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Equivalent circuit for mine power distribution systems for the analysis of insulation leakage current

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Abstract
Successful mining businesses rely heavily on the safety and reliability of their mine power distribution systems. Mine power distribution systems are designed to withstand an aggressive environment with a range of hazards. The harsh operating conditions require improvement to personnel protection systems through the study and simulation of the electric network's normal and emergency operations. The purpose of this study is to assess insulation leakage current using an equivalent circuit of a mine power distribution system. The simulation identified the key properties of the equivalent circuit which can model potential hazardous situations. We also selected the quantitative metrics and the equivalent circuit property ranges. In order to simulate the transients, we recommended using the time constants for the oscillation damping in circuits, the insulation phase resistance properties, and the absorption currents. This paper presents the equations to estimate these values. As an example, we considered the equivalent circuit of a mine power distribution system with an R-L filter in the residual current device line. The equivalent circuit helps analyze the current leakage when a person touches a live phase conductor accounting for low-frequency polarization in the phase insulation. The proposed approach to the simulation and analysis of the insulation current makes it possible to generate an equivalent circuit of the mine power distribution system to analyze phase voltage asymmetry, trip currents of residual current devices, low-frequency polarization of the insulation, and the leakage current effects on the human body.

Keywords
mine power distribution system, leakage current, residual current device, insulation properties, EMF sources, electrical safety

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ЭНЕРГЕТИКА, АВТОМАТИЗАЦИЯ И ЭНЕРГОЭФФЕКТИВНОСТЬ

Научная статья

Обоснование схемы замещения шахтной подземной электрической сети для анализа режимов утечки тока через изоляцию

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Аннотация
Характеристики безопасности и надежности шахтных электротехнических комплексов и систем во многом обеспечивают успешность горных предприятий. Сложные технологические условия, особенно при ведении подземных горных работ, многообразие индивидуальных факторов определяют совокупность требований, которые предъявляются к подземным электрическим сетям горных предприятий. Все это определяет необходимость совершенствования систем защиты персонала на основе исследования характеристик сетей, моделирования режимов работы, в том числе аварийных. Основная цель исследований – обоснование схемы замещения шахтной подземной электрической сети путем синтеза ее структуры для последующего анализа режимов утечки тока через изоляцию. На основе методов математического моделирования дано обоснование параметров схемы замеще-

ния шахтной подземной электрической сети с учетом условий возникновения и развития аварийных и травмоопасных ситуаций. Определены количественные показатели и диапазоны изменения параметров элементов схемы замещения электрической сети. Для математического моделирования переходных процессов рекомендовано использование электромагнитных постоянных времени затухания колебаний в контурах, образованных параметрами фазных сопротивлений изоляции, а также абсорбционных составляющих токов утечки, и приведены соответствующие расчетные соотношения. В качестве примера приведена схема замещения шахтной подземной электрической сети с активно-индуктивным фильтром присоединения устройства защитного отключения, позволяющая выполнить анализ утечки тока при однополюсном прикосновении человека к токоведущей фазе, с учетом процесса низкочастотной поляризации в фазной изоляции. Предложенный методический подход к моделированию и анализу режимов утечки тока через изоляцию позволяет осуществить синтез схемы замещения подземной электрической сети для анализа несимметрии фазных напряжений, токов срабатывания устройств защитного отключения, процессов низкочастотной поляризации в изоляции, воздействия тока утечки на человека.

Ключевые слова
шахтная подземная электрическая сеть, режимы утечки тока, защитное отключение, параметры изоляции, источники ЭДС, электробезопасность

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Terms and Definitions

Leakage Current: the current that flows from exposed live parts or protective conductors to the ground in normal operation.

Leakage current type: the current that depends on the earth-to-phase voltages for different active resistance and insulation capacitance values.

Absorption current: the amount of current that flows and is absorbed by the dielectric insulation, which is caused by polarization and redistribution of free charges.

Ion conductivity: the movement of charged particles (ions) under voltage applied to the insulation with the charge neutralization on the conductor's insulation layer.

Introduction

Successful mining businesses rely heavily on the safety and reliability of their mine power distribution systems. Mine power distribution systems [1, 3, 4] are designed to withstand aggressive environments [1, 2] with a range of hazards [1, 5, 6]. The harsh operating conditions require improvement to personnel protection systems through the study and simulation of the electric network's normal and emergency operations.

As mine conductors age, their insulation resistance reduces. The insulation resistance of each phase may change either steadily (symmetric leakage current) or abruptly (single-phase and two-phase leakage current) [1–3, 5]. Asymmetric leaks lead to significant phase voltage surges (the undamaged phase voltage raises to the linear voltage). Such surges may damage the electrical equipment and are an electric hazard, if the exposed phase wire are touched.

The simulation of leakage currents provides a sufficiently accurate definition of the most complicated electric processes (e.g., transients).

Our study included the following stages: selecting the simulation model structure and inputs; definition of the simulation target; definition of the numerical experiment procedure; and the processing of the results.

The core of the simulation model is a system of equations deducted from the equivalent circuit. These equations estimate the effects of voltage and insulation properties on the leakage current.

The literature review identified several approaches to the leakage current studies applicable to specific operating conditions of the electric equipment.

Many researchers use equivalent circuits, in order to simulate the insulation behavior [2, 6, 7]. The key cable insulation properties are *distributed resistance* determined by the quality of the insulating material along the entire conductor length, and *lumped resistance* affected by mechanical damage, aging, moisture ingress, etc. The *ground capacitance* is mainly determined by the length and cross-section of the cables. Note that the insulation resistance and capacitance vary as the mine power distribution system components are powered up or down according to the startup/shutdown procedure. For example, the backbone cable is energized first, and then the branch cables connecting the switchboard to the consumers are powered.

The simulation of leakage currents is challenging because, for more complicated equivalent circuits, it is extremely difficult to model the transients. Conventional simulation methods are not quite suitable, if we need to consider the properties of residual current devices, phase insulation, current leakage circuits, capacitive current compensation devices, and shunt-connected surge protection devices, etc. These components generate transients in the RC oscillator circuits which lack proper mathematical interpretation. A possible solution to this problem is the simulation of the leakage currents which requires an appropriate equivalent circuit and a set of variables.

Goals and Objectives

The purpose of this study is the assessment insulation leakage current using an equivalent circuit of a mine power distribution system.

This paper presents the solutions to the following problems:

– selection of the equivalent circuit structure for a mine power distribution system and its component properties;

– deriving the equations for the time constants of damped EM oscillations in circuits consisting of the insulation and current leakage paths;

– development of an equivalent circuit to solve a specific problem related to insulation monitoring and protective device performance.

Model Structure and Input Variables

We used a circuit equivalent to a typical mine power distribution system up to 1,140 V (Fig. 1).

Let us consider the key components of the equivalent circuit, in order to analyze the leakage current paths through the insulation and a person touching a live phase conductor.

The EMF source (Fig. 1, *a*) is the secondary winding of the power transformer installed on a mobile substation, 6,000/660 (1,140) V.

A residual current device (RCD) is represented as an RL filter (Fig. 1, *b*) or an RC filter (Fig. 1, *c*) (UAKI, AZAK, AZSH, SASU, ASZUS, AZUR models of RCD) [7, 8]. The RCD is defined with the RC filter properties. The phase resistances of the branch lines are $R_{Fa} = R_{Fb} = R_{Fc}$ = 15 kOhm, R_{PN} = 1 kOhm, and the capacitance is L_{PN} = 8 . The measuring instrument is connected between the neutral of the filter and the ground. For RCDs with RL filters: phase resistances *are* $R_{Fa} = R_{Fb} = R_{Fc}$ = 0.3 kOhm, phase inductances are $L_{Fa} = L_{Fb} = L_{Fc}$ = 75 H. The measuring circuit resistance and inductance are R_0 = 3.9 kOhm, and L_0 = 8 H, respectively [5].

The impedance components of the phase insulations (Z_a, Z_b, Z_c) vary in the following ranges: resistance R_I = 10.5...300 kOhm/phase; and capacitance: C_I = 0.1...1.5 µF/phase (Fig. 1, *d*). The resistance and capacitance of the absorption current circuit vary as follows: R_{ab} = 0.01...10 MOhm/phase, C_{ab} = 0.01...0.5 µF/phase. The impedance components

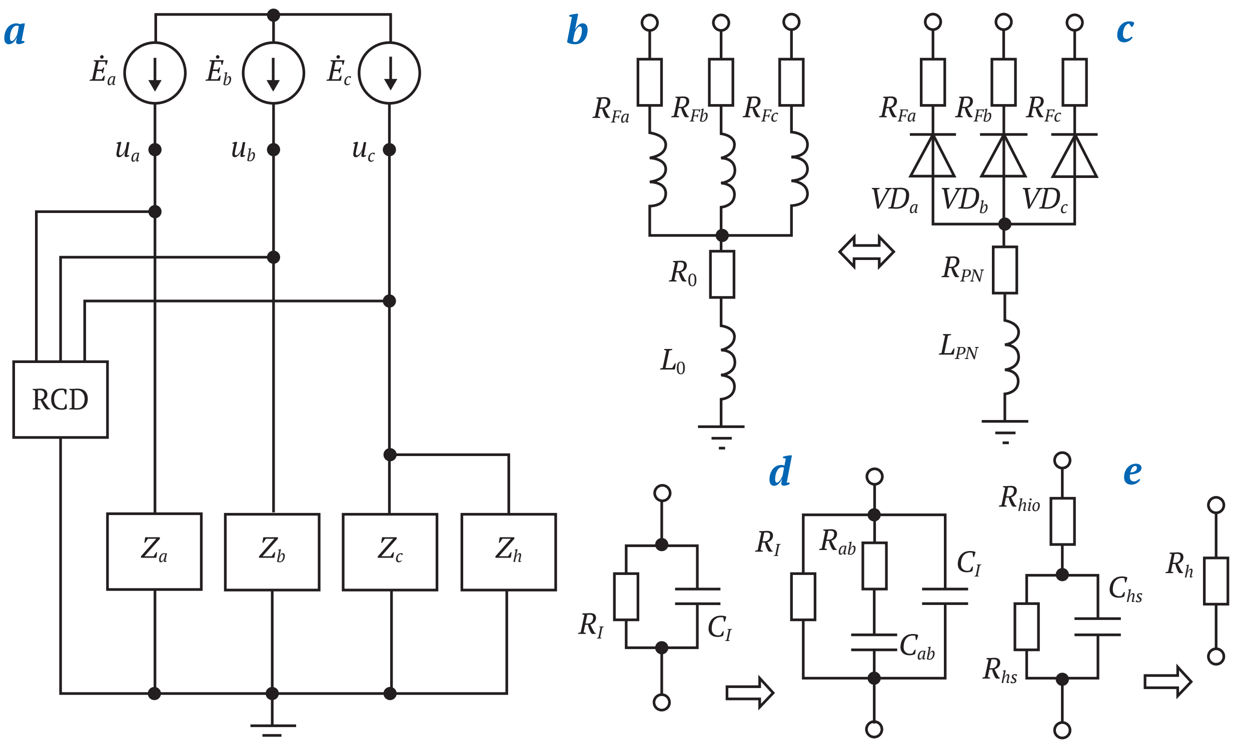

Fig. 1. Equivalent circuit for a current leakage path in a substitution in a mine power distribution system

of the equivalent leakage path through the human body (Z_h): internal body resistance is R_{hio} = 0.7...1 kOhm; skin resistance is R_{hs} = 0.5...3.5 kOhm; and skin capacitance is C_{hs} = 0.3...1 μF (Fig. 1, *e*). If the voltage exceeds 380 V, we can simplify the model to $Z_h \approx R_h = R_{hio}$ = 1 kOhm, since over 40 V the skin no longer protects from electric shocks, and the leakage path resistance is equal to the internal body resistance [9–11].

The inclusion of RCD in the equivalent circuit of the leakage path significantly complicates both the circuit and the simulation model [12–14]. Note that the introduction of a neutral displacement device and an additional leakage path through the RCD tester into the equivalent circuit results in a noticeable (15...20 %) increase in the insulation leakage current (especially if an RC filter is present) [5, 7, 15].

The symmetric leakage current values in 380 and 660 V networks are fairly well known for zero sequence equivalent circuits [4, 6, 12].

Among the variety of options, the most common are zero sequence substitution circuits, for which the equivalent insulation properties are expressed as:

$$R_I = \frac{R_a R_b R_c}{R_a R_b + R_b R_c + R_c R_a}; \ C_I = C_a + C_b + C_c, \qquad (1)$$

where R_a, R_b, R_c, C_a, C_b, and C_c are the phase resistances and capacitances.

For such circuits, the insulation properties vary within the ranges: R_I = 3.5...300 300 kOhm/phase, C_I = 0.03...1 μF/phase.

The representation of phase insulation with linear lumped capacitance and resistance models provides a more accurate description of the processes in a circuit with asymmetric leakage current.

For such circuits, the phase resistances and ground capacitances are in the range of R_I = 31.5...300 kOhm and C_I = 0.3...3 μF.

Since we studied leakage currents during a transient while the RCD trips, it is reasonable to represent the phase insulation as time constants of dumped EM oscillations in *RC* circuits:

$$T_{Ia} = \frac{X_{Ia}}{R_{Ia}}, \quad T_{Ib} = \frac{X_{Ib}}{R_{Ib}}, \quad T_{Ic} = \frac{X_{Ic}}{R_{Ic}}, \qquad (2)$$

where R_{Ia}, R_{Ib}, R_{Ic} are the insulation resistances; X_{Ia}, X_{Ib}, X_{Ic} are the insulation capacitances ($X_I = 1/(\omega_0 C_I)$); T_{Ia}, T_{Ib}, T_{Ic} are the time constants of dumped oscillations.

It was found that the amplitude and damping rate of EM oscillations largely depends on the ratio of the phase resistance and capacitance. The highest values correspond to the insulation resistances up to 60 kOhm/phase and capacitances less than 0.3 μF/phase. In the resistance range of R_I = 60...300 kOhm/phase and capacitances greater than 0.5 μF/phase, the T_I constants are less than 0.1 rad/s and tend to be zero.

The reason is that at high capacitances, the resistance does not significantly affect the oscillation damping in the phase insulation circuits. The leak is purely capacitive, and the insulation efficiency is sharply reduced. A phase current leak does not instantly reduce the phase voltage due to a sufficiently high charge potential of the insulation ground capacitance. In this case, the electric hazard increases dramatically [16–18].

In order to simulate the leakage with the human body equivalent circuit (Fig. 2), we specified the internal body resistance R_{hio}, skin resistance R_{hs}, and skin capacitance C_{hs} ($X_{hs} = 1/(\omega_0 C_{hs})$) and transformed the model as follows.

The equivalent resistances for the human body equivalent circuit are estimated as:

$$R_e = R_{hio} + \frac{R_{hs} X_{hs}^2}{X_{hs}^2 + R_{hs}}; \quad X_e = R_{hio} + \frac{X_{hs} R_{hs}^2}{R_{hs}^2 + X_{hs}}. \qquad (3)$$

Considering the inverse transformation of the $R_e C_e$ circuit, the human body impedance is:

$$R_h = \frac{X_e^2 + R_e^2}{R_e}; \quad X_h = \frac{X_e^2 + R_e^2}{X_e}. \qquad (4)$$

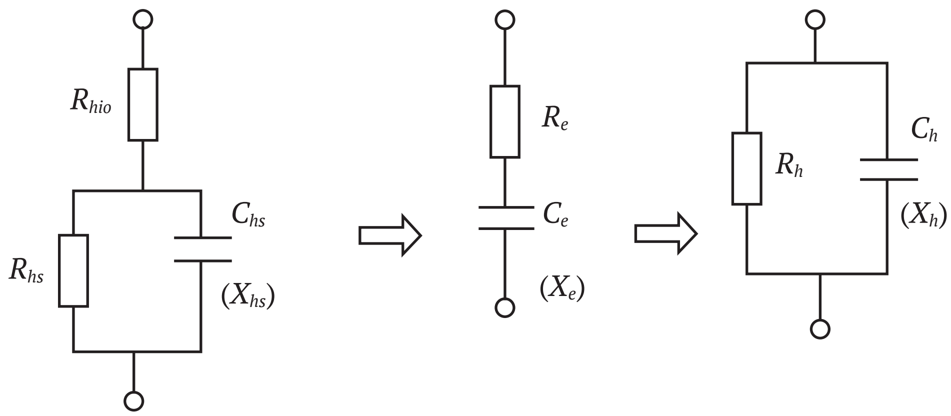

Fig. 2. Transformation of the human body equivalent circuit

Then phase resistance and capacitance for a circuit when a person comes into contact with a live component are estimated as:

$$R_{Ih} = \frac{R_I R_h}{R_I + R_h}; \quad X_{Ih} = \frac{X_I X_h}{X_I + X_h}. \tag{5}$$

The time constant of dumped oscillations in the phase insulation circuit accounting for the human body properties is:

$$T_{Ih} = \frac{X_{Ih}}{R_{Ih}}. \tag{6}$$

In the case of skin breakdown, the human body resistance is equal to the internal body resistance $R_{hio} \approx 1$ kOhm. Therefore, the leakage circuit properties are:

$$R_{Ih} = \frac{R_I}{1+R_I} \approx 1; \quad X_{Ih} = X_I; \quad T_{Ih} = \frac{X_I(1+R_I)}{R_I}; \tag{7}$$

We found that in this case, the T_I constant (2.5...35 rad/s) is an order of magnitude greater than the similar values of the T_{Ih} constant (0.1...3 rad/s). The greatest increment of T_{IH} occurs when the insulation resistance is less than 31.5 kOhm/phase and the insulation capacitance is less than 0.3 μF/phase. As the insulation resistance reaches R_I > 31.5 kOhm/phase, the T_{Ih} constants do not change and depend only on the phase insulation capacitance C_I.

The reason for this is that when a person touches a phase live wire, the resistance of the leakage path decreases sharply to 1 kOhm and is virtually independent of R_I. In this way, the insulation resistance is shunted. The leakage current I_y and the constant T_{IH} depend only on the phase insulation ground capacitance.

In order to incorporate the low-frequency polarization into the phase insulation model, we added an *RC* circuit consisting of the capacitor C_{ab} and resistor R_{ab} with the absorption current i_{ab} (Fig. 1, *d*) [5, 7, 18].

For the analysis of the transient occurring in the insulation, direct incorporation of the differential link (R_{ab}, X_{ab}) leads to a more complicated simulation model. This is because the series RC circuit is a source of interference in the oscillatory circuit. The equivalent circuit of the phase insulation can be transformed to include the resistance and capacitance into the absorption current (Fig. 3).

The following relationship indicates the time constant of dumped oscillations in a circuit representing the insulation resistance and capacitance:

$$T_{IF} = \frac{X_{IF}}{R_{IF}} = \frac{X_I(R_I R_{ab} + Z_{ab}^2)}{R_I(X_I X_{ab} + Z_{ab}^2)} = T_I \frac{R_I R_{ab} + Z_{ab}^2}{X_I X_{ab} + Z_{ab}^2}, \tag{8}$$

where R_{ab}, X_{ab}, Z_{ab} are the phase resistance, capacitance, and impedance; R_{IF}, X_{IF} are the insulation ground resistance and capacitance estimated as:

$$R_{IF} = \frac{R_I R_A}{R_I + R_A} = \frac{R_I Z_{ab}^2}{R_I R_{ab} + Z_{ab}^2};$$
$$X_{IF} = \frac{X_I X_A}{X_I + X_A} = \frac{X_I Z_{ab}^2}{X_I X_{ab} + Z_{ab}^2}. \tag{9}$$

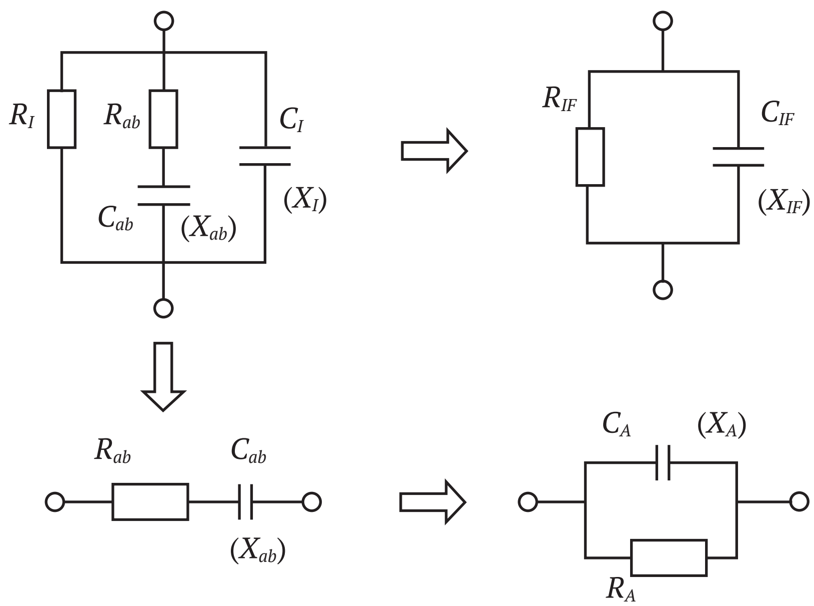

Fig. 3. Transformation of the equivalent circuit of the phase insulation to include the resistance and capacitance to the absorption current

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Where R_I, X_I are the insulation ground resistance and capacitance for ion conductivity; R_A, X_A are the resistance and capacitance to the absorption current estimated as:

$$R_A = \frac{R_{ab}^2 + X_{ab}^2}{R_{ab}}; \quad X_A = \frac{R_{ab}^2 + X_{ab}^2}{X_{ab}}. \tag{10}$$

When C_{ab} is comparable to the insulation capacitance C_I, T_{IF} reaches its maximum [14].

With the above relationships, equivalent circuits of mine power distribution systems suitable for a wide range of applications can be generated.

Fig. 4 shows a *Simulink* simulation model of a mine power distribution system with an RC filter in the RCD circuit.

The simulation model functionality is as follows:

– simulation of current leakages through the phase insulation accounting for the presence of the RC filter in the RCD circuit;

– analysis of the low-frequency polarization effect on electrical safety in transient and steady-state current phase insulation leakages;

– analysis of transient and steady-state phase insulation leakages to assess the electric hazard when a person comes into contact with a live component;

– analysis of current and voltage variations in the filter and RCD tester circuits for various current leakage types.

As an example, Figs. 5 and 6 show oscilloscope patterns of the leakage currents and phase ground voltages for a single-phase leakage to a human body (contact with phase A, R_h = 1 kOhm), symmetric insulation properties R_I = 300 kOhm, C_I = 0.03 μF, R_{ab} = 1 MOhm, C_{ab} = 0.01 μF, U_L = 1140 V.

With the oscilloscope patterns, we could assess the instantaneous and effective currents and voltages in the equivalent circuit nodes, phase angle shifts, surge currents, and transient periods in case of a single-phase leakage through a human body.

A comparative analysis of the simulation results showed good agreement (more than 0.95) with similar research results [5, 7, 13]. The proposed simulation model applies to a wide range of insulation and emergency trip monitoring problems to ensure the electrical safety of mine power distribution systems.

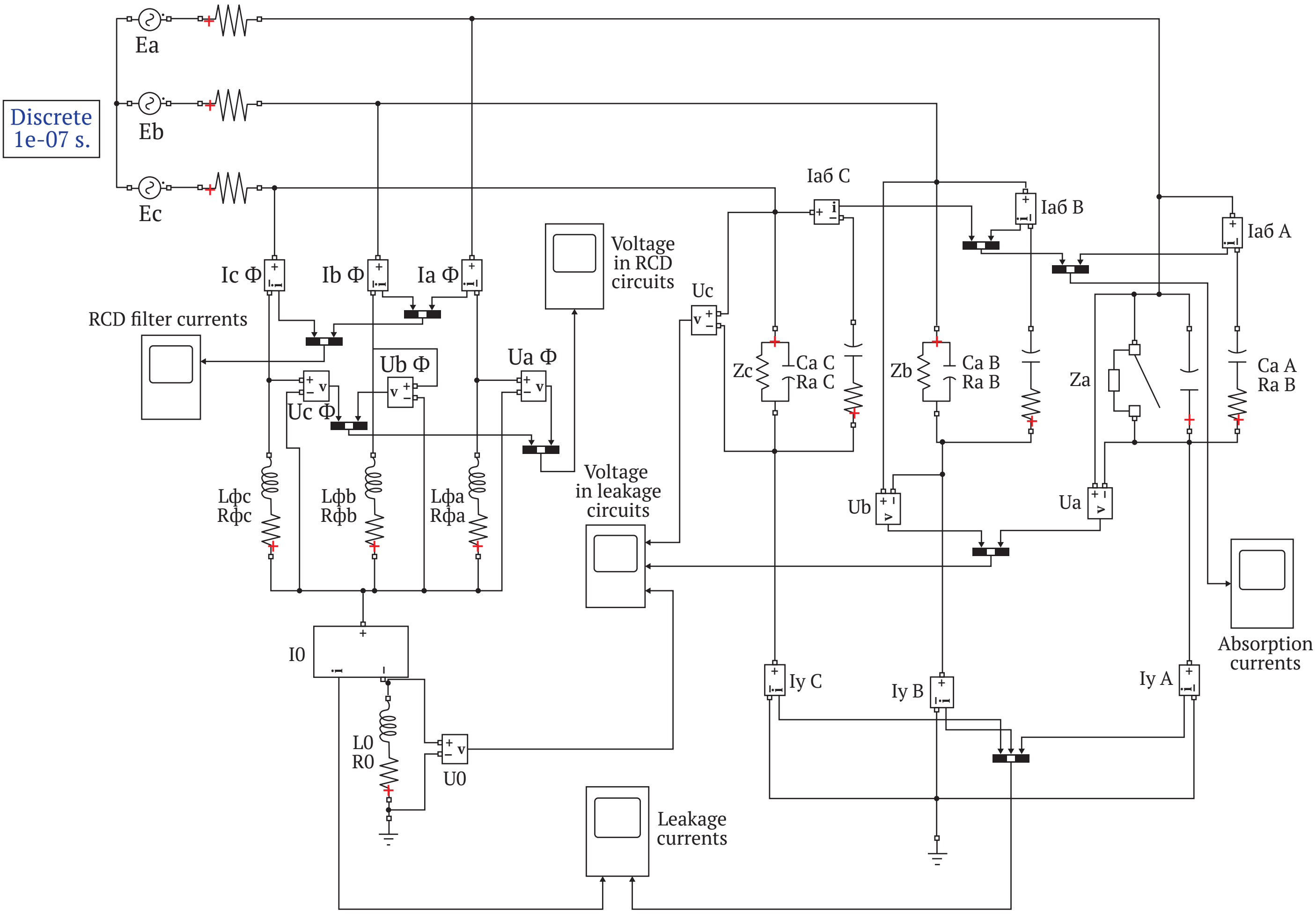

Fig. 4. Simulation model of a mine power distribution system with an RC filter in the RCD circuit

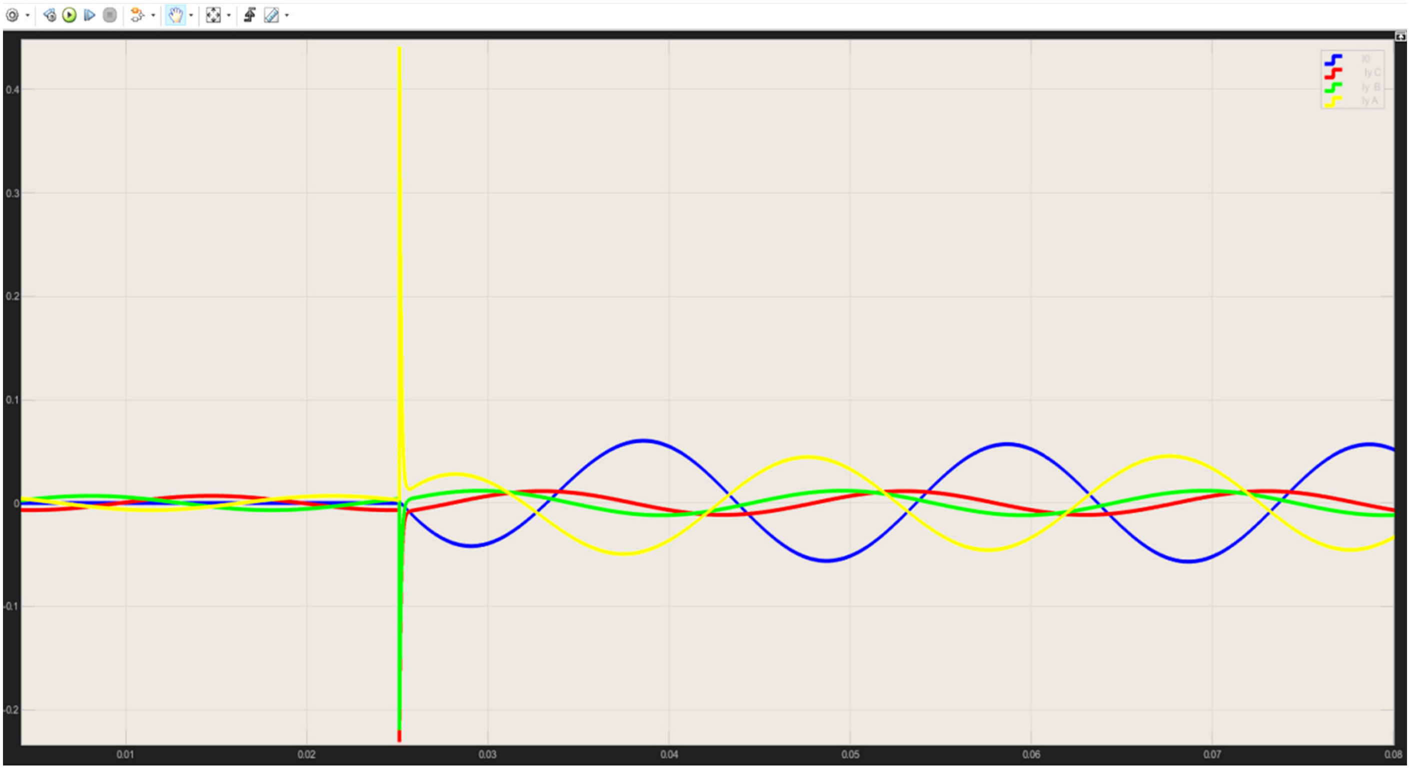

Fig. 5. Oscilloscope pattern of the leakage currents through insulation, human body, and RCD tester circuit with an RC filter

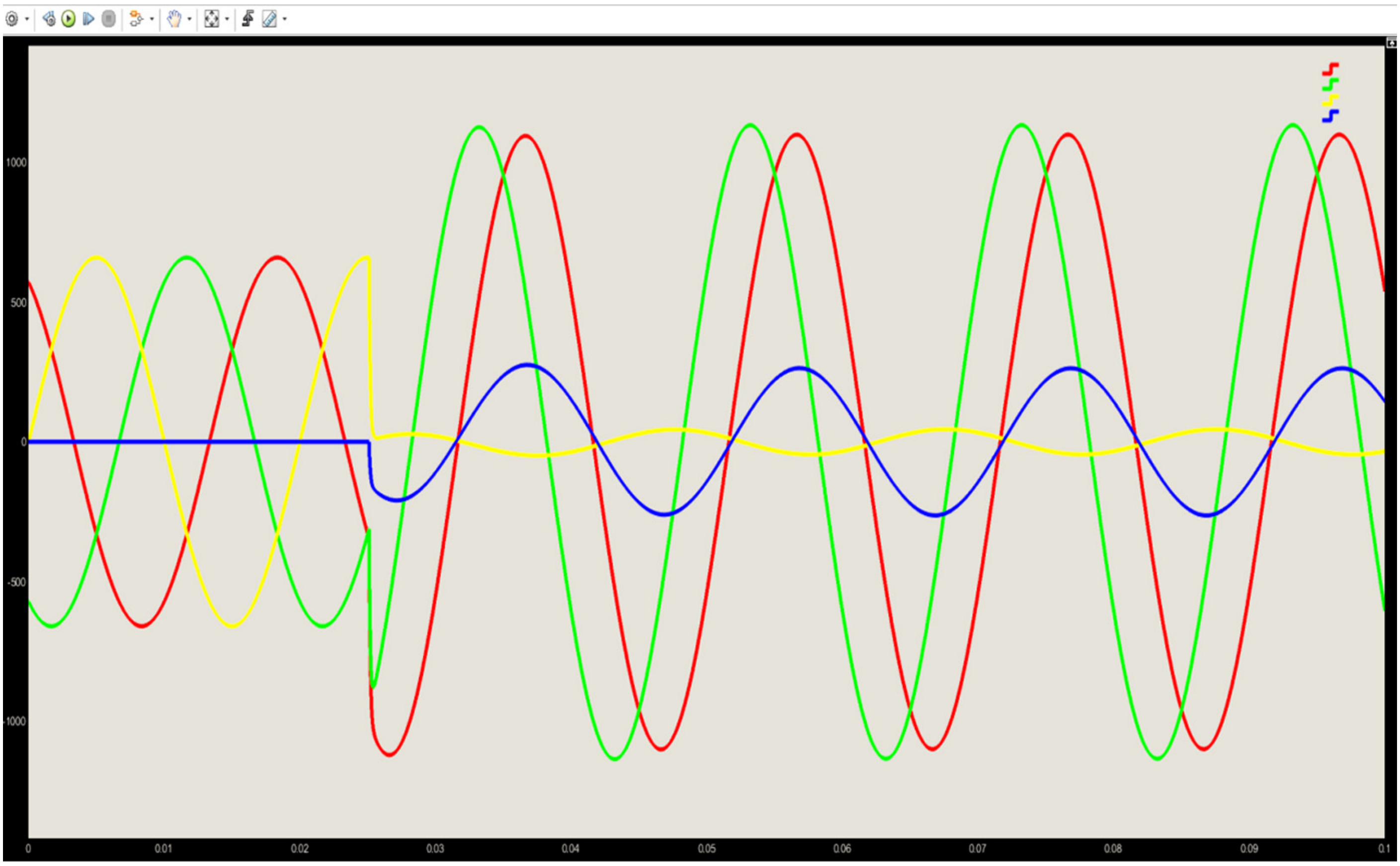

Fig. 6. Oscilloscope pattern of the phase voltages and zero sequence voltages before and after a person touches live phase A

Conclusions

The proposed equivalent circuit of a mine power distribution system can be used to analyze insulation currents and phase voltages as the insulation resistance changes under symmetric, single-phase, and two-phase leakages also caused by a person coming into contact with live components.

The equivalent circuit includes the EMF source, RCD, and insulation leakage paths. The model supports extensive ranges of its component properties including their critical values. The model gives a more accurate quantitative and qualitative assessment of the RCD efficiency. It assesses the acceptable insulation resistance and current passing through the person, the contribution of low-frequency polarization to the required insulation resistance, and selects the insulating material, shunt-connected surge protection devices, and protective bypassing of damaged phases and residual current arrestors.

The equivalent circuit of the power distribution system addresses a range of problems related to insulation and trip monitoring in the mining industry.

References

1. Gladilin L.V., Shchutsky V.I., Batsezhev Yu.G. et al. *Electrical safety in the mining industry*. Moscow: Nedra; 1977. 327 p. (In Russ.)

2. Shchutsky V.I., Sidorov A.I., Sitchikhin Yu.V. et al. *Electrical safety in open–pit mining*. Moscow: Nedra; 1996. (In Russ.)

3. Pichuev A.V., Peturov V.I., Suvorov I.F. *Effects of non-stationary modes on electrical safety of mining electrical equipment.* Moscow: Gornaya kniga; 2011. 326 p. (In Russ.)

4. Klyuev R.V., Bosikov I.I., Gavrina O.A., Lyashenko V.I. Assessment of operational reliability of power supply to developing ore mining areas at a high-altitude mine. *Mining Science and Technology* (*Russia*). 2021;6(3):211–220. (In Russ.) https://doi.org/10.17073/2500-0632-2021-3-211-220

5. Kim K.E. *Non-stationary modes in mine electrical networks up to 1,000 V and their impact on electrical safety*. [Ph.D. Thesis] Moscow: Moscow Mining University; 1975. (In Russ.)

6. Kolosyuk V.P. *Emergency tripping in mine electrical installations*. Moscow: Nedra; 1980. 334 p. (In Russ.)

7. Sidorov A.I., Peturov V.I., Pichuev A.V. et al. Electrical safety of power supply systems. *Advances in Current Natural Sciences.* 2010;(2):114. URL: https://natural-sciences.ru/ru/article/view?id=7752 (In Russ.)

8. Peturov V.I. Method for measuring phase insulation properties in insulated neutral systems. *Elektrobezopasnost*. 1998;(1):9–12. (In Russ.)

9. Kano Murga J. *Electricity. The danger of its use and protection of people from electric shock*. MF. Per. GPNTB, “Instalador”. 1976;(106):75–78.

10. Pouvel I. Problems de protection dans les reseaux miniers. *Revue de l’industrie minerale*. 1983;25(7). (In French)

11. Kupfer J., Bastek R., Eggert S. Grenzwerte zur Vermeidung von unfallen durch electrischen strom min tödlichem Ausgang. *Zeitschrift für die Gesamte Hygiene*. 1981;27(1):9–12. (In German)

12. Suvorov I.F. *Integrated electrical safety systems for electrical installations up to 1000 V*. Chita: Chita State University; 2005. 328 p. (In Russ.)

13. Khusainov Sh.N., Sidorov A.I., Khusainova N.A. Improved method for insulation conductivity estimation of a grid segment with a branch line from the electric parameter measurements. *Bulletin of South Ural State University. Series: Power Engineering.* 2002;(7):24–29. (In Russ.)

14. Pichuev A.V. Parametric relationships for the insulation resistance of mine electrical networks. *Mining Informational and Analytical Bulletin.* 2011;(4):398–400. (In Russ.)

15. Tsapenko E.F. Resonant overvoltages in mine networks caused by the use of UAKI, AZAK, AZSh, AZUR RCP Devices. *Mining Informational and Analytical Bulletin.* 2000;(3):106–109. (In Russ.)

16. Tsapenko E.F. Leackage current protection monitoring in mine networks up to 1,200 V. *Mining Informational and Analytical Bulletin.* 2003;(6):155–156. (In Russ.)

17. Pichuev A.V. Unsymmetrical current leakage through the insulation in mine electrical networks. *Elektrobezopasnost*. 2011;(2):28–33. (In Russ.)

18. Abderrezak H., Mizane A. Hybrid model for insulation active component control in an isolated neutral electrical network. In: *Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management.* Istanbul, Turkey, July 3–6, 2012. Pp. 1961–1970. URL: https://ieomsociety.org/ieom2012/pdfs/466.pdf

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