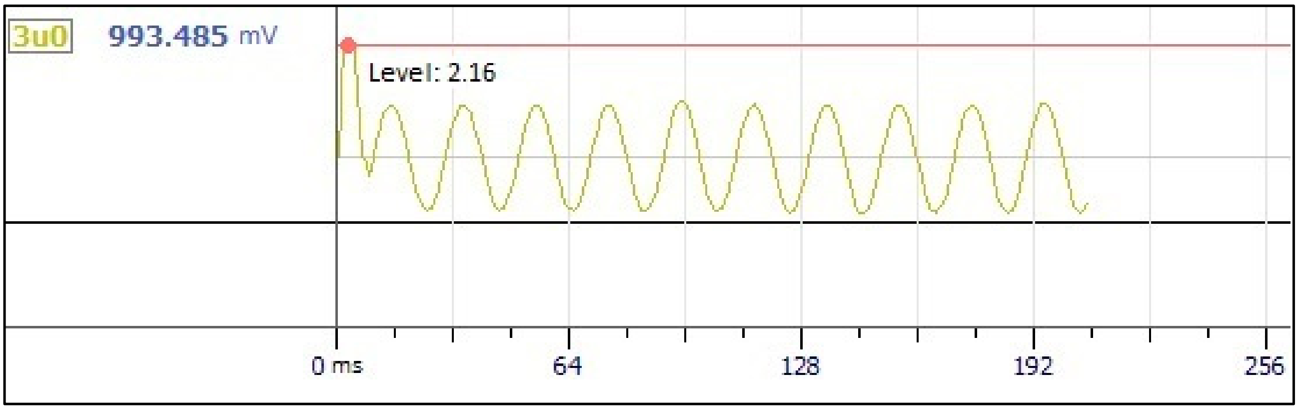


Figure 6. Oscillogram of the zero-sequence voltage of a single-phase ground fault through a 5 kOhm transient resistance, recorded during the ground fault experiment.

The experiment was carried out on the outgoing line No. 6 (see Figure 3) according to the following algorithm:

1. Measurement of the current and voltage of the zero-sequence in the metal SPGF mode has been performed;
2. In parallel to the load at point K1, resistances of various sizes ranging from 0 kOhm to 100 kOhm were connected in order to simulate the incomplete SPGF mode with different ground fault completeness factors;
3. The values of the voltage and current of the zero-sequence circuit were recorded in the incomplete SPGF mode;
4. On the basis of the experimental zero-sequence parameter values, the protection sensitivity factor was calculated in the incomplete SPGF mode with a different ground fault completeness factor.

During the research study, seven experiments were conducted, and the results are presented in Table 2.

Table 2. The results of the experiment of single-phase ground fault through transient resistance on the site of the distribution network of JSC "Polosukhinskaya Mine".

Experiment	Resistance R_i, Ω	Factor ß	Zero-Sequence Current $3I_0$, mA	Zero-Sequence Voltage $3U_0$, V
1	0	1	15,121	5700
2	2500	0.232	1100	924
3	5000	0.128	185	475
4	10,000	0.067	173	254
5	25,000	0.028	147	142
6	50,000	0.014	77	46.2

Figure 6 shows the oscillogram of the zero-sequence voltage with an incomplete single-phase GF, with a resistive value of 5 kOhms at the fault location. Taking into account the transformation factors of the RIGOL DS1052E digital oscilloscope and the NTMI-6 measuring transformer, the effective value of the voltage 3U0 in Figure 6 was 475 V.

Having analyzed the results of the experimental study presented in Figure 7, it can be noted that with a decrease in the value of the GF's completeness factor in the mode of incomplete single-phase GF and, taking into account a sensitivity factor of 1.25, the applied current's SPGF protection is able to detect the presence of an emergency mode on the protected connection with a resistance at the point of damage of no more than 3.2 kOhm and 4.5 kOhm, with the values of K_{pd_max} = 2.34 and K_{pd_min} = 1.8, respectively.

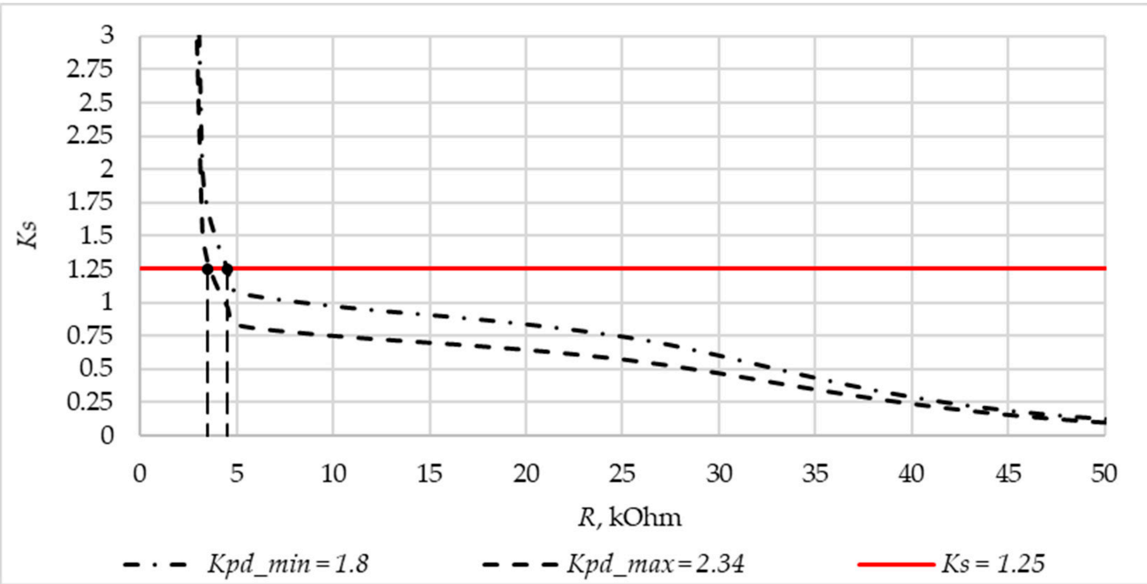


Figure 7. Experimental setup for creating a single-phase ground fault through a transient resistance on a section of a 6 kV distribution network of JSC "Polosukhinskaya Mine".

The value of the sensitivity factor K_s is also determined by the level of capacitive current of the network section connected to one transformer. During the experimental studies, the capacitance of the 6 kV distribution network section of the JSC "Polosukhinskaya Mine" was constant and came up to 7.2 µF. Due to the peculiarity of technological processes at mining enterprises, the electrical capacitance of galvanically connected lines is unstable and can range from 0.05 to 5 µF. Having this in mind, and by using the Expression (8), the sensitivity coefficient K_s of protection against single-phase short circuits, were plotted against the change in: (1) the transient resistance value at the fault location and (2) the total capacitance of galvanically connected cable lines. The plots are shown in Figure 8.

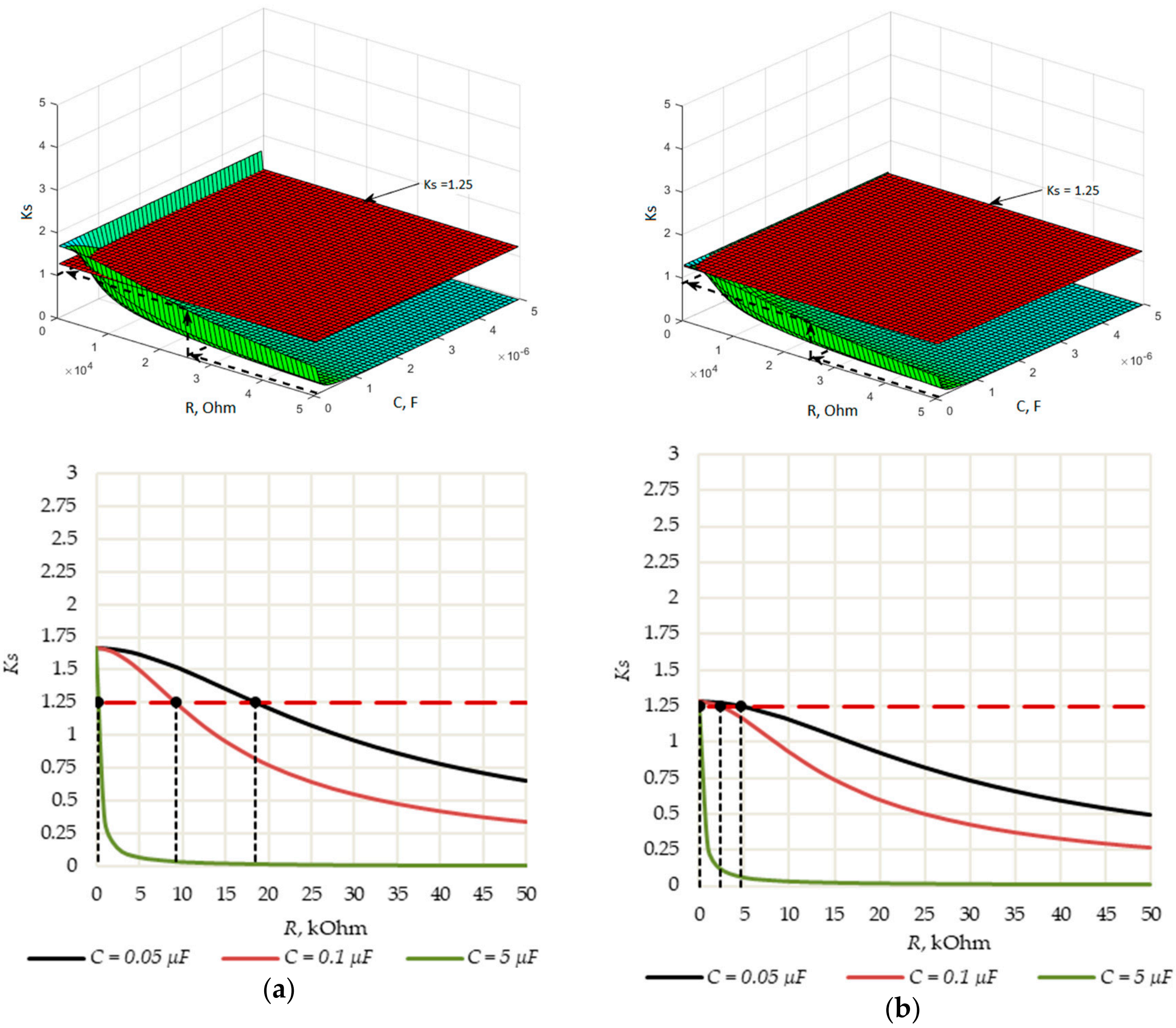


Figure 8. Dependences of the sensitivity factor of SPGF protection on the transient resistance at the point of SPGF and the total capacity of the 6 kV power supply section network of JSC "Polosukhinskaya Mine": (**a**) K_{pd_min} = 1.8, (**b**) K_{pd_max} = 2.34.

The obtained results allow us to determine the boundary conditions of the resistance at the ground fault location and the total capacitance of the network with respect to the ground. With such conditions the requirements for the sensitivity of protection against ground faults are met. (The results were obtained at K_{pd_min} = 1.8 and K_{pd_max} = 2.34). It is established that in the ground fault mode through transient resistance, at the 6 kV power supply site of the JSC "Polosukhinskaya Mine", the protection will satisfy the sensitivity condition in the following transient resistance ranges: 0–18 kOhm, 0–4 kOhm and network capacity ranges: 0.95–0.05 μF, 0.25–0.05 μF (Figure 8).

Analysis of the experimental data obtained has shown that one of the primary problems of low selectivity and sensitivity of protection is the variability of the zero-sequence current and voltage values. Based on this, one of the priority tasks aimed at ensuring the safety and reliability of medium-voltage power supply systems is the development of measures that will allow establishing an effective single-phase GF protection, which has the necessary selectivity and sensitivity of action in conditions of incomplete SPGF, taking into account the variation of zero-sequence parameters.

4. Discussion

With an increase in the length and branching of the 6–35 kV voltage networks, the value of the capacitive current increases. During operation, the dielectric parameters of the insulation of cable lines deteriorate and their wear increases, but at the same time, the level of redundancy of the power supply of busbars of substations increases, which leads to minor interruptions in the power supply of consumers when the damaged sections are disconnected. Therefore, it is currently advisable to ground the grid through a resistor instead of systems with isolated neutral [38–40]; see Figure 9.

Figure 9. Appearance of neutral grounding equipment.

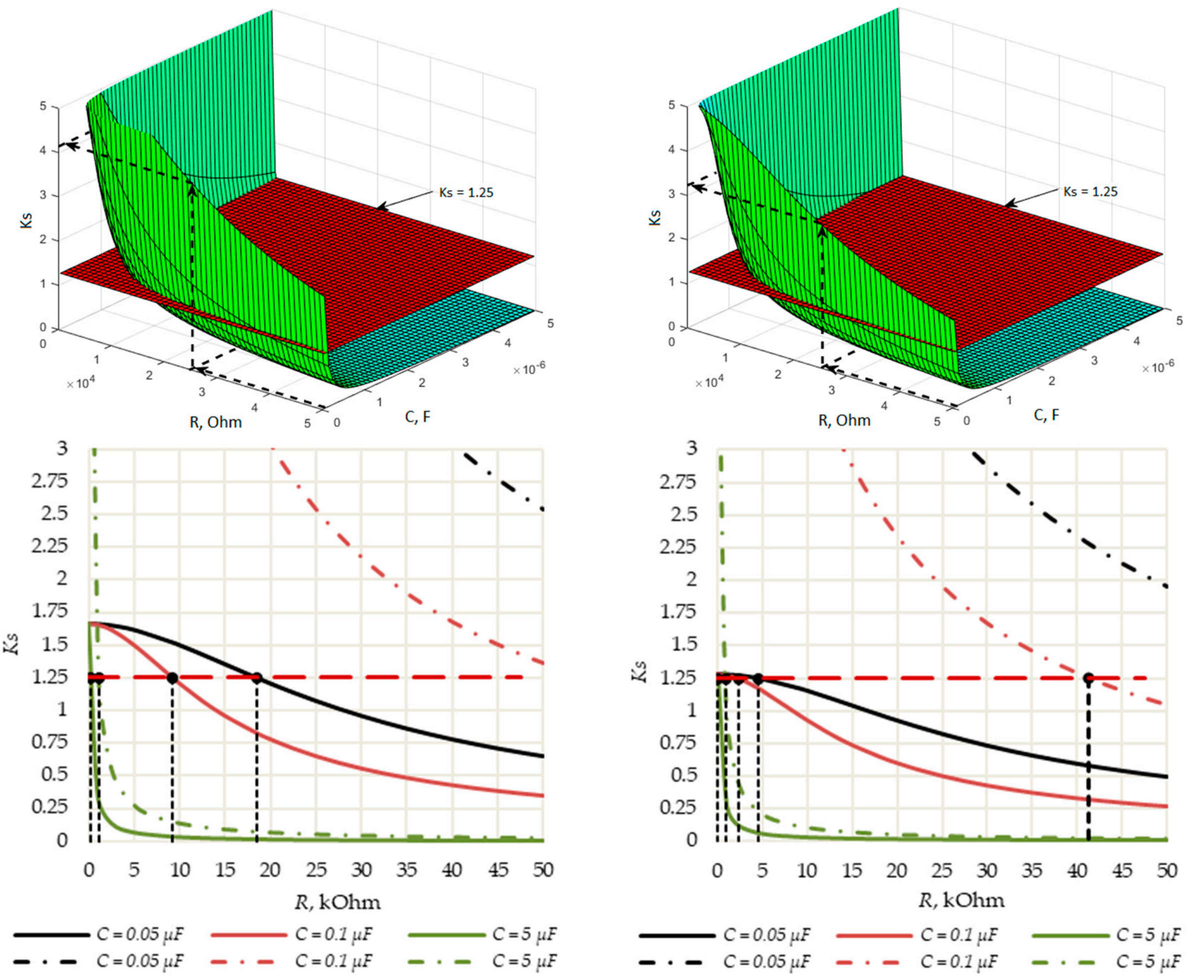
The main feature of networks grounded through a resistor is the reduction of overvoltage and the creation of conditions for high-speed and selective elimination of the SPGF mode. In turn, this ensures a reduction in electrical injuries of the service personnel.

The neutral grounding resistor is connected either to the neutral of the power transformer, to the winding connected in a triangle, or to a special neutral output transformer with a star-triangle winding connection [41,42]. In the normal grid operation, the voltage value in the neutral of the transformer with respect to the ground is almost zero, and no current flows through the active resistance connected to the neutral.

In case of a ground fault, capacitive currents appear in all outgoing connections, which is determined by the length and cross-section of the cable line. In the damaged section there is a total capacitive current flowing to the phase-to-ground fault location, and an active current appearing due to the inclusion of a grounding resistor in the zero-sequence circuit. This method provides the most effective identification of the SPGF location, increases the speed of RPA systems, simplifies the execution of RPA algorithms, reduces the probability of arcing, and improves the electrical safety of operational personnel, as well as the safety of people and animals who accidentally find themselves at the fault site. Unlike grounding through an arc-extinguishing reactor, this method requires relatively less capital investment.

In the course of an experimental study of the mode of single-phase ground fault under conditions of transient resistance in the distribution network section of the JSC "Polosukhinskaya Mine", it was found that with an increase in the resistance value at the point of fault, the sensitivity factor becomes lower than 1.25, which is unacceptable in distribution networks and can lead to protection failure. Since the aim is in providing selectively sensitive protection against ground faults under the conditions of variation of the electrical network's parameters in order to minimize the influence of the SPGF mode on the elements of power supply system, a transition from an isolated neutral to grounding the neutral through a resistor is necessary.

Figure 10 shows the result of the proposed measures implementation into the 6 kV power supply system section, the relative conductivity factor d_n was selected based on the conditions for ensuring the selectivity of protection and chosen to be d_n = 4.



(**a**) (**b**)

Figure 10. Dependence of the sensitivity factor of single-phase ground fault protection on the transient resistance at the site of SPGF and the total capacity of the 6 kV power supply section network of JSC "Polosukhinskaya Mine" with the factor of relative conductivity of neutral grounding d_n = 4 (**a**) K_{pd_min} = 1.8, (**b**) K_{pd_max} = 2.34.

Analytical studies of the results show that the operability of the applied ground fault protection is 0–36 kOhm and 5–0.05 μF and 0–27 kOhm and 4.05–0.05 μF at K_{pd_min} = 1.8 and K_{pd_max} = 2.34, respectively.

The introduction of a resistor into the neutral of the power system makes it possible to increase the sensitivity of the current non-directional protection by more than five times, during which it is possible to create reliable protection, both at low ground fault currents and at a significant transient resistance at the short circuit location.

5. Conclusions

During theoretical and experimental studies, it has been established that 30–35% of the total number of a timely unremoved SPGFs lead to phase-to-phase short circuits. This will increase the economic losses in the distribution networks of the MRC mining enterprises. Such losses are determined by the cost of repairing the failing equipment and the downtime technological process. At the same time, any SPGF can exist accompanied by overvoltage with a multiplicity of 3.1 to 3.4 U_{ph}. This increases cable lines insulation wear and aging.

This research was conducted in the distribution networks of the MRC mining enterprises. It was found that the increase in sensitivity of ground fault protection is determined by choosing the installation location of separation transformers on the out-going connections that have a greater share of the line's own capacitive current in the total capacitive ground fault current.

In order to increase the reliability and safety of operation of medium-voltage distribution networks of MRC mining enterprises, to ensure the stability and selectivity of the SPGF protection, a transition from isolated neutral grounding to neutral grounding through a resistor is necessary.

While performing the experimental study of the existing level of SPGF capacitive current in the JSC "Polosukhinskaya "Mine", it was found that its value is 16 A. To transfer the 6 kV distribution network of this mining enterprise to resistive neutral grounding, it is possible to recommend the installation of a 400 Ohm high-voltage resistor. A resistor of this magnitude will completely eliminate the possibility of high multiplicity overvoltage. It is optimal in terms of minimizing the current through the human body directly touching the phase of the network and creates a guaranteed active current in the damaged feeder, which will ensure the selectivity and reliability of the SPGF protection.

The information given in this article makes it possible to expand the scope of the available experience of experimental evaluation of the influence of the zero-sequence current circuit's parameters in the incomplete earth fault mode, on the effectiveness of the current protection from SPGF in the conditions of mining enterprises. Although performing field studies in the electrical networks of mining enterprises is a very dangerous and time-consuming event, it allows for a reliable assessment of the values of the zero sequence values and the features of their change during fault mode. Based on the results of the conducted research, mathematical and graphical patterns of changes in the operating signals of protections during incomplete SPGF mode have been established. This will form the prerequisites for an optimal solution for improving the safety of power supply mining enterprises.

The direction of further research may be the development of an algorithm for the action of SPGF protection during short circuits through transient resistances. It is necessary in order to ensure the immutability of the protection action in conditions of zero-sequence circuit non-constant parameters, as well as to consider the possibility of using current and directional protections taking into account the resistive grounding of the neutral.

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