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Special Issues of Ensuring Electrical Safety in Networks with Isolated Neutral Voltage up to 1000 V at Mining Enterprises

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Abstract

In the practice of operating mining machines and complexes, there are no effective ways to monitor the state of insulation and protect a person from electric shock in a network with voltages up to 1000 V. There is a risk of electric shock with a fatal outcome for personnel. Consequently, the issue of development of methods for monitoring the state of insulation and protection against electric shock in a network up to 1000 V for mining machines and complexes is relevant and urgent. The existing protection of a person from electric shock effectively works provided that the total insulation resistance is commensurate with the capacitive insulation resistance of the phases of the electrical network relative to the ground. But, at mining enterprises, a violation of ratio takes place between the total and capacitive insulation resistance of the network, which leads to failure of the protection against electric shock. Therefore, to ensure electrical safety criteria when operation of electrical installations in the network is up to 1000 V, it is necessary to consider the insulation condition and the technical capabilities of available protection against electric shock in a complex.

Keywords: current, voltage, neutral, insulation, network, resistance

1. Introduction

The implementation of modern technological processes in quarries, which are directly related to the growth of unit capacity of stripping and mining machines, is making increasingly stringent requirements to ensure the safety and security of the operation of electrical system [1, 2].

However, the increase in the length of electrical networks, which feed stripping and mining machines, increases the likelihood of single-phase ground fault, which, as a rule, is the main cause of the interruption of power supply. Relay protection and automation actions allow maintaining the continuity of power supply only if it is possible to control periodic insulation parameters mains phases with respect to ground.

Among the range of issues related to ensuring security of supply of electric power-electrified mining equipment and the safety of its operation, there is a

development of methodology for determining the insulation parameters, which occupies a special place, as the results of the method used are derived from the main provisions of organizational and technical measures that promote a culture of service of the internal power supply of mining enterprises. The importance of developing the method to determine the insulation value is also determined by the fact that it can be used in other industries where there is three-phase electrical network with isolated neutral with voltages up to and above 1000 V.

For experimental studies of the state of insulation of three-phase electrical networks with isolated neutral with voltages up to and above 1000 V, a number of methods were proposed [1–9], taking into account the inherent specific characteristics in the internal power supply of open-cast mining. For the insulation parameters measuring methods, a number of requirements are presented, namely:

1. Measurements should be carried out without interruption in the supply of electricity to consumers.
2. The process of measurement should not cause damage to the insulation of electrical networks and electrical accidents.
3. The measurements must be carried out using a small amount of electrical equipment and appliances.
4. Execution of determining the insulation parameters should be safe both for researchers and for personnel servicing electrical systems.
5. Measurements of baseline values should be sufficiently accurate and if possible have a short duration of works on measurement.
6. Accuracy of the method must not exceed 10%.

Based on the analysis of existing methods [1, 2], considering the aforementioned requirements for experimental research of insulation parameters of three-phase electrical networks with isolated neutral, it was concluded that the methods developed earlier are not fully met the essential requirements. Therefore, at present, in mines, previously proposed methods were not used as a primary means of prevention, ensuring uninterrupted power supply and operational safety of electrical installations.

In this regard, there are problems of further improvement of means of controlling insulation parameters of electrical networks in conjunction with the implementation of preventive measures and periodic measurements in different operating conditions. The method of determining the phase insulation parameters to earth of electrical networks must not affect the operation of the electricity system, and the calculation of insulation parameters must contain a minimum of computation.

In practice of operation of electrical networks with isolated neutral with voltage up to 1000 V and above, it is necessary to know the value of the insulation parameters by which the organizational and technical measures are developed to ensure the safety and security of the electricity supply of mining enterprises.

One of the most important issues in the mining industry is the problem of increasing the reliability of power supply systems and reduced level of electrical safety for electrical installations in mines. This condition is associated with physical

obsolescence of much of the equipment. Intensive increase in productivity mining leads to complication of the network configuration, which significantly affects the state of electrical networks, reducing the reliability of their operation. At the same time, there is an increase in the number of damages in electrical networks, which are the major causes of wear and the aging network isolation [9].

During coal mining, open-pit mining machines and equipment operate in harsh conditions, which are caused by the constant movement of the front of the mining operations, vibration, dust, and climate-meteorological conditions. This leads to the fact that during operation, the electrical insulation is subjected to a change in the electrical network, changing the properties of the electrical insulating materials. This fact affects the decrease of electrical resistance and electric strength [10].

The main factors of aging of the insulation are operating voltage, transient increase in the voltage at the external and internal overvoltages, oxidation processes caused by the ionization of air and leading to the development of a surface discharge, mechanical effects, bulk and surface contamination, heating, and humidification, influencing the quality of the voltage caused by the use of controlled semiconductor converters. Mining machines' component failure occurs due to changes in the nominal loads; data equipment failures may lead to production downtime [11].

The aforementioned factors intensify the process of reducing the insulation resistance phase of electrical network with respect to earth in coal extraction. Reduced insulation resistance phase electrical network with respect to earth increases the likelihood of the emergency operating modes of the operation of electrical installations, which may be a consequence of electric shocks to persons. With the exception of electric shock, it is necessary to ensure a high level of insulation in a network with an isolated neutral voltage up to 1000 V, through activities related to the systematic and effective control of the condition of insulation. This is one of the main areas to ensure electrical safety in the specific conditions in the development of coal deposits in an open way [12].

According to the "safety regulations for electrical installations," what is required is the mandatory application of the automatic control of insulation with the action off, with periodic measurements of insulation resistance phase of electrical network with respect to earth in electrical installations up to 1000 V [13, 14].

In the development of coal deposits, there is a growing number of electric shocks mainly due to the weak formulation of organizational and technical measures for inspection, repair, and the condition of insulation in electrical networks and electrical equipment. Timely determination of the degree of the deterioration of the insulation can prevent equipment failure [15]. It should be noted that the operational personnel rely on protection against current leakage, which in the operation of electrical networks and electrical equipment may be damaged or artificially out of operation.

Great contributions to the definition of criteria for electrical scientists have been made by the Moscow State Mining Academy, University of California, Georgia State University. One criterion for electrical safety in emergency operation is the limit value of the current flowing through the human body $I_h = 6.0$ mA, with the contact voltage $U_c = 20.0$ V with the duration of the current flowing through the human body $t > 1.0$ s, with the main frequency $f = 50$ Hz, a three-phase network with an isolated neutral voltage up to 1000 V [16].

In general, the analysis of research into condition of insulations and single-phase ground fault current showed that used residual current devices (RCDs) in underground coal mining and mining meet the criteria for electro security under normal

and emergency operating modes in a three-phase network with isolated neutral voltages up to 1000 V.

In excavator mining, the electrical network voltage up to 1000 V does not contain lines more than 10 m long, and therefore, the data network is similar to the networks of electric arc furnaces, which are called short. Studies on the condition of insulations in the development of coal deposits and mining open pits in short networks up to 1000 V on excavators are not sufficient to be produced. Installed residual current devices in short networks up to 1000 V excavators have not been studied in relation to the criteria for electric normal and emergency operating modes [17].

Studying the technical parameters of the residual current devices for compliance with electrical safety criteria of normal and emergency operating modes in the three-phase electrical short network with an isolated neutral voltage up to 1000 V is necessary to research the condition of insulation.

The practice of electrical networks up to 1000 V in the development of coal deposits in the enterprise shows a lack of insulation resistance measurement techniques, and if so, then the insulation resistance measurement is made, usually very irregularly with large errors. The most widely used method to measure is found by applying the insulation resistance of the measuring device Megger [1].

It should be noted that the results of the measurements of Megger providing “electric installation code” (EIC) [18] and “rules of technical operation of electrical installations” do not correspond to the real values of the insulation resistance of the network, since the measurements are made in the absence of a working line voltage and disconnected power consumers [19].

Using a Megger measure at low values of insulation resistance in the electrical network and disconnected power consumers allows damage to be established qualitatively. It follows that the use of Megger as a means to assess the conditions of electrical safety for electrical installations is insufficient, since it is impossible to determine the resistance, reactance, and impedance of phase insulation of electrical network with respect to earth under the working voltage [1].

According to the EIC, the rate on the insulation resistance shall not be less than -0.5 MOhm ohmic resistance in the individual circuit element and the electrical network appliance. It is not possible to assess the state of the insulation as a whole. Therefore, the norm EIC relative to -0.5 MW ohmic resistance cannot be accepted as a criterion for operational insulation monitoring conditions and, therefore, as a measure of electrical safety, since from the point of view of safety production work on electrical impedes an evaluation of the insulation and its components [18].

On the basis of the foregoing information, the main task of studying the state of electrical insulation in the development of coal deposits’ open method is to determine the main parameters of the insulation of the electrical networks up to 1000 V and to identify factors influencing the state of insulation in conditions of single and bucket wheel excavators and drilling rigs.

Mining companies are currently equipped with high-electrified mining machines that provide high productivity. These companies are heavy consumers of electricity. The power of the electrical installations in the modern excavators reaches 20 MW or more and can be compared with the power of a large industrial company. Indeed, in these companies, reliable and continuous power supply to the electrical receiver depends largely on the condition of the electrical equipment in operation, as well as the intensity of the electrical damage and electrical networks [20].

Frequent movement of flexible cables supplying mobile mining machines leads to mechanical deformation and damage. Thus, attendants are at risk of sustaining electric shocks as they work with cable, electrical equipment, and the metal structure. The number of electrical shocks in an electrical installation is in direct proportion to the frequency of damage to electrical equipment. In this way, more than 80% of electrical shocks are related to direct contact between a man and current-carrying parts, while 3–10% are related to contact between the enclosures of electrical equipment at the time of the existence of single phase-to-earth fault [21].

According to the mine works regulations, safety shutdown is obligatory at mining enterprises. Safety shutdown is fast-operating protection, which automatically switches off the electric equipment under 1000 V when the risk of electric shock is present [22]. This hazard can occur as a result of case-to-phase fault, reduction of phase-to-ground insulation resistance below a certain value, and live-line bare-hand touching [23]. In such cases, residual current devices provide rapid shutdown of the power section. The response time of modern residual current devices (RCDs) does not exceed the time of let-go current supply [24].

To a large extent, the reliability of the electric equipment and the safety of its services depend on the condition of the insulation of live parts of electric equipment [25]. Insulation damage is the major source of accidents and the cause of many electrical shocks with differing levels of severity, as well as fatalities. Insulation monitoring in electrical networks with insulated neutral under 1000 V at mining enterprises is carried out using automatic insulation monitoring devices, such as AIMD-380s, mining protection devices, such as MPD, devices to protect networks from leakage with automatic compensation of capacitive component of leakage current (e.g., PDAC-380), and insulation monitoring devices A-ISOMETER of IRDH575 (Bender) series as well as a number of others.

Automatic insulation monitoring devices are designed to protect people from electric shocks, continuously monitor insulation resistance, and cut off three-phase electric networks with isolated neutral of 50 Hz alternating current in the case of resistance reduction between their phases and earth up to dangerous level. Automatic compensation of the capacitive component of leakage current is used in leakage current protection devices like PDAC, unlike automatic insulation monitoring devices, such as AIMD [26].

On excavators of mining, enterprises use residual current devices such as AIMD, which are designed for mine electric networks, that is, for deep mining. Mine electric networks under 1000 V contain long-distance cable lines, where total admittance of insulation measures is much like capacity admittance of network insulation and active admittance of isolation is lower than total and capacity admittance of isolation. As such, in mine networks, the current in single phase-to-earth fault exceeds the current of the RCD set point. This provides people with effective protection from electric shocks. The effectiveness of RCD in mine electrical networks under 1000 V is shown in the work of professor Manoilov [27].

In the mining industry, it is not uncommon for people to receive electric shocks during maintenance work of excavators and drill-rings when extracting minerals. There are, as yet, no causal inferences of RCD ineffectiveness to protect people from electric shocks during operation of excavators and drill-rings. In order to improve the efficiency of residual current devices, research should be conducted on the condition of insulation in three-phase electric networks with isolated neutral under 1000 V on the excavator.

2. The method of determining the insulation parameters in three-phase electrical networks with isolated neutral with voltages up to and above 1000 V

2.1 Introduction

One of the factors of electric shock is the weakening of insulation condition of a three-phase electrical network with insulated neutral voltages up to and above 1000 V. In order to ensure the increase of efficiency of the power supply system, it is necessary to develop a method of determining the parameters of isolation under operating voltage. Under the effectiveness, we accept ensuring growth of electrical safety and reliability in the operation of electrical installations with voltage up to and above 1000 V. The known [1] method of determining the parameters of isolation, “Ammeter-voltmeter” is a classical method, as it provides a satisfactory accuracy of the unknown quantities, but it does not ensure work safety in electrical installations production works and reduces the reliability of power supply of industrial machinery and equipment. Reduction of electrical installations work reliability and level of electrical safety in the operation of three-phase power networks up to and above 1000 V determined that by using the method “Ammeter-voltmeter,” it is necessary to make the metal circuit of a mains phase to earth and measure the total current single-phase fault ground. Since during a metal closure of any phase to earth phase, voltage of the two other phases of the mains with respect to the ground reaches linear values and can thus lead to a short circuit in a multi-phase mains operated, which determines the reliability of power decrease in production machinery. A reduction in electrical safety determined by that in the metal closure of any phase of electrical network and ground, contact voltage, and step voltage will have the maximum value, and thereby provides maximum increase the probability electric shock to persons.

2.2 Method for determining the insulation parameters in an electrical network with insulated neutral

The method presented in the work [6] of determining the insulation parameters in three-phase electrical network with insulated neutral voltages above 1000 V, based on the measurement values of the modules of the line voltage, zero sequence voltage, and phase voltage with respect to ground when connected known active extra conduction between electrical network of the measured phase and ground, has a significant error. A significant error determined by that in determining the insulation parameters using the value of zero sequence voltage module, and thus, it is necessary to use a voltage transformer windings, allowing to allocate the residual voltage.

On the basis of the foregoing methods for determining the insulation parameters in three-phase mains with insulated neutral voltages up to and above 1000 V, which provides a satisfactory accuracy of the unknown quantities by eliminating the measurement of the modulus of the residual voltage, the operational safety of electrical installations, and the reliability of the electricity system, in connection excluding the measurements of the total current of the module for single-phase earth fault between a mains phase with respect to ground.

A method for determining the insulation parameters in three-phase balanced networks with voltage up to and above 1000 V, based on the measurement values of the modules of the line voltage, the phase voltages A and C relative to the ground after connecting additional active conductivity between the phase A and the mains ground was developed.

As a result of the measurement values of the modules of the line voltage and phase voltage C and A with respect to the ground, taking into account the magnitude of the additional active conductivity by mathematical formulas, the following are defined:

- the total conductance of network insulation

$$y = \frac{1.73U_l U_A}{U_C^2 - U_A^2} g_o, \quad (1)$$

- the active conductance of network insulation

$$g = \left(\frac{3U_l^2 (U_l^2 - 3U_A^2)}{(U_C^2 - U_A^2)^2} - 1 \right) 0.5g_o, \quad (2)$$

- capacitive conductance of network insulation

$$b = (y^2 - g^2)^{0.5}, \quad (3)$$

where U_l is the line voltage; U_A is the A phase voltage with respect to the ground; U_C is C the phase voltage with respect to the ground; and g_o is the additional active conductance.

The method developed in the implementation does not require the creation of a special measuring device, since the measuring devices, that is, voltmeters, available in the service manual. The PE-200 resistance is used as an active additional conductivity with $R = 1000$ Ohms, where by means of parallel and serial connection provides the required power dissipation. To switch, the active standby is used more conductivity cell load switch.

The developed method provides satisfactory accuracy and is simple and safe in its implementation in the three-phase electrical networks with isolated neutral voltages up to and above 1000 V.

2.3 Analysis of error of method determining the insulation parameters in an electrical network with isolated neutral

The obtained mathematical dependences for determining the total and active conductance of electrical network insulation provide easy and safe work of electrical installations with voltage up to and above 1000 V.

Error analysis of the developed method for determining the insulation parameters in symmetrical three-phase electrical networks with isolated neutral which is based on measurement of unit line voltage, phase voltage C and A relative to the earth, after the active connection of additional conduction between phase A and the electric network and earth is performed.

To improve the efficiency of the developed method for determining the parameters of isolation in a symmetrical three-phase network with isolated neutral, based on error analysis, for each specific network, additional active conductivity is selected, in order to ensure satisfactory accuracy of required quantities.

Random relative error in determining the total conductivity of insulation and its components in three-phase balanced networks with voltage up to and beyond 1000, based on the measurement values of the modules of the line voltage, phase voltage C and A with respect to the ground, after connecting the active additional

conduction between the phase and the electric network and earth, is determined according to (1), (2), and (3).

Random relative error in determining the total conductance of mains phase insulation relative to the ground is determined from the formula (1):

$$y = \frac{1.73U_l U_A}{U_C^2 - U_A^2} g_o,$$

where U_l , U_A , U_C , and g_o are values that define the total conductance of network insulation and obtained by direct measurement. The relative mean square error in determining the total conductance of mains phase insulation relative to the ground is determined from the expression [28, 29]:

$$\Delta y = \frac{1}{y} \left[\left(\frac{\partial y}{\partial U_A} \Delta U_A \right)^2 + \left(\frac{\partial y}{\partial U_C} \Delta U_C \right)^2 + \left(\frac{\partial y}{\partial U_l} \Delta U_l \right)^2 + \left(\frac{\partial y}{\partial g_o} \Delta g_o \right)^2 \right]^{0.5}, \quad (4)$$

where $\frac{\partial y}{\partial U_A}$, $\frac{\partial y}{\partial U_C}$, $\frac{\partial y}{\partial U_l}$, and $\frac{\partial y}{\partial g_o}$ are partial derivatives $y = f(U_l, U_A, U_C, g_o)$.

Here ΔU_l , ΔU_A , ΔU_C , and Δg_o are absolute errors of direct measurement values U_l , U_A , U_C , and g_o which are defined by the following expressions:

$$\begin{aligned} \Delta U_l &= U_l \times \Delta U_{l*}; \\ \Delta U_C &= U_C \times \Delta U_{C*}; \\ \Delta U_A &= U_A \times \Delta U_{A*}; \\ \Delta g_o &= g_o \times \Delta g_{o*}. \end{aligned} \quad (5)$$

To determine the errors of measuring devices, accept that $\Delta U_{l*} = \Delta U_{A*} = \Delta U_{C*} = \Delta U_*$, where: ΔU_* is the relative error of voltage measurement circuits and $\Delta g_{o*} = \Delta R_*$ is the relative error of the measuring instrument, which measures the resistance which is connected between the phase A electrical and ground. Determine the partial derivative functions $y = f(U_l, U_A, U_C, g_o)$ by the variables U_l , U_A , U_C , g_o :

$$\begin{aligned} \frac{\partial y}{\partial U_l} &= \frac{1.73U_A}{U_C^2 - U_A^2} g_o; \\ \frac{\partial y}{\partial U_A} &= \frac{1.73U_l(U_C^2 + U_A^2)}{(U_C^2 - U_A^2)^2} g_o; \\ \frac{\partial y}{\partial U_C} &= -\frac{3.46U_l U_A U_C}{(U_C^2 - U_A^2)^2} g_o; \\ \frac{\partial y}{\partial g_o} &= \frac{1.73U_l U_A}{U_C^2 - U_A^2}. \end{aligned} \quad (6)$$

Solving the Eq. (4), substituting the values of the partial derivatives of Eq. (6) and private values of absolute errors (5), at the same time, assuming that $\Delta U_* = \Delta R_* = \Delta$, we obtain:

$$\varepsilon_y = \frac{\Delta y}{\Delta} = \frac{1.73U_l U_A g_o}{U_C^2 - U_A^2} \left(2 + \frac{4U_C^4 + (U_C^2 + U_A^2)^2}{(U_C^2 - U_A^2)^2} \right)^{0.5}. \quad (7)$$

The obtained Eq. (7) is divided into the Eq. (1):

$$\varepsilon_y = \frac{\Delta y}{\Delta} = \left(2 + \frac{4U_C^4 + (U_C^2 + U_A^2)^2}{(U_C^2 - U_A^2)^2} \right)^{0,5} \quad (8)$$

The obtained Eq. (8) is expressed in relative units, and after the conversion, we obtain:

$$\varepsilon_y = \frac{\Delta y}{\Delta} = \left(2 + \frac{4 + (1 + U_*^2)^2}{(1 - U_*^2)^2} \right)^{0,5}, \quad (9)$$

where $U_* = \frac{U_A}{U_C}$.

Random error in determining the active conductance of mains phase insulation relative to the ground is determined from the formula (2):

$$g = \left(\frac{3U_l^2(U_l^2 - 3U_A^2)}{(U_C^2 - U_A^2)^2} - 1 \right) 0.5g_o,$$

where U_l , U_A , U_C , and g_o are values that define the active conductance of network isolation and obtained by direct measurement.

Relative mean square error of the method when determining the active conductivity of phase insulation of electrical network relative to the ground is determined from the expression:

$$\Delta g = \frac{1}{g} \left[\left(\frac{\partial g}{\partial U_A} \Delta U_A \right)^2 + \left(\frac{\partial g}{\partial U_C} \Delta U_C \right)^2 + \left(\frac{\partial g}{\partial U_l} \Delta U_l \right)^2 + \left(\frac{\partial g}{\partial g_o} \Delta g_o \right)^2 \right]^{0.5}, \quad (10)$$

where $\frac{\partial g}{\partial U_A}$, $\frac{\partial g}{\partial U_C}$, $\frac{\partial g}{\partial U_l}$, and $\frac{\partial g}{\partial g_o}$ are partial derivatives, $g = f(U_l, U_A, U_C, g_o)$.

Here ΔU_l , ΔU_A , ΔU_C , and Δg_o are absolute errors of direct measurement values U_l , U_A , U_C , and g_o , which are defined by the following expressions:

$$\begin{aligned} \Delta U_l &= U_l \cdot \Delta U_{l*}; \\ \Delta U_C &= U_C \cdot \Delta U_{C*}; \\ \Delta U_A &= U_A \cdot \Delta U_{A*}; \\ \Delta g_o &= g_o \cdot \Delta g_{o*}. \end{aligned} \quad (11)$$

To determine the accuracy of measuring devices, accept that $\Delta U_{l*} = \Delta U_{A*} = \Delta U_{C*} = \Delta U_*$, where ΔU_* is the relative error of voltage measurement circuits and $\Delta g_{o*} = \Delta R_*$ is the relative error of a measuring instrument that measures resistance which is connected between the phase A electrical and the ground.

Determine the partial derivatives $g = f(U_l, U_A, U_C, g_o)$ by the variables U_l , U_A , U_C , and g_o :

$$\begin{aligned} \frac{\partial g}{\partial U_l} &= \frac{3U_l(2U_l^2 - 3U_A^2)}{2(U_C^2 - U_A^2)^2} g_o; \\ \frac{\partial g}{\partial U_A} &= -\frac{3U_l^2 U_A (3U_C^2 + 3U_A^2 - 2U_l^2)}{(U_C^2 - U_A^2)^3} g_o; \\ \frac{\partial g}{\partial U_C} &= -\frac{6U_l^2 U_C (U_l^2 - 3U_A^2)}{(U_C^2 - U_A^2)^3} g_o; \\ \frac{\partial g}{\partial g_o} &= \frac{3U_l^2 (U_l^2 - 3U_A^2)}{2(U_C^2 - U_A^2)} - 0.5. \end{aligned} \quad (12)$$

Solve Eq. (10), substituting the values of the partial derivatives of Eq. (12) and the values of the partial absolute errors (11), at the same time, assuming that $\Delta U_* = \Delta R_* = \Delta$, we obtain:

$$\frac{\Delta g}{\Delta} = \frac{3g_o}{(U_C^2 - U_A^2)^3} \left(\frac{(U_C^2 - U_A^2)^2 [2U_l^4 (U_1^2 - 3U_A^2)^2 - (U_C^2 - U_A^2)^4] +}{+ U_l^4 \{ U_A^4 [3(U_C^2 - U_A^2) - 2U_l^2]^2 + U_C^4 (U_1^2 - 3U_A^2)^2 \}} \right)^{0.5} \quad (13)$$

Obtained Eq. (13) divided by Eq. (2):

$$\varepsilon_g = \frac{\Delta g}{\Delta} = \left(\frac{\frac{2U_l^4 (U_1^2 - 3U_A^2)^2 - (U_C^2 - U_A^2)^4}{[3U_l^2 (U_1^2 - 3U_A^2) - (U_C^2 - U_A^2)^2]^2} +}{+ \frac{U_l^4 \{ U_A^4 [3(U_C^2 - U_A^2) - 2U_l^2]^2 + U_C^4 (U_1^2 - 3U_A^2)^2 \}}{(U_C^2 - U_A^2)^2 [3U_l^2 (U_1^2 - 3U_A^2) - (U_C^2 - U_A^2)^2]^2}} \right)^{0.5} \quad (14)$$

In the resulting Eq. (14), the value of the line voltage is expressed in terms of the phase voltages in accordance with the fact that $U_1 = 1.73U_\phi$:

$$\varepsilon_g = \frac{\Delta g}{\Delta} = 3 \left(\frac{\frac{18U_{ph}^4 (U_{ph}^2 - U_A^2)^2 - (U_C^2 - U_A^2)^4}{[27U_{ph}^2 (U_{ph}^2 - U_A^2) - (U_C^2 - U_A^2)^2]^2} +}{+ \frac{3U_{ph}^4 U_A^4 (U_C^2 - U_A^2 - 2U_{ph}^2)^2 + U_C^4 (U_{ph}^2 - U_A^2)^2}{(U_C^2 - U_A^2)^2 [27U_{ph}^2 (U_{ph}^2 - U_A^2) - (U_C^2 - U_A^2)^2]^2}} \right)^{0.5} \quad (15)$$

Simplifying the formula (15), we obtain the Eq. (16):

$$\varepsilon_g = \frac{3}{27U_{ph}^2 (U_{ph}^2 - U_A^2) - (U_C^2 - U_A^2)^2} \left(\frac{18U_{ph}^4 (U_{ph}^2 - U_A^2)^2 - (U_C^2 - U_A^2)^4 +}{+ \frac{3U_{ph}^4 U_A^4 (U_C^2 - U_A^2 - 2U_{ph}^2)^2}{(U_C^2 - U_A^2)^2} +}{+ \frac{U_C^4 (U_{ph}^2 - U_A^2)^2}{(U_C^2 - U_A^2)^2}} \right)^{0.5} \quad (16)$$

Obtained Eq. (16) is expressed in relative units and after the conversion, we obtain:

$$\varepsilon_g = \frac{\Delta g}{\Delta} = \frac{3}{27(1 - U_{A*}^2) - (U_{C*}^2 - U_{A*}^2)^2} \left(\frac{18(1 - U_{A*}^2)^2 - (U_{C*}^2 - U_{A*}^2)^4 +}{+ \frac{3U_{A*}^4 (U_{C*}^2 - U_{A*}^2 - 2)^2}{(U_{C*}^2 - U_{A*}^2)^2} +}{+ \frac{U_{C*}^4 (1 - U_{A*}^2)^2}{(U_{C*}^2 - U_{A*}^2)^2}} \right)^{0.5}, \quad (17)$$

where $U_{A*} = \frac{U_A}{U_{ph}}$ and $U_{C*} = \frac{U_C}{U_{ph}}$.

Relative mean square error method for determining the conductivity of the capacitive isolation mains phases relative to the ground is determined by the expression (3):

$$\Delta b = \frac{1}{b} \left[\left(\frac{\partial b}{\partial y} \Delta y \right)^2 + \left(\frac{\partial b}{\partial g} \Delta g \right)^2 \right]^{0.5}, \quad (18)$$

or

$$\varepsilon_b = \frac{\Delta b}{\Delta} = \frac{\left[(1 - \tan^2 \delta)^2 \left(\frac{\Delta y}{\Delta} \right)^2 + \left(\frac{\Delta g}{\Delta} \right)^2 \right]^{0.5}}{\tan^2 \delta}. \quad (19)$$

Solving Eq. (19) and substituting the values of mathematical descriptions of the relative rms dependences of total (8) and active (16) conductivities of electrical installations phase insulation relative to the ground phase, we get the following equation:

$$\varepsilon_b = \frac{\Delta b}{\Delta} = \frac{\left((1 - \tan^2 \delta)^2 \left[2 + \frac{4U_C^4 + (U_C^2 + U_A^2)^2}{(U_C^2 - U_A^2)^2} \right] + \frac{9}{[27U_{ph}^2 (U_{ph}^2 - U_A^2) - (U_C^2 - U_A^2)^2]^2} \times \left[18U_{ph}^2 (U_{ph}^2 - U_A^2)^2 - (U_C^2 - U_A^2)^4 + \frac{3U_{ph}^4 U_A^4 (U_C^2 - U_A^2 - 2U_{ph}^2)^2 + U_C^4 (U_{ph}^2 - U_A^2)^2}{(U_C^2 - U_A^2)^2} \right] \right)^{0.5}}{\tan^2 \delta}. \quad (20)$$

Obtained Eq. (21) is expressed in relative units and after the conversion, we obtain:

$$\varepsilon_b = \frac{\Delta b}{\Delta} = \frac{\left((1 - \tan^2 \delta)^2 \left[2 + \frac{4U_{C*}^4 + (U_{C*}^2 + U_{A*}^2)^2}{(U_{C*}^2 - U_{A*}^2)^2} \right] + \frac{9}{[27(1 - U_{A*}^2) - (U_{C*}^2 - U_{A*}^2)^2]^2} \times \left[18(1 - U_{A*}^2)^2 - (U_{C*}^2 - U_{A*}^2)^4 + \frac{3U_{A*}^4 (U_{C*}^2 - U_{A*}^2 - 2)^2 + U_{C*}^4 (1 - U_{A*}^2)^2}{(U_{C*}^2 - U_{A*}^2)^2} \right] \right)^{0.5}}{\tan^2 \delta}. \quad (21)$$

Based on the results of random relative mean square errors in determining the active, capacitive, and total conductivities of mains phase isolation relative to the ground, build the dependence:

$$\begin{aligned} \varepsilon_y &= \frac{\Delta y}{\Delta} = f(U_*); \\ \varepsilon_g &= \frac{\Delta g}{\Delta} = f(U_{A*}, U_{C*}); \\ \varepsilon_b &= \frac{\Delta b}{\Delta} = f(U_{A*}, U_{C*}, \tan \delta), \end{aligned}$$

shown in **Figures 1–3**. Mathematical dependence of the relative mean square errors of the total— ε_y , active— ε_g , and capacitive— ε_b conductivities of phase insulation of electrical network with insulated neutral on graphic illustrations

(**Figures 1–3**) characterize the change in error depending on the amount of additional active conduction g_o , which is inserted between the A-phase of electrical network and earth.

In determining the parameters of isolation in a symmetrical three-phase electrical network with isolated neutral on the basis of the method of analysis of error for each specific network, select additional active conduction, so as to ensure the satisfactory accuracy required.

In determining the total conductance of mains phases isolation relative to the ground is chosen such additional active conductivity, the values were within $U_* = 0.2–0.8$, at the same time as shown in **Figure 1**, the error does not exceed 5% when using measuring devices with accuracy class 1.0, and 2.5% when using measuring devices with accuracy class 0.5.

In determining the value of the active conductance in the three-phase electrical network with insulated neutral voltage up to 1000 V and above, select this additional g_o , so that $U_{A*} = 0.2–0.8$, when $U_{C*} = 1.1–1.6$, then on the basis of graphic illustrations of **Figure 2**, error does not exceed 3.5% when using measuring devices with accuracy class 1.0.

In determining the capacitive conductance mains phase isolation relative to the ground selection of additional active conductance g_o based on a graphic illustrations of **Figure 3** so that $U_{A*} = 0.2–0.8$, when $U_{C*} = 1.1–1.6$, when $\tan \delta = 1.0$, to provide error to 4% when using measuring devices with accuracy class 1.0.

It should be noted that when using measuring instruments with an accuracy class of 0.5, errors of ε_y —total, ε_g —active, ε_b —capacitive admittances of isolation is reduced by half, to provide more reliable data when determining the insulation parameters developed method.

According to the research undertaken by Professor L. Gladilin, a method was developed for determining the parameters of the insulation in networks with an isolated neutral voltage up to 1000 V (method ammeter-voltmeter) [1]. The disadvantage of the method ammeter-voltmeter is the production of single-phase ground

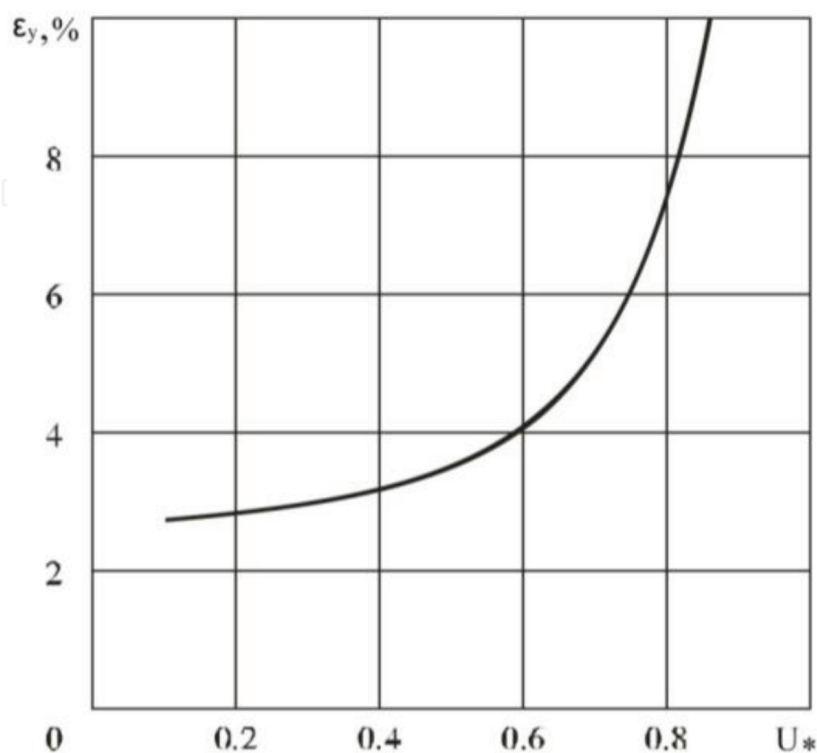


Figure 1.
Analysis of the error in determining the total conductance of the network insulation.

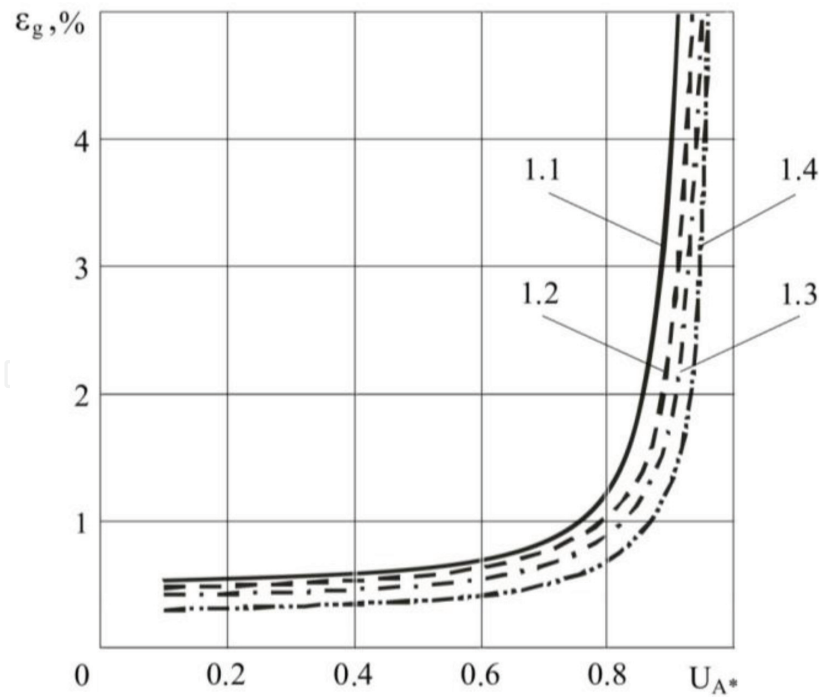


Figure 2.
Analysis of the error in determining the active conductance of the network insulation. $U_{C*} = 1.1; 1.2; 1.3; 1.4$.

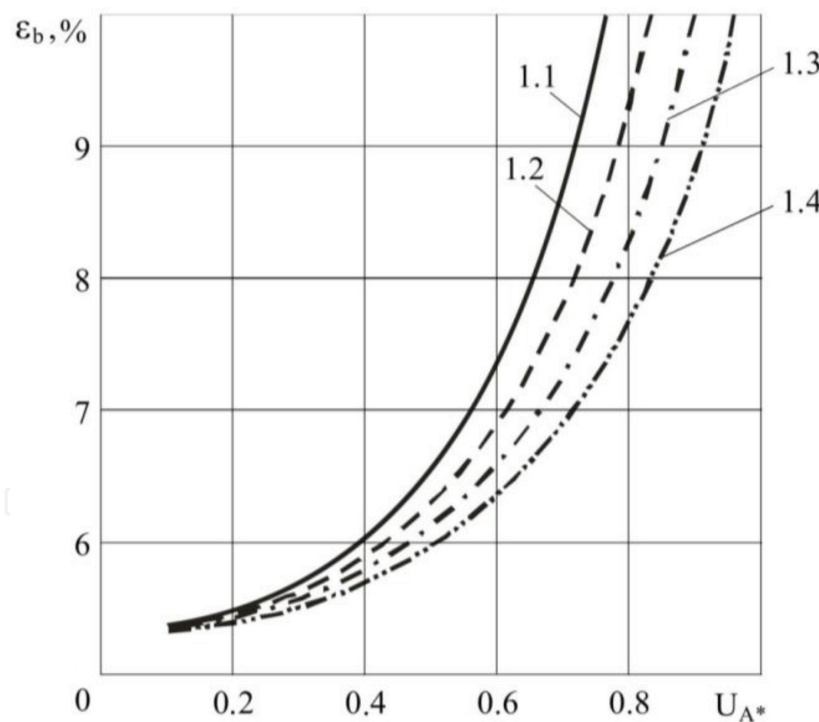


Figure 3.
Analysis of the error in determining the capacitive conductance of the network insulation when $\tan \delta = 1.0$.
 $U_{C*} = 1.1; 1.2; 1.3; 1.4$.

fault current measurement in the study of a three-phase power network with an isolated neutral. When measuring single-phase ground fault current in three-phase power network, the magnitude-phase voltage is equal to zero. The voltages of the other two phases achieve linear value, it can lead to a two- or three-phase short circuit, and it is emergency operating mode. This leads to a break in supply, as well as increased contact voltage, which is dangerous in the operation of mining machines and systems [1].

The developed method provides satisfactory accuracy when determining the parameters of isolation, as well as the ease and safety of production work in existing electrical installations voltages up to and above 1000 V.

3. Modeling method for measuring the admittance of insulation in a network with an isolated neutral voltage up to 1000 V in mines using Matlab/Simulink

3.1 Introduction

Note that the conductance characterizes the insulating properties of the dielectric, and the susceptance, respectively, characterizes the network capacity, that is, the number of connected electrical receivers and the length of overhead lines and cables. Admittance characterizes the single-phase ground fault current. Therefore, in practice, it is necessary to know the operation of the electrical conductance, susceptance, and admittance of phase of electrical network with respect to earth. This will allow choosing the right strategy to develop organizational and technical measures to increase the level of electrical networks up to 1000 V in the development of coal deposits [30].

Developed in [31], a phase-sensitive method for determining the parameters of insulation in a symmetric network with an isolated neutral voltage up to 1000 is based on the measurement of the modulus of the line voltage and phase voltage to earth after the connection between it and the earth an additional conductance and measuring the phase angle between the vector of the line voltage and vector of the phase voltage to earth. The above phase-sensitive method for determining the insulation contains significant disadvantages in using a special measuring device for measuring the phase angle between the voltage vectors.

3.2 Theoretical studies of the insulation on the basis of a circular chart

For simplicity of measurements, consider a method for measuring the admittance of insulation in a network with an isolated neutral voltage up to 1000 V [7]:

$$y = \frac{U_{pho}}{U_o} g_o, \quad (22)$$

where U_{pho} is phase voltage to earth after connecting additional conductance g_o ; g_o is additional conductance; and U_o is zero phase-sequence voltage.

To measure the admittance of insulation in a network in accordance with the formula (22), it is necessary to enter into the electrical network adjustable resistance between the phase of network and earth. Changing the value of resistance between the phase of network and earth will change the quantities of module phase voltage to earth and zero phase-sequence voltage. From Eq. (22) is obtained the conclusion that with equal admittance of insulation in a network and additional conductance, which is inserted between the phase of network and earth, measured values of the quantities of module phase voltage to earth and zero phase-sequence voltage will be equal:

$$y = g_o \text{ at } U_{pho} = U_o.$$

On the basis of the foregoing information, for measuring the admittance of insulation in a network with an isolated neutral, it is necessary to enter adjustable resistance to fulfill equality conditions between the values of the modules phase voltage to earth and zero phase-sequence voltage $U_{pho} = U_o$.

To determine the conductance network isolation by using the equal quantities of module phase voltage to earth and zero phase-sequence voltage $U_{pho} = U_o$, equation is

$$y = \frac{U_{ph}^2 - 2U_{pho}^2}{2U_{pho}^2} g_o. \tag{23}$$

Capacitive susceptance of isolation is found as a geometric difference between the admittance of insulation and conductance [7].

The method for determining the parameters of insulation in a network with an isolated neutral voltage above 1000 V describes circular chart changes in the modulus phase voltage to earth and zero phase-sequence voltage as shown in **Figure 4**. Changes in the modulus phase voltage to earth and zero phase-sequence voltage are produced in accordance with the circular chart of changes in the magnitude of the additional conductance.

Figure 4 shows the phase voltages U_{ph} of three phases A, B, and C, before connecting additional conductance to phase A; neutral-point displacement voltage U_o ; and phase voltage to earth after connecting additional conductance g_o to phase A— U_{pho} . Point O_2 corresponds to equal quantities of U_{pho} and U_{o2} .

Experimental studies of the circular chart have shown that changes of the modulus phase voltage to earth and zero phase-sequence voltage depends on the selection of the magnitude of the additional conductance. Hereby it is consistent with the fundamental provisions of the theoretical fundamentals of electrical engineering.

3.3 The method of measuring the admittance in a network with an isolated neutral voltage up to 1000 V

To ensure the equal quantities of phase voltage to earth and zero phase-sequence voltage with the connected additional conductance, an additional conductance

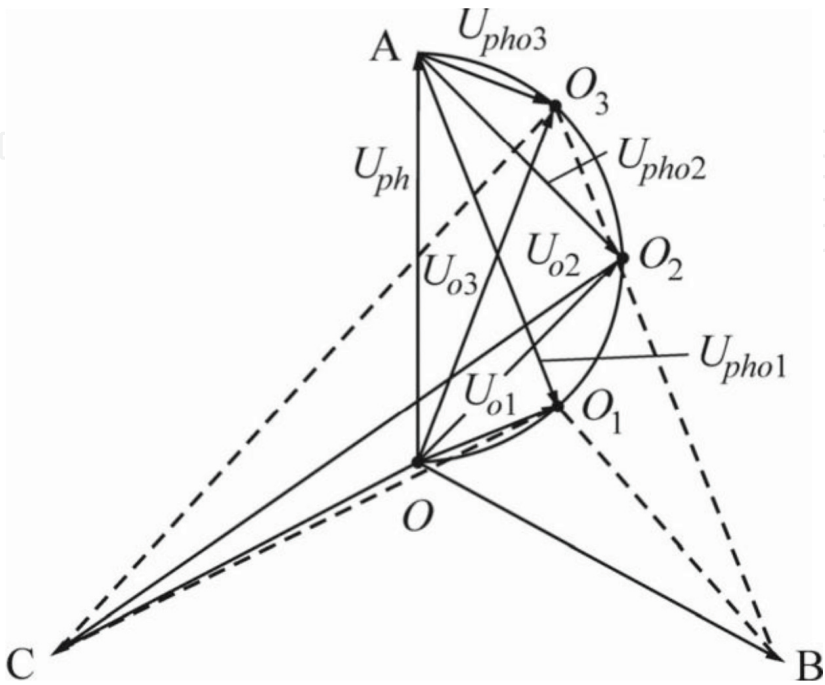


Figure 4.
A circular chart changes the modulus phase voltage to earth and zero phase-sequence voltage, depending on the size of the additional conductance.

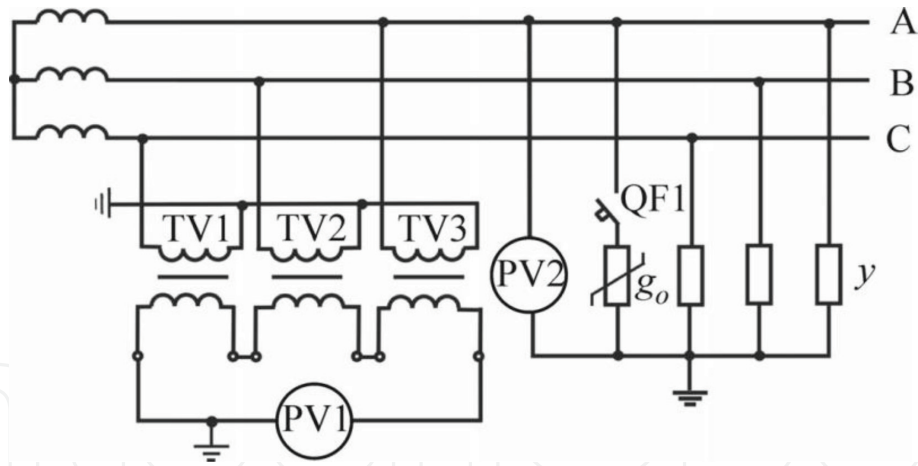


Figure 5.
Electrical schematic diagram of a method of measuring the admittance of network.

variable resistance is used. The variable resistor is connected between the measured electrical network phase and earth. Then the resistance regulation is provided to ensure equality between the voltage phase to earth and zero sequence voltage. In case of equal voltage, magnitude of admittance will correspond to the value of variable resistance, which is connected between the phase of network and earth. The method for measuring the admittance of insulation in a network with an isolated neutral voltage up to 1000 V will provide improved accuracy and speed measurement admittance network insulation [32].

The measurements of phase voltage to earth and zero phase-sequence voltage produced an AC voltmeter. The zero phase-sequence voltage is released from the network by using three single-phase transformers; the primary windings are connected in a star and the secondary windings are connected into an open triangle.

Developing the method of measuring the admittance in a network with an isolated neutral voltage 1000 V is explained in the schematic circuit diagram shown in **Figure 5**. The electrical schematic circuit comprises the electrical network, with phases A, B, and C; three single-phase voltage transformers TV1, TV2, and TV3; voltmeter PV1, measured quantities of module of the zero phase-sequence voltage; voltmeter PV2, measured module of phase voltage to earth; switching device QF1, introduction of adjustable additional conductance; additional conductance g_o ; and admittance of network y .

The method is as follows: for measuring the admittance of the network, the voltmeter PV2 measures the phase voltage to earth; the voltmeter PV1 measures the zero phase-sequence voltage on the secondary winding of single-phase voltage transformers TV1, TV2, and TV3. Switching device QF1 connects the adjustable additional conductance g_o , making the regulation of the magnitude of additional conductance to achieve the equality of the modulus of the phase voltage to earth and the zero phase-sequence voltage. In this case, the value of additional conductance will fit the admittance of network [32].

3.4 Modeling method of measuring the admittance of insulation in a network with an isolated neutral voltage up to 1000 V using Matlab/Simulink

As a tool for analyzing the operating conditions of power network, the package Matlab/Simulink has been used. The package has a sufficiently developed set of special blocks for modeling elements of the power system.

Matlab/Simulink enables an electrical schematic diagram of a method of measuring the admittance of insulation to be implemented (**Figure 6**). The diagram

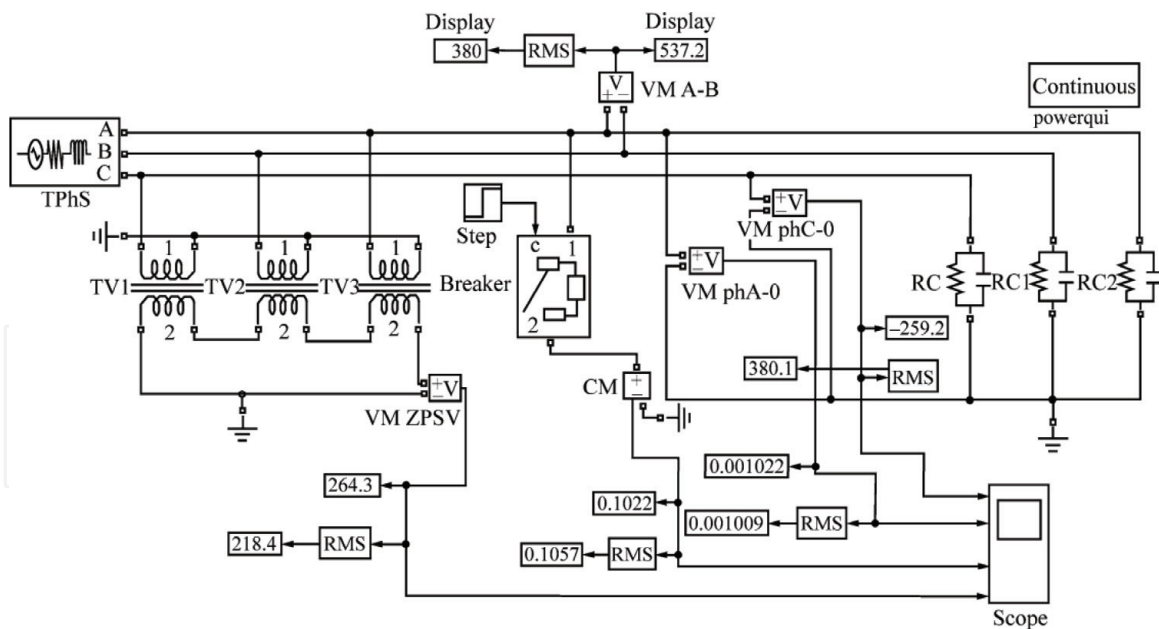


Figure 6. *Simulation model of the metal single phase ground short circuit.*

comprises three-phase source voltage 380/220 V; active-reactive resistance RC-RC2; zero phase-sequence voltage filter made by three single-phase voltage transformers; voltage and current measurements; oscillograph (scope) to display network settings; and displays to show the amplitude and true values of the electrical parameters.

To test the electrical schematic diagram, operating conditions were simulated by using a metal single-phase ground short circuit, which was carried out by way of a block breaker. A time-modulating circuit of 0.2 s was implemented by way of a block step. Block RMS allows for the calculation of the true RMS value of the input signal [33].

In the metal single-phase A ground short circuit operating conditions, the amplitude value of phase C voltage to earth was equal to 537 V, which corresponds to the true value of 380 V. The RMS value of phase A voltage to earth after the metal single-phase ground short circuit corresponds to 0.001009 V, with the current value of the faulty phase A being equal to 0.1057 A. From the findings of the zero phase-sequence voltage filter, the true value of the voltage increased from zero to 218.4 V (**Figure 7**).

The simulation model of the method of measuring the admittance of insulation with variable resistor R is shown in **Figure 8**. From the diagram, as a variable resistor R is connected between the measured phase of network and earth, a nonlinear resistor R diagram is used [34].

An application of the variable resistor enables the production of multiple controls for the electrical network parameters. According to the method described previously, a switching device is introduced to adjust the additional conductance. A block breaker is then added to the switching device. The additional conductance is represented by a variable resistor, namely, nonlinear R. A subsystem of the variable resistor R is shown in **Figure 9**. It is possible to use block slider gain to adjust the parameters of the resistor.

In the diagram, the controlled current source is connected in parallel with a voltage measurement. Between the output of the voltage measurement and the input of the controlled current source, the Simulink model is turned on, which implements the voltage-current characteristic of the device. In parallel to the controlled current source, decoupling resistor series RLC branch is also connected. Its

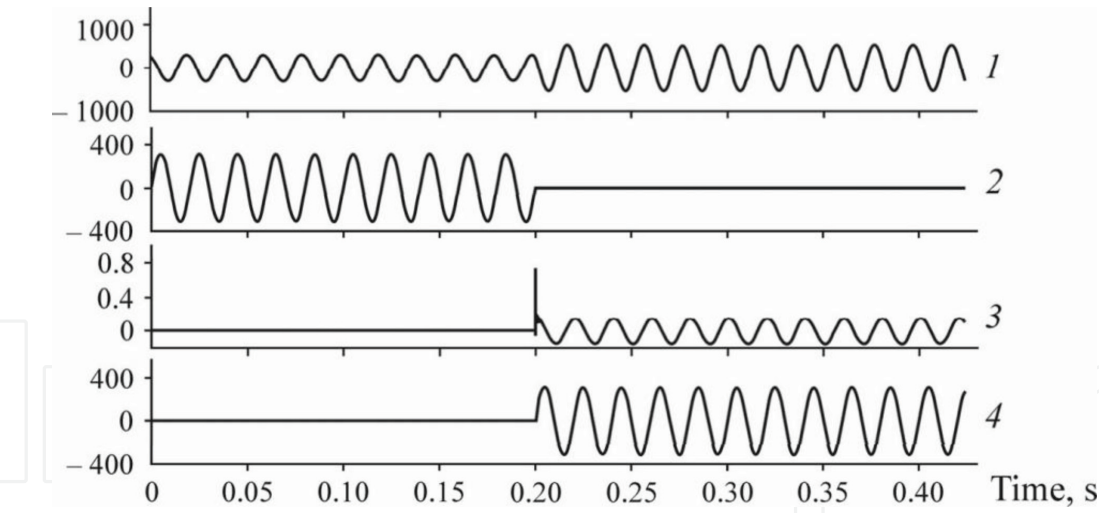


Figure 7. Voltage and current for metal single phase ground short circuit: 1—phase C voltage to earth, V; 2—phase A voltage to earth, V; 3—current under A phase-to-ground fault, A; 4—zero phase-sequence-voltage, V. Phase-to-ground fault time 0.2 s.

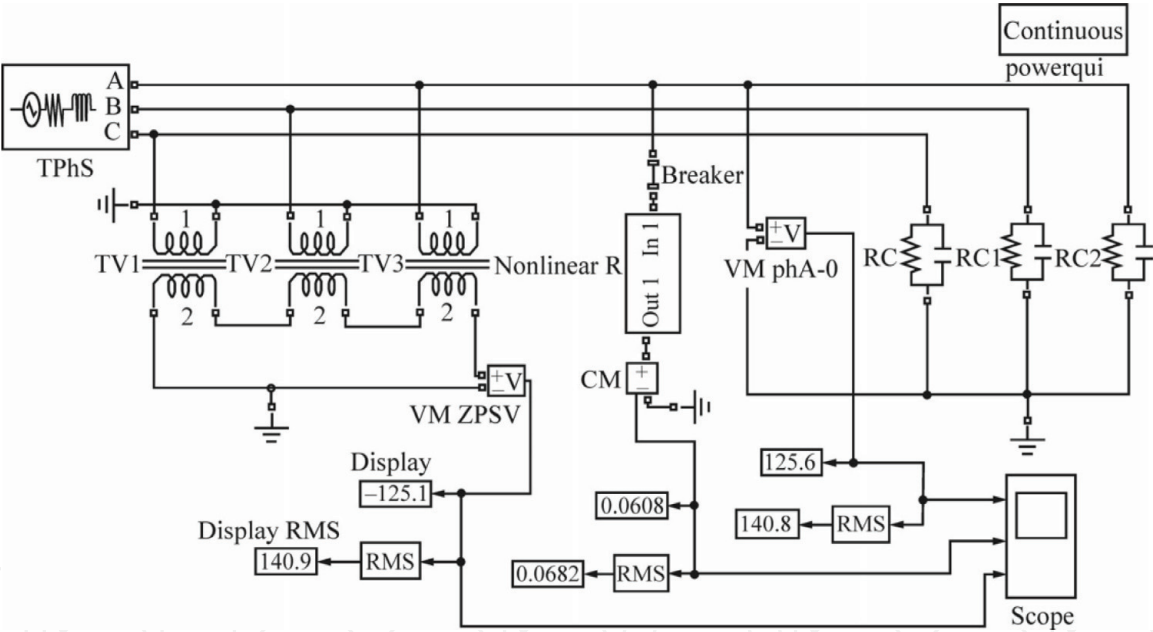


Figure 8. Simulation model of a method of measuring the admittance of insulation in Simulink: display RMS—display of the actual data of power grid; nonlinear R—variable resistor to adjust extra conductance, the rest of legend find in Figure 3.

presence is due to the fact that a large number of SimPowerSystems blocks are made on the basis of the current sources. When these blocks are connected in series, the current sources are also connected in series which is unacceptable. The presence of the decoupling resistor enables the connection of these blocks in series. The value of the resistor chosen should be sufficiently large to minimize its effect on the characteristics of the created block [34].

The Simulink model of the variable resistor is implemented using a block slider gain, which allows for a change in scalar gain during the simulation using the slider. Thus, the value of the slider gain is regulated until the zero phase-sequence voltage equals the A phase voltage to earth.

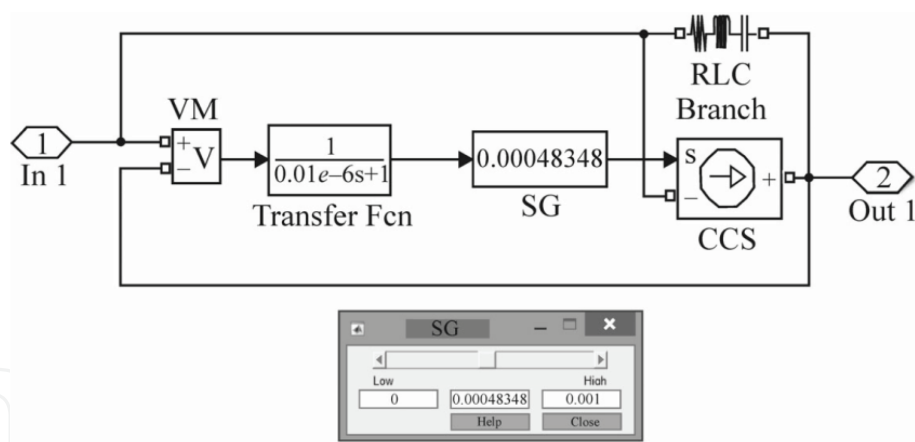


Figure 9. Subsystem of the variable resistor R: VM—voltage meter; transfer Fcn—gain transfer characteristic block; SG—resistor adjustment slide; RLC branch—decoupling resistor; CCS—adjustable current source.

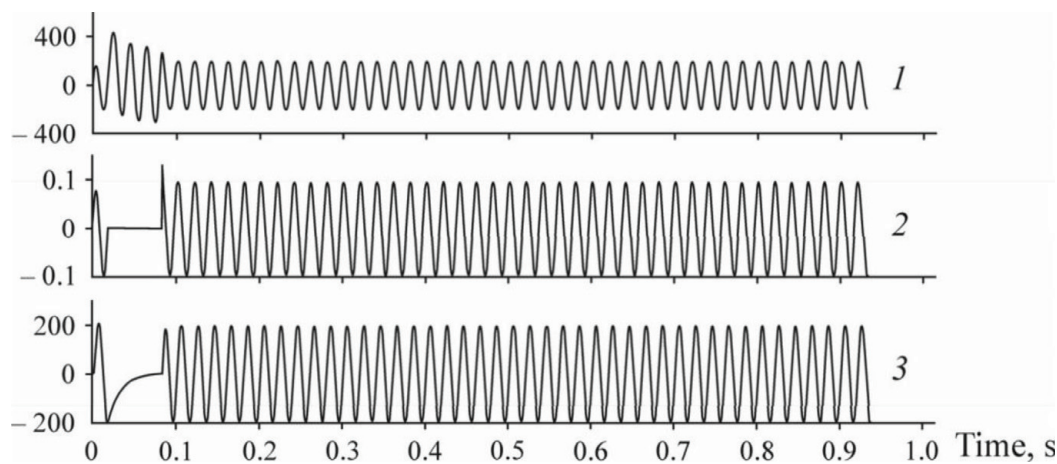


Figure 10. Phase voltage, current and zero phase-sequence voltage: 1—phase A voltage to earth, V; 2—phase A current to earth, A; 3—zero phase-sequence-voltage, V.

Due to the data received in the regulation of the variable resistor to 2068 Ohms, the true value of the zero phase-sequence voltage and phase A voltage to earth are equal to 140.8 V. **Figure 10** shows the amplitude values of the phase voltage and current and zero phase-sequence voltage for the value of the variable resistor $R = 2068$ Ohms.

Thus, according to the circular chart above, when phase voltage to earth U_A equals the zero phase-sequence voltage U_o , the variable of the admittance of insulation y corresponds to the variable resistance which is connected between A phase and earth.

According to the developed method of measuring the admittance of isolation in a network with isolated neutral voltage up to 1000 V, the variable of the admittance y corresponds to 2068 Ohms which composes 0.48 mS.

The simulation model of the method of measuring the admittance of insulation in the Matlab/Simulink environment allows for the regulation of variable resistor to be used and to simplify the calculations of the magnitude of the admittance of insulation in a network with isolated neutral voltages up to 1000 V. The method for measuring the admittance of insulation in a network with an isolated neutral voltage up to 1000 V will allow for an increase in the accuracy and speed of measurement of the admittance of network.

4. Development of method to improve efficiency of residual current device under 1000 V on excavators of mining enterprises

4.1 Introduction

The principle of voltage stabilization in the system with the series SC and variable frequency can be explained with a vector diagram of the first harmonics of current and voltages. For such generators that are on the basis of the numerical values of the insulation parameters, it is clear that loss-angle tangent and current in single phase-to-earth fault can evaluate the work of a residual current device on the excavator. Experimental studies regarding the parameters of insulation, loss-angle tangent, and current in single phase-to-earth fault have evaluated the condition of short network under 1000 V in terms of electrical production work in the operation of electrical equipment excavators [1].

The experimental studies were carried out in the coal mine Ekibastuz, Angrensor LLP in the Pavlodar Region of Kazakhstan, to establish the actual values of the basic parameters of the insulation of electrical networks under 1000 V on the excavator EKG-8I.

Compulsory use of the system with insulated neutral networks under 1000 V on the excavators is caused by electricity safety conditions. During the process of solving electrical safety issues in the mining industry, considerable expertise has been built up, especially in the field of research on the condition of electrical insulation with insulated neutral voltage under 1000 V [1]. Neither the methods used to investigate the insulation condition nor the results of these studies can be taken for excavators because the power supply system of the excavator has its own characteristics, namely that there are no long cable lines and the electrical receivers are concentrated in a small area. Put differently, the power of the electrical receiver, such as excavator EKG-8I, is produced by a short network. Electrical receivers operate in different geological, climatic, and meteorological conditions, and this also affects the measurements.

4.2 The study of the condition of insulation

In surveyed excavators, with Ekibastuz coal mine used as the insulation control device, safety rules were prescribed, while automatic insulation monitoring devices were applied, including AIMD, and leakage current LC-2M. Experience in operating electrical equipment positively recommended leakage relay, such as AIMD, which are designed to mine district networks with voltage under 1000 V, that is, for deep mining [14]. Mine networks with voltage under 1000 V contain lengthy branching cable lines, which are powered by the electrical receivers of mining machines and systems. The main reason of ineffective relay is discrepancy between the technical capabilities of RCD and parameters of the insulation network voltage under 1000 V on excavator. However, in most cases, the existing power supply for excavators, which have, as a rule, one main substation, does not make it possible to meet this requirement. This is due to the fact that the relay AIMD, which is a device providing network-wide protection from leakage, switches off all networks when there is any dangerous earth leakage; this in turn can result in a downtime excavator [35].

Consequently, for the safe and efficient operation of the relay leakage, AIMD must review the principles of power supply with users of the excavator and lead parameters of electricity networks in compliance with the technical data relay.

Measurements on the coal mine Ekibastuz were taken by the developed methodic of determining the insulation parameters in networks with isolated

neutral under 1000 V at normal operating conditions of the electrical network of excavators with operating electrical receivers [8].

The developed methodic is based on the method of determining the parameters in the short network with isolated neutral. The method consists of measuring the modulus of linear voltage, phase voltage in respect to earth after the connection between phase and earth the auxiliary conductance. From the measured values of the modulus of linear stress, voltage to earth after the connection between phase and earth the auxiliary conductance, bear the auxiliary conductance in mind, admittance, conductance, and capacitive susceptance of phase-to-ground are determined with satisfactory accuracy [6, 36].

According to the measured values of the modulus of linear voltage, U_l , phase voltage in respect to earth, U_{pho} , when connecting auxiliary conductance, g_o , is determined admittance, conductance and capacitive susceptance of isolation by mathematical dependences [37]:

- admittance of isolation

$$y = \frac{1.73U_{pho}}{U_l - 1.73U_{pho}}g_o, \tag{24}$$

- conductance of isolation

$$g = \left(\frac{3U_{pho}^2}{U_l^2} - \frac{3U_{pho}^2}{(U_l - 1.73U_{pho})^2} - 1 \right) 0.5g_o, \tag{25}$$

- capacitive susceptance of isolation

$$b = (y^2 - g^2)^{0.5}. \tag{26}$$

Based on the results of the determination of admittance, conductance, and capacitive susceptance of isolation in a short line 0.4 kV on the excavator EKG-8I in the coal mine Ekibastuz, Angrensor LLP, the results were processed by using the small sample method. The results from the experimental research regarding the parameters of the insulation as well as an assessment of the results collected using the small sample method are shown in **Table 1**.

Studying the isolation of electric networks under 1000 V of the excavator showed that the insulation resistance is due to active resistance which characterizes the properties of the dielectric of insulating material used for insulation of live parts

Parameters of the insulation	The number of measurements								X mean value of parameters
	1	2	3	4	5	6	7	8	
Admittance of isolation, $y \times 10^{-5}$, Ohm	2.20	2.21	2.18	2.24	2.17	2.22	2.15	2.17	2.19
Conductance of isolation, $b \times 10^{-5}$, Ohm	1.34	1.35	1.37	1.40	1.39	1.41	1.35	1.37	1.37
Capacitive susceptance of isolation, $g \times 10^{-5}$, Ohm	1.74	1.75	1.69	1.75	1.67	1.71	1.67	1.68	1.71

Table 1.
The results of determination of the parameters of the insulation in a short line 0.4 kV on excavator EKG-8I in the coal mine Ekibastuz, Angrensor LLP.

Z, Ohm	R, Ohm	X, Ohm	tan δ, –	I _o , mA
$\frac{45662}{44643-46512}$	$\frac{58480}{57143-59880}$	$\frac{72993}{70922-74627}$	$\frac{0.80}{0.80-0.81}$	$\frac{4.93}{4.84-5.04}$

Table 2.
Numeric values of parameters of the insulation and the current of single phase-to-earth fault in the network under 1000 V on the excavator EKG-8I. Z – impedance, R – resistance, X – reactance, tan δ – loss tangent of a dielectric, I_o – single-phase earth current.

of the conductors with respect to the ground. Capacitive resistance is higher than active resistance of insulation in networks under 1000 V. As such, the current of single phase-to-earth fault under 1000 V on an excavator is not due to a capacitive component but an active component. Experimental studies showed that the current of a single phase-to-earth fault in the network under 1000 V on the excavator EKG-8I of coal mine Ekibastuz, Angrensor LLP, is about 5 mA. The current of the single phase-to-earth fault in the network under 1000 V on the excavator has a lower value than the set point of RCD. In light of this, it is obvious that the RCD used on excavators by their specification does not provide people with effective protection from electric shocks in networks under 1000 V.

The determined absolute value of the expected capacity of the network is 4.30×10^{-5} uF, and the range of the network capacity under 1000 V is $4.20 - 4.42 \times 10^{-5}$ uF based on the data in **Table 2**.

According to the received data, the parameters of the insulation electrical short network are changed insignificantly and are at a high level. This can be explained by the fact that the power supply circuit of the excavator does not contain a network with distributed parameters and the capacity of the network consists of a phase-to-earth capacitance only for the electrical receiver. This stipulates for high loss-angle tangent of isolation in the network under 1000 V on the excavator EKG-8I. The current of the single phase-to-earth fault in the network under 1000 V on the excavator EKG-8I has a small value and a small range of variation. There is a range of variation when it comes to the parameters of network isolation, loss-angle tangent of isolation, and current of single phase-to-earth fault in the network under 1000 V due to changes in the supply voltage [38].

Based on the aforementioned evidence, it follows that the workers of mining enterprises receive electric shocks during excavator maintenance work due to the ineffectiveness of RCD. Indeed, as the RCDs used on excavators do not work, this leads to a violation of safety rules regarding the use of electrical equipment of excavators in mining companies. As such, it is necessary to develop RCD for three-phase mains under 1000 V on excavators and develop technical measures to increase efficiency of RCD on excavators.

4.3 The method to improve efficiency of residual current device

The development of RCD for a three-phase electric network under 1000 V on excavators is a complex and expensive task, as the principle of operation of RCD for the three-phase electric network with isolated neutral under 1000 V must be changed.

RCDs such as AIMD are used on excavators of mining enterprises. The principle of their operation was based on Scheme 3B developed by Professor. Leybov in the 1950s. This principle is still used today and was thoroughly studied by Shishkin in the 1960s at the Skochinsky Mining Institute. All these studies were conducted to improve the efficiency of RCD in mining electric networks under 1000 V. With this said, however, no detailed investigation into the electric network under 1000 V on excavators has been carried out [39]. In light of this, the most vital area relates to

the development of technical measures with which to improve the effectiveness of RCD on excavators, taking into account the study of insulation parameters in short electric networks under 1000 V.

There is a drawback when it comes to the existing method of RCD in the network with isolated neutral under 1000 V on excavators. Indeed, this method is based on setting-up a direct current into three-phase mains with a fixed set-point of protection from electric shock. The disadvantage is that the fixed set-point of current of protection does not protect people from electric shocks, as short networks under 1000 V on the excavator have a current of single-phase earth fault, which is less than the set-up value of RCD. In order to overcome this problem, it is necessary to develop a method to improve the efficiency of RCD in a network with isolated neutral under 1000 V on excavators.

Improving the efficiency of RCDs in a network with isolated neutral under 1000 V is based on switching off the supply due to increase in the phase capacity with respect to earth when insulation is damaged.

A method for improving the effectiveness of RCD in a network with isolated neutral under 1000 V on excavators is explained by the electrical circuit diagram found in **Figure 11**. The circuit diagram contains: a power transformer T; load interrupt switch QF1, which supplies voltage to the three-phase electric network; three-phase electric network with the phases A, B, and C; electrical receivers; load interrupt switch QF2, which switches capacitors between phases of network and ground; capacitors C1, C2, and C3, being provided by an increase in the current of single-phase ground fault; load interrupt switch QF3, which switches residual current device; residual current device—RCD; total admittance of network isolation Z1, Z2, and Z3 [40].

The principle of operation of the scheme of safety shutdown in the short electric network with insulated neutral under 1000 V on excavators is as follows: the power is supplied to three-phase electric network with the phases A, B, and C from power transformer T by load interrupt switch QF1, where electrical receivers are supplied with voltage under 1000 V of excavator. The capacitors C1, C2, and C3 are connected by load interrupt switch QF2 between the electric network phase and earth to provide increased current of single-phase earth fault. The RCD is connected to a three-phase electric short excavator network by load interrupt switch QF3 [41].

An RCD with a fixed set-point does not allow for the shutting off of the three-phase electric network by load switch QF1 when any phase-to-earth insulation of network is damaged. Thus, there is the risk of electric shock. The RCD does not turn off the three-phase electric network when any phase-to-earth insulation is damaged, as the set-up point of current for protection is more than the current of

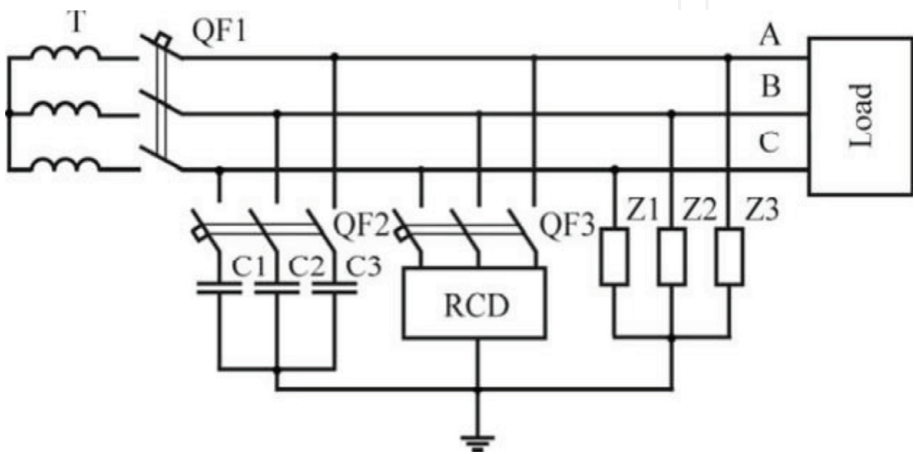


Figure 11.
The scheme of residual current device in electric network with isolated neutral under 1000 V on excavators.

single-phase earth faults in the three-phase network of the excavator. In order to disable the three-phase network when insulation is damaged, the current of single-phase fault in the network is increased by means of connecting capacitors C1, C2, and C3 between the phases of the electric supply and the ground by load switch QF2. In this case, the current of single-phase circuits in the excavator's three-phase network will be more than the current of the set-up point of RCD, which will activate the RCD. Thus, the switching off is made possible thanks to the load interrupter switch QF1 supplying voltage from the power transformer [40].

Implementation of the developed method to improve the effectiveness of RCDs in electric networks under 1000 V will ensure the growth of level of electrical safety when using electrical installations and reduce the number of accidents on excavators.

5. Conclusion

The following results were obtained in this work:

1. A method for determining the parameters in three-phase networks with isolated neutral voltage up to 1000 V and above is to measure the modulus of the line voltage and phase voltage with respect to ground and A, and after you connect, an additional active conductivity between the A-phase mains and earth was developed.
2. Error analysis of method for determining the parameters of isolation in three-phase electrical network with isolated neutral showed that it is necessary to select a certain value of additional active conductance, so as to ensure satisfactory accuracy required when determining the:
 - the total conductance of mains phase insulation relative to the ground is chosen such additional active conductance, the values were within $= 0.2\text{--}0.8$, with the error does not exceed 5% when using measuring devices with accuracy class 1.0, and 2.5% using measuring devices with accuracy class 0.5;
 - active conductance in three-phase electrical network with isolated neutral voltages up to and above 1000 V select such active additional conductance g_o , so that $U_{A*} = 0.2\text{--}0.8$, when $U_{C*} = 0.2\text{--}0.8$, then the error does not exceed 3.5% when using the measuring devices with accuracy class 1.0;
 - capacitive conductance of electrical network phase insulation relative to the ground select such additional active conductance g_o , so that $U_* = 0.2\text{--}0.8$, with the change $\tan \delta = 0.6\text{--}1.6$, then the error does not exceed 5% when using the measuring devices with accuracy class 1.0, and 2.5% when using the measuring devices with accuracy class 0.5.
3. The developed methods provide satisfactory accuracy, simplicity, and security in its implementation in the three-phase electrical networks with isolated neutral voltages up to and above 1000 V.
4. The chapter presents new evidence-based results that solve the important scientific task of ensuring electrical safety in networks with an isolated neutral

voltage up to 1000 V in mining enterprises through the development of methods to control the condition of insulation.

A method of measuring the admittance of network with an isolated neutral voltage up to 1000 V is based on the measurement of the modulus of the zero phase-sequence voltage and phase voltage to earth, with an additional conductance where the value of the regulation is made additional conductance in conduction to ensure the equality of the modulus of phase voltage to earth and zero phase-sequence voltage. In ensuring the equality of zero phase-sequence voltage and phase voltage to earth connection of additional conductance, it corresponds to the admittance network isolation.

The simulation model of method of measuring the admittance of insulation in the Matlab/Simulink environment was modulated. The developed model allows for the regulation variable resistor to be used to simplify the calculations of the parameters of network isolation. Due to the data received in the regulation of the variable resistor to 2068 Ohms, the true value zero phase-sequence voltage and phase A voltage to earth are equal to 140.8 V. Thus, the variable of the admittance y corresponds to 2068 Ohms, which comprises 0.48 mS.

Developing a method of measuring the admittance of insulation networks with an isolated neutral voltage up to 1000 V will provide improved accuracy and speed measurement admittance network isolation. The proposed method is simple, as the instrumentation, single-phase voltage transformers, required for measuring the admittance network isolation is in the service manual enterprise energy management.

5. The experimental data obtained are composed of numerical values of the parameters of the insulation on the excavator EKG-8I of coal mine Ekibastuz, Angrensor LLP. It was established that the insulation resistance is due to active resistance, which characterizes the properties of the dielectric of insulating material used for insulation of live parts of the conductors with respect to ground. Capacitive resistance is higher than active resistance of insulation in networks under 1000 V.

It is found that the RCDs used on excavators by their specifications do not provide effective protection from electric shocks in a short network with voltages under 1000 V as the current of single-phase earth faults in the network under 1000 V on the excavator has less value than the current of the RCD set-up point.

A new method aimed at improving the effectiveness of RCDs in electric network under 1000 V has been developed and is based on setting up the DC into a three-phase network with a fixed set-point of protection from any phase-to-earth insulation damage, where the equipment is switched off by residual current device when live-line bare-hand touching of electric equipment occurs. This is due to increases in the phase capacity with respect to earth.

Organizational and technical measures aimed at improving the reliability and level of electrical safety in electrical mining enterprises will help to protect people from electric shocks while also reducing the number of accidents at work.

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