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EFFECT OF VOLTAGE FLICKER ON LEAKAGE CURRENT IN MINE ELECTRICAL NETWORKS CONTAINING POWER ELECTRONIC DEVICES

Purpose. To build a mathematical and simulation model to evaluate the effect of voltage flicker on leakage current in an underground mine AC power network containing power electronic devices.

Methodology. The research methods used in this study include theoretical method to build the equation of leakage current and simulation modeling method on Matlab/Simulink software to determine the leakage current values in each case of voltage flicker.

Findings. In addition to the theoretical analysis on the mine power network model, the paper also evaluates the mine power network model containing the converter on Matlab/Simulink with the model parameters U = 1,140 V, C = 0.19 uF/phase, R = 168 kΩ/phase. The research results show that in the case of low voltage flicker with voltage amplitude lower than 50 % of rated voltage in ½ network cycle, the leakage current before the inverter decreases by the largest 19.7 % and the leakage current after the inverter decreases by the largest 5.2 % compared to the leakage current value at normal voltage. In the case of overvoltage flicker with voltage amplitude higher than 150 % of rated voltage in ½ network cycle, the maximum leakage current before the inverter increases by 33.6 %, the maximum leakage current after the inverter increases by 47.4 % compared to the leakage current value at normal voltage. This problem causes the phenomenon of mistaken operation of the leakage protection relay and causes unsafety in mining.

Originality. The study includes the introduction of a leakage current model in an underground mine's AC power network containing power electronic devices and the simulation to find out the influence of voltage flicker on the leakage current in that power network using Matlab/Simulink software.

Practical value. The research results indicate the need for measures to minimize voltage flicker, thereby improving the reliability of leakage protection and improving safety in mining.

Keywords: *voltage quality, voltage flicker, power electronics, leakage current, mine power network*

Introduction. The mine power network has a ray-shaped structure, large network length, and many large-capacity loads (pumps, excavators, scrapers, etc.), so during the operation of the mine power network, voltage fluctuations often occur during operation [1, 2]. This reduces the power quality of the network, negatively affecting the operation of electrical equipment. Low power quality including voltage flicker (voltage sag and swell) is a phenomenon of voltage degradation, imbalance, voltage transients or short-term power interruptions. According to IEEE Std.1159-1995, voltage sag and swell is defined as the phenomenon of voltage RMS value decreasing in the range of 10–90 % or exceeding 110 % compared to the rated voltage for a short period of time, from half of the network voltage cycle to one minute [3].

Many studies have shown that voltage fluctuations greatly affect the operation of the power network as well as cause unsafety in the operation of the mine power network. According to research [4], when switching large capacity motors in the mine power network, it causes voltage fluctuations (voltage drop, overvoltage), this phenomenon can cause unsafety in the mine power network.

Power quality and energy efficiency in mining power systems are the focus of research [5]. Study on the requirements in using common types of power electronic devices to improve the reliability of power systems in

mining. According to research [6], it is pointed out that electric leakage is one of the most common fault forms of low-voltage power network in mining, and it is proposed to design a leakage protection system of low-voltage mine power network based on the framework of Internet of Things using ZigBee technology to collect and transmit relevant data.

In the study [7], it was shown that the voltage drop caused by the starting current of the asynchronous motor can affect the neighboring equipment. This paper proposes the use of STATCOM devices to reduce the voltage drop caused by the starting of the asynchronous motor. In the study [8, 9], it was shown that the main power quality problems are high harmonics, low power factor, voltage flicker, etc. These problems affect the working efficiency of equipment in the mine power network.

The study [10, 11] presented the results of the investigation related to the impact of voltage fluctuations on the performance of electrical equipment, from which an analytical expression was developed to establish a direct relationship between electrical fluctuations and electrical loads. The design of remote monitoring system for mine power network leakage protection includes intelligent power network leakage protection device with ZigBee and LabVIEW based monitoring software designed on PC, the power network data is sent to the mine monitoring center through the ground through the industrial ring network and published on the Web, to build a remote monitoring system for low voltage power network leakage protection in coal mine [12].

The insulation status of high-voltage power cables in coal mines has a direct impact on the reliability of power supply in coal mines and the level of safe production. Based on the principle of cable degradation judgment method, a degradation mechanism of cable insulation and online monitoring technology of cable insulation in coal mines are analyzed in this study [13, 14].

Analysis of problems of failures and interruptions in the production process directly related to the power quality of the power supply network is presented in the study [15]. This directly leads to increased production costs and significantly affects the safety of workers. In the study [16], a theoretical analysis of leakage current in the mine power network is given, and the paper describes the leakage protection of the mine power network based on zero-sequence voltage and zero-sequence power direction based on DC power source. In the study [17], an overvoltage and leakage protection system based on PLC LM3108K for power network with supply voltage 660 V and rated current 200 A was designed.

Reliable detection and limitation of ground currents is a key factor for safety in mining as shown in the study [18]. The risks and ways to mitigate them have been discussed in detail in the literature. What has not been considered in the past is that variable speed drives (VSDs) are complex voltage sources that can bypass or interfere with conventional protective equipment. Even in earth fault limited networks, VSDs can create local leakage current loops that exceed the maximum levels specified in the operating standards.

Mining loads are very sensitive to voltage fluctuations, as shown in studies [19–21]. The machines used are mainly asynchronous motors; these motors are very sensitive to voltage fluctuations because the torque is proportional to the square of the voltage. In the process of increasing the capacity of the mine, causing the mining depth to increase, the voltage value continues to decrease, causing a large voltage drop, causing serious consequences for the equipment in the mine. In the study [22–24], it is shown that some problems such as flicker and harmonics are now more concerned in mining. Therefore, the analysis of these power quality problems is very important for network operators to improve their network infrastructure when designing new networks.

Nowadays, power electronic devices such as inverters and soft starters are widely used in mining. When using power electronic devices, it greatly affects the leakage current in mining [25, 26]. However, the influence of voltage flicker on leakage current in mine power networks containing power electronic devices has not been mentioned, which causes a lack of theoretical basis for it and unsafety for mine power networks containing power electronic devices. The article focuses on researching the impact of voltage flicker on leakage current in mine power networks containing power electronic devices, the research results are shown in the theoretical model as well as demonstrated on the simulation model. Part 1 of the paper presents an overview of the related issues. Part 2 presents a Leakage current model in the mine network under voltage flicker. Part 3 presents the results of the study on the influence of voltage flicker on leakage current with typical cases. The final part is the conclusion of the study.

Leakage current model in the mine network under voltage flicker. ***Leakage current model in mine power network containing power electronic devices.*** In the mine power network containing power electronic devices (most commonly inverters), the power network will include three types of current components including: a 50 Hz alternating current component; a direct current component; an alternating current component with frequency other than 50 Hz. The general replacement diagram for the underground mine power network containing power electronic devices is shown in Fig. 1 [27].

In the diagram in Fig. 1, the symbols R_A, R_B, R_C, C_A, C_B, C_C are the insulation resistance and phase capacitance to ground of the network section before the inverter (BI); R_{Af}, R_{Bf}, R_{Cf}, C_{Af}, C_{Bf}, C_{Cf} are the insulation resistance and phase capacitance to ground of the network section after the inverter (AI); R_+, R_-, C_+, C_- are the insulation resistance and capacitance between the positive (+) and negative (–) terminals relative to ground of the direct current (DC) network section; U_f is the secondary phase voltage of the area transformer; U_0 is the average value of the three-phase bridge rectifier voltage.

Suppose when there is an electric leakage in the AC power network, the leakage current i_a from the 50 Hz AC

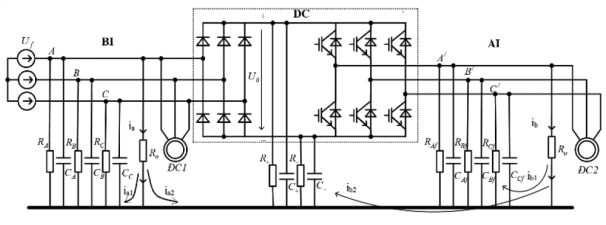


Fig. 1. General replacement diagram of a mine power network containing power electronic devices

power network is divided into two current components i_{a1} and i_{a2}, which are the leakage current components to the AC and DC power networks. Similarly, the leakage current on the AC side of the network with a frequency other than 50 Hz i_b is divided into currents i_{b1} and i_{b2} for the DC and AC networks. To determine these current components, it is necessary to determine the insulation resistance parameters of the network and the voltage of the phases relative to ground in the mine power network.

Leakage current on 50 Hz AC power network. When leakage occurs before the inverter through the leakage resistor R_0, the corresponding leakage current i_a is divided into two components. The leakage current component i_{a1} flows back to the 50 Hz AC network, the leakage current component i_{a2} flows back to the DC network. The leakage current before the inverter is determined by the formula (1 and 2) [27].

$$I_{a1} = U_f \frac{\sqrt{R^2 + X_C^2}}{\sqrt{R^2 R_0^2 + X_C^2 (R + R_0)^2}}; \quad (1)$$

$$I_{a2} = I_2^- - I_2^+ = \\ = 1.17 U_f \left(\frac{1}{R_0 (R + R_-) + R R_-} - \frac{1}{R_0 (R + R_+) + R R_+} \right) R. \quad (2)$$

RMS value of leakage current on the 50 Hz AC network side is calculated according to formula.

$$I_a = \sqrt{I_1^2 + I_2^2} = U_f \sqrt{\frac{R^2 + X_C^2}{R^2 R_0^2 + X_C^2 (R + R_0)^2} + 1.17^2 R^2 \left[\frac{1}{R_0 (R + R_-) + R R_-} - \frac{1}{R_0 (R + R_+) + R R_+} \right]^2}. \quad (3)$$

When the DC power network is symmetrical ($R_+ = R_- = R_{dc}$), then the leakage current has only the AC component and is calculated according to formula

$$I_a = I_{a1} = U_f \frac{\sqrt{R^2 + X_C^2}}{\sqrt{R^2 R_0^2 + X_C^2 (R + R_0)^2}}. \quad (4)$$

Leakage current on AC power network with frequency other than 50 Hz. Similar to the above case, when there is an electric leakage on the power network after the inverter through the leakage resistor R_0, the leakage current i_b consists of two components i_{b1}, i_{b2} respectively closing the loop towards the 50 Hz AC power network and the DC power network, the leakage current i_b is determined according to formula (5 and 6) [27].

RMS value of leakage current of power network with frequency other than 50 Hz is calculated according to formula (7).

When the DC power network is symmetrical ($R_+ = R_- = R_{dc}$), then the leakage current has only the AC component and is calculated according to formula (8).

Formulas (3, 4, 7 and 8) show that in an AC power network containing converters, the leakage current in the power network depends not only on the insulation parameters of the network but also on the voltage of the mine power network. This proves that when voltage flicker occurs, the voltage value changes, leading to a change in the leakage current.

$$I_{b1} = U'_f \frac{\sqrt{R_f^2 + X_{Cf}^2}}{\sqrt{R_f^2 R_0^2 + X_{Cf}^2 (R_f + R_0)^2}}; \quad (5)$$

$$I_{b2} = \frac{2.34 U_f}{R_- R_+ R_f + R_- R_+ R_0 + R_- R_f R_0 + R_+ R_f R_0} R_+ R_f; \quad (6)$$

$$I_b = \sqrt{\frac{U'^2_f \left(R_f^2 + X_{Cf}^2 \right)}{R_f^2 R_0^2 + X_{Cf}^2 (R_f + R_0)^2} + \frac{2.34^2 U_f^2 R_+^2 R_f^2}{(R_- R_+ R_f + R_- R_+ R_0 + R_- R_f R_0 + R_+ R_f R_0)^2}}; \quad (7)$$

$$I_b = \sqrt{\frac{U'^2_f (R_f^2 + X_{Cf}^2)}{R_f^2 R_0^2 + X_{Cf}^2 (R_f + R_0)^2} + \frac{2.34^2 U_f^2 R_f^2}{(R_{dc} R_f + R_{dc} R_0 + 2 R_f R_0)^2}}. \quad (8)$$

Insulation parameters of underground mine power network. To determine the insulation parameters of underground mine power network, the three-voltmeter method in Fig. 2 is often used [28].

Assuming the source voltage is symmetrical, when adding an additional resistor R_f, the voltage vector graph

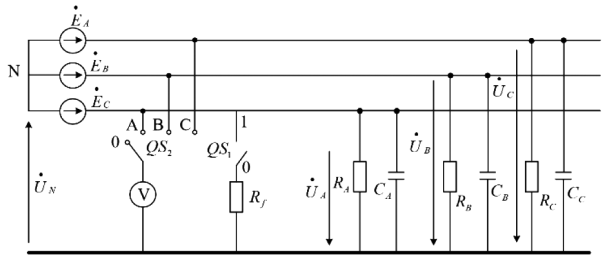


Fig. 2. Schematic diagram of insulation parameter measurement using the three-voltmeter method

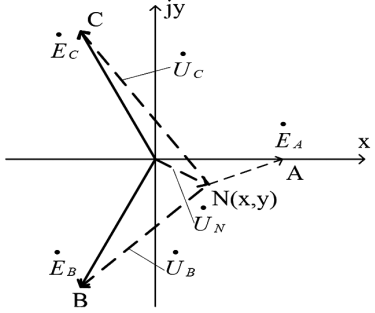


Fig. 3. Voltage vector graph with additional resistor R_f

of the network is depicted in Fig. 3.

From the vector plots, the neutral point voltage $\dot{U}_N$ can be calculated in terms of the phase voltages $\dot{U}_A,\dot{U}_B,\dot{U}_C$. The equation of a circle with center at points *A*, *B*, *C* and radii U_A, U_B, U_C is according to formulas.

$$\begin{gathered}\left(x-\frac{U_d}{\sqrt{3}}\right)^2+y^2=U_A^2;\\ \left(x+\frac{U_d}{2\sqrt{3}}\right)^2+\left(y+\frac{U_d}{2}\right)^2=U_B^2;\\ \left(x+\frac{U_d}{2\sqrt{3}}\right)^2+\left(y-\frac{U_d}{2}\right)^2=U_C^2.\end{gathered} \quad (9)$$

From there, *x* and *y* are calculated according to formula

$$x=\frac{U_B^2+U_C^2-2U_A^2}{6U_f};\quad y=\frac{U_B^2-U_C^2}{2\sqrt{3}U_f}.$$

Therefore, the neutral point voltage is expressed according to formula

$$\dot{U}_N=\frac{U_B^2+U_C^2-2U_A^2}{6U_f}+j\frac{U_B^2-U_C^2}{2\sqrt{3}U_f}. \quad (10)$$

The phase voltages are calculated according to formulas

$$\dot{U}_A=U_f-\dot{U}_N=\frac{2U_A^2-(U_B^2+U_C^2)}{6U_f}+U_f+j\frac{U_C^2-U_B^2}{2\sqrt{3}U_f}; \quad (11)$$

$$\begin{gathered}\dot{U}_B=a^2U_f-\dot{U}_N=\\ =\frac{2U_A^2-(U_B^2+U_C^2)}{6U_f}-\frac{1}{2}U_f+j\left[\frac{U_C^2-U_B^2}{2\sqrt{3}U_f}-\frac{\sqrt{3}}{2}U_f\right];\end{gathered} \quad (12)$$

$$\begin{gathered}\dot{U}_C=aU_f-\dot{U}_N=\\ =\frac{2U_A^2-(U_B^2+U_C^2)}{6U_f}-\frac{1}{2}U_f+j\left[\frac{U_C^2-U_B^2}{2\sqrt{3}U_f}+\frac{\sqrt{3}}{2}U_f\right].\end{gathered} \quad (13)$$

In the case of short circuit of phase A to ground, short circuit current of phase A is calculated according to formula

$$\dot{I}_{An}=\dot{U}_A\cdot Y_\Sigma. \quad (14)$$

When adding an additional resistor R_f, the short circuit current is calculated according to formula

$$\dot{I}_{An}=\dot{U}'_A\cdot(Y_\Sigma+Y_f), \quad (15)$$

where, $\dot{U}'_A$ is phase A voltage relative to ground when adding additional resistor R_f; $Y_\Sigma=G_\Sigma+j\omega C_\Sigma$ is total admittance of the electrical network insulation relative to ground; $Y_f=\frac{1}{R_f}=g_f$ is additional admittance connected to phase A of the network.

From expressions (14, 15) and because the short-circuit current in the two cases is constant, we have the expression.

$$\dot{U}_A\cdot Y_\Sigma=\dot{U}'_A\cdot(Y_\Sigma+Y_f)\to Y_\Sigma=\frac{\dot{U}'_A\cdot Y_f}{\dot{U}_A-\dot{U}'_A}. \quad (16)$$

The total insulation conductance and total insulation susceptance of the network relative to ground are calculated according to formula.

$$\begin{gathered}G_\Sigma=\mathrm{Re}\left(\frac{\dot{U}'_A\cdot Y_f}{\dot{U}_A-\dot{U}'_A}\right);\\ b_\Sigma=\omega C_\Sigma=I_m\left(\frac{\dot{U}'_A\cdot Y_f}{\dot{U}_A-\dot{U}'_A}\right).\end{gathered} \quad (17)$$

Assuming

$$\begin{gathered}\dot{U}_A=a+jd;\\ \dot{U}'_A=a'+jd',\end{gathered} \quad (18)$$

where

$$\begin{gathered}a=\frac{2U_A^2-(U_B^2+U_C^2)}{6U_f}+U_f;\\ a'=\frac{2U_A'^2-(U_B'^2+U_C'^2)}{6U_f}+U_f;\\ d=\frac{U_C^2-U_B^2}{2\sqrt{3}U_f};\\ d'=\frac{U_C'^2-U_B'^2}{2\sqrt{3}U_f},\end{gathered}$$

we substitute $Y_f=1/R_f$ and (18) into expressions (16) and (17), and get the formula (19).

$$\begin{gathered}G_\Sigma=\frac{1}{R_\Sigma}=\frac{a'(a-a')+d'(d-d')}{R_f\left[(a-a')^2+(d-d')^2\right]};\\ C_\Sigma=\frac{ad'-a'd}{\left[(a-a')^2+(d-d')^2\right]R_f}.\end{gathered} \quad (19)$$

From the above theoretical basis, it can be seen that when the voltage and frequency parameters of the network change, the insulation parameters including the resistance and conductivity of the network change, causing the leakage current in the power network to also change.

Phase to ground voltage in the electrical network containing the converter. To determine the average value of the phase voltage relative to ground on the AC side of the mine power network containing the converter equipment, consider an equivalent circuit diagram as shown in Fig. 4 [29, 30].

Assume the symmetrical three-phase AC source voltage has the following form

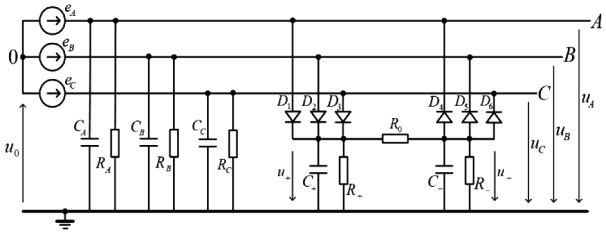


Fig. 4. Equivalent diagram for calculating the average value of phase voltage

$$e_A = E_m \sin \omega t;$$
$$e_B = E_m \sin [\omega(t - T/3)];$$
$$e_C = E_m \sin [\omega(t - 2T/3)],$$

where E_m, ω, T respectively are the amplitude, angular frequency and period of the three-phase source electromotive force.

Phase voltage to ground is calculated as follows

$$u_A = e_A - u_0;$$
$$u_B = e_B - u_0;$$
$$u_C = e_C - u_0,$$

where u_0 is the voltage between ground and neutral of the source.

During one cycle of network voltage, the diodes have different working states, specifically as follows.

During the period $T/12 < t < 3T/12$, diodes D_1 and D_5 conduct with the equivalent calculation diagram as shown in Fig. 5.

From the diagram in Fig. 5, the equation of Kirchhoff's first law is shown as follows formula.

$$i_{CA} + i_{GA} + i_{CB} + i_{GB} + i_{CC} + i_{GC} + i_{C+} + i_{G+} + i_{C-} + i_{G-} = 0. \quad (20)$$

The parameters being substituted in, the above equation becomes according to formulas.

$$\begin{aligned} &C_A \frac{du_A}{dt} + G_A u_A + C_B \frac{du_B}{dt} + G_B u_B + C_C \frac{du_C}{dt} + \\ &+ G_C u_C + C_+ \frac{du_A}{dt} + G_+ u_A + C_- \frac{du_B}{dt} + G_- u_B = 0; \\ &(G_A + G_+) u_A + (C_A + C_+) \frac{du_A}{dt} + (G_B + G_-) u_B + \\ &+ (C_B + C_-) \frac{du_B}{dt} + C_C \frac{du_C}{dt} + G_C u_C = 0. \end{aligned} \quad (21)$$

Substituting phase voltage to ground, we get the above equation according to formula.

$$\begin{aligned} &(G_A + G_+)(e_A - u_0) + (C_A + C_+) \frac{d(e_A - u_0)}{dt} + \\ &+ (G_B + G_-)(e_B - u_0) + (C_B + C_-) \frac{d(e_B - u_0)}{dt} + \\ &+ G_C (e_C - u_0) + C_C \frac{d(e_C - u_0)}{dt} = 0. \end{aligned} \quad (22)$$

Similarly, in the period $3T/12 < t < 5T/12$ the diodes D_1 and D_6 conduct. The equation of Kirchhoff's first law for the circuit is according to formula.

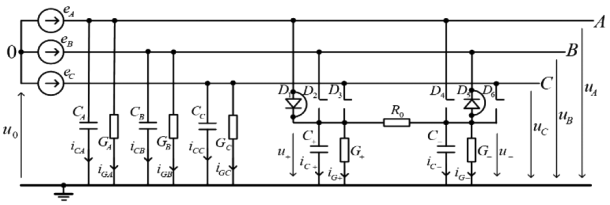


Fig. 5. Equivalent diagram when diodes D_1 and D_5 are conducting

$$\begin{aligned} &(G_A + G_+)(e_A - u_0) + (C_A + C_+) \frac{d(e_A - u_0)}{dt} + \\ &+ G_B (e_B - u_0) + C_B \frac{d(e_B - u_0)}{dt} + (G_C + G_-)(e_C - u_0) + \\ &+ (C_C + C_-) \frac{d(e_C - u_0)}{dt} = 0. \end{aligned} \quad (23)$$

Similarly, in the period $5T/12 < t < 7T/12$ the diodes D_2 and D_6 conduct. The equation of Kirchhoff's first law for the circuit is according to formula.

$$\begin{aligned} &G_A (e_A - u_0) + C_A \frac{d(e_A - u_0)}{dt} + (G_B + G_+)(e_B - u_0) + \\ &+ (C_B + C_+) \frac{d(e_B - u_0)}{dt} + (G_C + G_-)(e_C - u_0) + \\ &+ (C_C + C_-) \frac{d(e_C - u_0)}{dt} = 0. \end{aligned} \quad (24)$$

Similarly, in the period $7T/12 < t < 9T/12$ the diodes D_2 and D_4 conduct. The equation of Kirchhoff's first law for the circuit is according to formula.

$$\begin{aligned} &(G_A + G_-)(e_A - u_0) + (C_A + C_-) \frac{d(e_A - u_0)}{dt} + \\ &+ (G_B + G_+)(e_B - u_0) + (C_B + C_+) \frac{d(e_B - u_0)}{dt} + \\ &+ G_C (e_C - u_0) + C_C \frac{d(e_C - u_0)}{dt} = 0. \end{aligned} \quad (25)$$

Similarly, in the period $9T/12 < t < 11T/12$ the diodes D_3 and D_4 conduct. The equation of Kirchhoff's first law for the circuit is according to formula.

$$\begin{aligned} &(G_A + G_-)(e_A - u_0) + (C_A + C_-) \frac{d(e_A - u_0)}{dt} + \\ &+ G_B (e_B - u_0) + C_B \frac{d(e_B - u_0)}{dt} + \\ &+ (G_C + G_+)(e_C - u_0) + (C_C + C_+) \frac{d(e_C - u_0)}{dt} = 0. \end{aligned} \quad (26)$$

Similarly, in the time period $11T/12 < t < 13T/12$ the diodes D_3 and D_5 conduct. The equation of Kirchhoff's first law for the circuit is according to formula.

$$\begin{aligned} &G_A (e_A - u_0) + C_A \frac{d(e_A - u_0)}{dt} + (G_B + G_-)(e_B - u_0) + \\ &+ (C_B + C_-) \frac{d(e_B - u_0)}{dt} + (G_C + G_+)(e_C - u_0) + \\ &+ (C_C + C_+) \frac{d(e_C - u_0)}{dt} = 0. \end{aligned} \quad (27)$$

By integrating expressions (22) to (27) in its limits and after transformation, the average value of voltage u0 (which is also the average value of phase voltages relative to ground) is expressed by the following formula [31].

$$U_{0\,AV} = \frac{3\sqrt{3} E_m}{2\pi} \frac{G_+ - G_-}{G_i}, \quad (28)$$

where $G_i = G_A + G_B + G_C + G_+ + G_-$ is the equivalent insulation conductivity of the entire electrical network relative to ground. The average value of the voltage u0 and of the phase voltage are obviously equal.

Expression (28) can also be written in the formula (29).

$$U_{Atb} = \frac{3\sqrt{3}E_m}{2\pi}\frac{R_2 - R_1}{R_1 + R_2}\frac{R_{\approx}}{R_{=} + R_{\approx}}, \quad (29)$$

where $R_{\approx} = R_A // R_B // R_C = \frac{R_A R_B R_C}{R_A R_B + R_B R_C + R_C R_A}$, $R_{=} = R_{+} // R_{-} = \frac{R_{+} R_{-}}{R_{+} + R_{-}}$ are the equivalent insulation resistances of the AC and DC network parts relative to ground.

Voltage flicker phenomenon in mine power network. The voltage flicker phenomenon caused by closing or opening a switching device is similar to the instantaneous insertion of a voltage of value $\{u_1(0) - u_2(0)\}$ between the two contacts of the switching device in Fig. 6 [32–34].

In the simple case, the voltage and current on both sides of the switching device are determined by the following formulas (30) and (31).

$$\begin{cases} u_1(t) = Z_1 \cdot i_1(t) = \frac{Z_1}{Z_1 + Z_2}\{e_1(0) - e_2(0)\} \\ u_2(t) = Z_2 \cdot i_2(t) \frac{-Z_2}{Z_1 + Z_2}\{e_1(0) - e_2(0)\} \end{cases}; \quad (30)$$

$$\begin{cases} i_1(t) = \frac{1}{Z_1 + Z_2}\{e_1(0) - e_2(0)\} \\ i_2(t) = \frac{-1}{Z_1 + Z_2}\{e_1(0) - e_2(0)\} \end{cases}, \quad (31)$$

where $e_1(0)$, $e_2(0)$ are the voltage sources on both sides of the switching device at the moment before switching; Z_1 and Z_2 are the impedances of the two-way conductors connected to the switching device.

The voltage flicker phenomenon mainly depends on the switching of large power loads and the location of the switching device, whether it is far or near. The parameters of voltage flicker are determined as amplitude, increase and duration in the mine power network.

Results and discussion. ***Simulation of leakage current in mine power network containing converter.*** The mine power network model to evaluate the impact of converters (specifically here is the inverter) on leakage current in the mine power network is built based on the power network parameters suitable for mining in Quang Ninh region of Vietnam corresponding to the values of the model: $C = 0.19$ uF/phase; $R = 168$ kΩ/phase; $U = 1{,}140$ V; frequency 50 Hz, leakage resistance $R_0 = 1$ kΩ [27]. The simulation model is built on Matlab – simulink software as shown in Fig. 7.

In case the voltage of the power network is normal, if there is an electric leakage before and after the inverter at time 0.3 s, the leakage current value will give the result in Fig. 8.

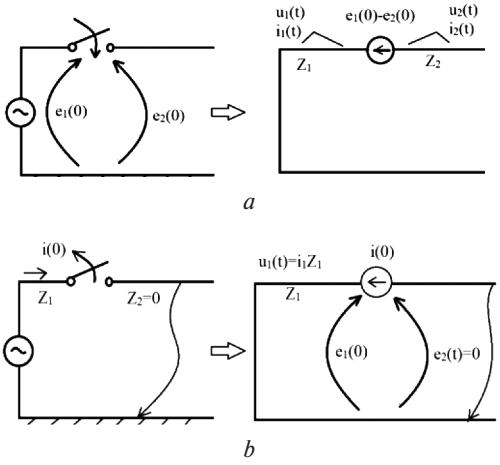


Fig. 6. Alternative model when closing (a) and when breaking (b) of the switching device

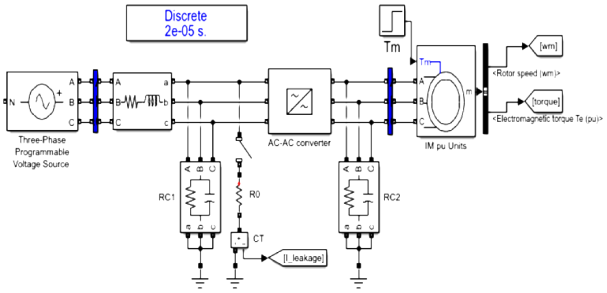
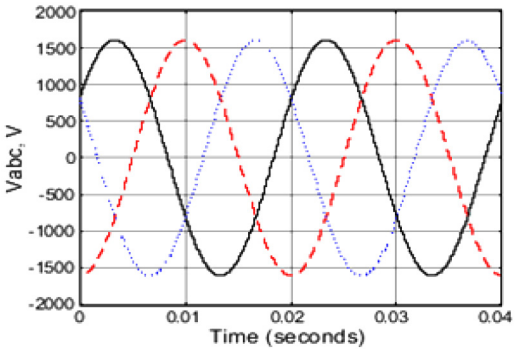
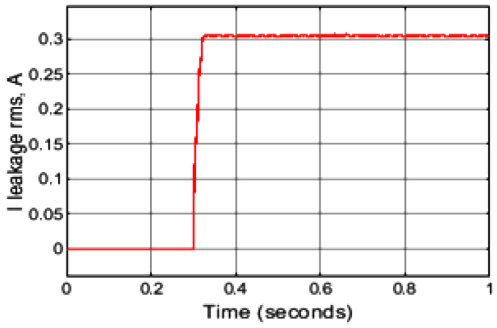


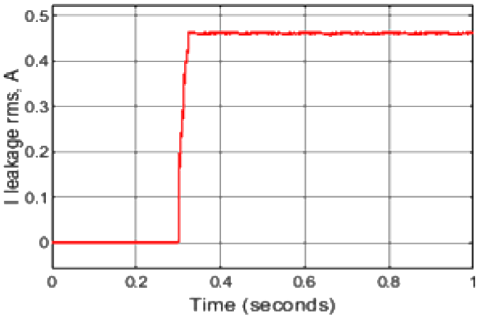
Fig. 7. Mine power network simulation model containing conversion equipment



a



b



c

Fig. 8. Network voltage (a) and RMS leakage current value before the inverter (b) and after the inverter (c)

The results in Fig. 8 show that the leakage current after the inverter in the mine power network fluctuates strongly and contains more harmonic components than the leakage current before the inverter. Although the level of harmonics in the leakage current before the inverter is not high, there is still a harmonic current that causes the current to flicker unevenly, which will also cause confusion in the leakage protection relay. The RMS values of the leakage current before and after the inverter are 304 and 462 mA respectively.

Case of low voltage flicker. Considering the case of voltage flicker with voltage amplitude lower than 50 % of rated voltage in ½ network cycle at time 0.5 s, the results obtained for voltage and leakage current before and after the inverter are shown in Fig. 9.

At the time of voltage drop, the leakage current both before and after the inverter will decrease. The leakage current before the inverter is reduced to 244 mA (lowest), which is a reduction by 19.7 % (60/304 mA) compared to the leakage current value at normal voltage. The leakage current after the inverter is reduced by 438 mA (lowest), which is a reduction by 5.2 % (24/462 mA) compared to the leakage current value at normal voltage. This shows that the leakage current after the inverter is also strongly affected by the voltage drop phenomenon, but the level of influence is lower than the leakage case before the inverter.

Case of over voltage flicker. Considering the case of overvoltage flicker with voltage amplitude higher than 150 % of rated voltage in ½ network cycle at time 0.5 s, the results obtained for voltage and leakage current before and after the inverter are shown in Fig. 10.

In case of voltage increase, the leakage current both before and after the inverter increases. In the studied case, the maximum leakage current before the inverter reached 406 mA, corresponding to an increase of 33.6 % (102/304 mA) compared to the leakage current value at normal voltage. The maximum leakage current after the inverter reached 681mA, corresponding to an increase of 47.4 % (219/462 mA) compared to the leakage current value at normal voltage. This shows that the leakage current values both before and after the inverter fluctuate greatly in case of overvoltage in the mine power net-

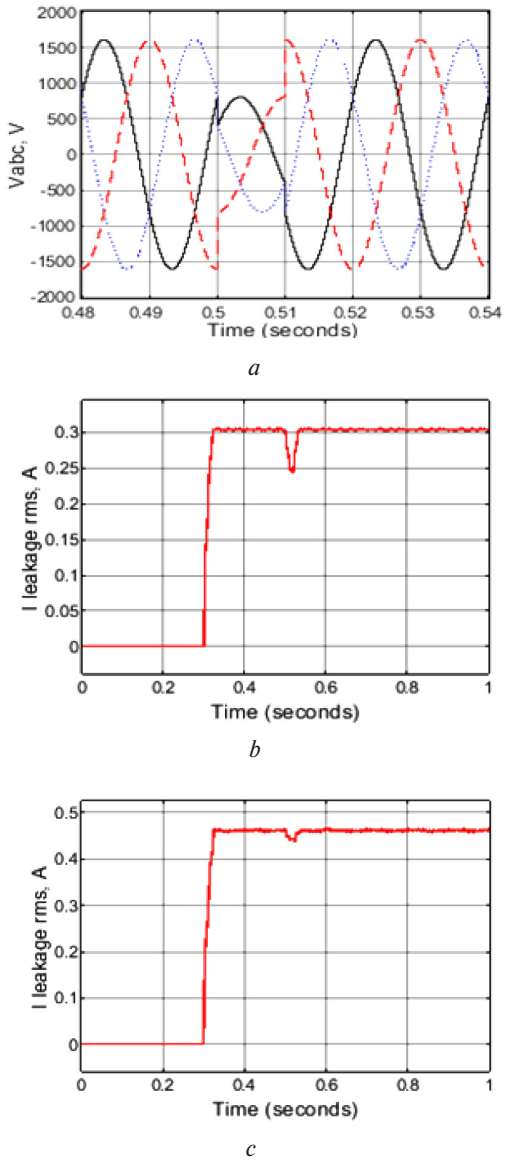


Fig. 9. Case of low voltage flicker:
a — Network voltage; b — Leakage current before the inverter; c — Leakage current after the inverter

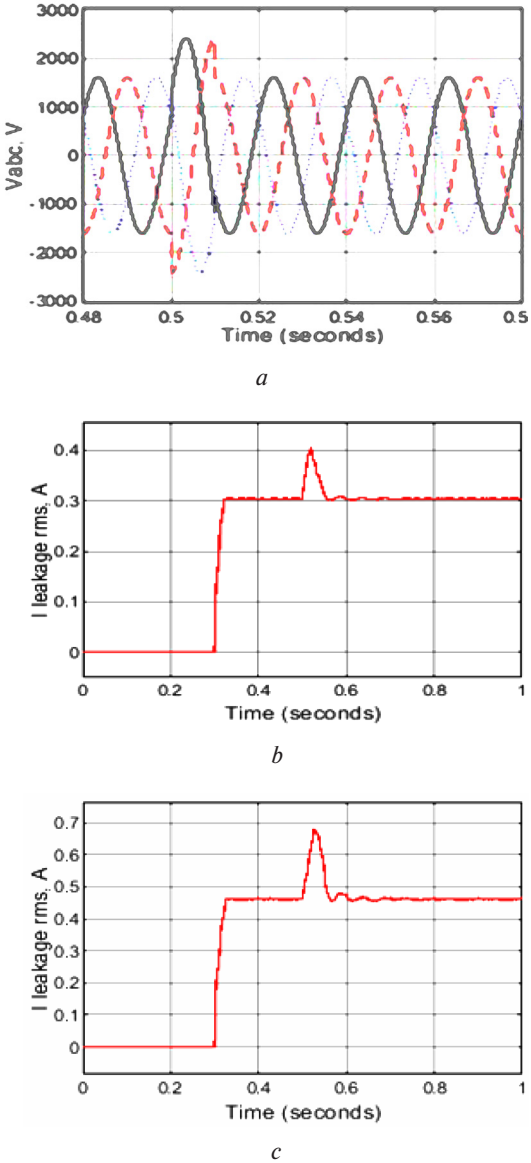


Fig. 10. Case of over voltage flicker:
a — Network voltage; b — Leakage current before the inverter; c — Leakage current after the inverter

work, the leakage current behind the inverter has a larger increase than that in front of the inverter. This problem causes the leakage protection relay to operate incorrectly and causes unsafety in mining.

Conclusions. The mine power network is characterized by a beam-shaped structure, large network length, and many large-capacity loads, so the operation of the mine power network often occurs under voltage fluctuations, which greatly affects the working efficiency, especially the leakage protection relay in the mine power network. Along with that, the increased use of power electronic devices in the mine power network increases the impact of voltage flicker, leading to poor performance of leakage protection devices, causing unsafe mining operations.

The research results are shown on the theoretical model and simulation model on Matlab/Simulink with the model parameters $U = 1{,}140$ V, $C = 0.19$ uF/phase, $R = 168$ kΩ/phase. The research results show that in the case of low voltage flicker with voltage amplitude lower than 50 % of rated voltage in ½ network cycle, the leakage current before the inverter decreases by the largest 19.7 % and the leakage current after the inverter decreases by the largest 5.2 % compared to the leakage current value at normal voltage. In the case of overvoltage flicker with voltage amplitude higher than 150 % of rated voltage in ½ network cycle, the maximum leakage current before the inverter increases by 33.6 %, the maximum leakage current after the inverter increases by 47.4 % compared to the leakage current value at normal voltage.

The above research results show that voltage flicker has a great influence on leakage current in the mine power network, especially when there is leakage after the inverter. Therefore, it is necessary to have a solution to minimize voltage flicker, thereby improving power quality, improving the reliability of leakage protection, and improving safety in mining.

In addition to the voltage flicker phenomenon, the leakage protection relay in the mine power network also depends greatly on the quality of the power supply network, especially the problems that arise when using power electronic equipment in the mine power network such as harmonics, power supply radius, and load types in the power network. Therefore, the next direction will focus on studying the influence of many factors on the leakage current in the mine power network to find solutions to improve the working reliability of the leakage protection relay in the mine power network.

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Вплив флікера напруги на струм протікання в електромережах шахт із силовими електронними пристроями

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Мета. Побудова математичної та імітаційної моделей для оцінювання впливу флікера напруги на струм протікання в мережі змінного струму шахти, що містить силові електронні пристрої.

Методика. У цьому дослідженні використані теоретичний метод для побудови рівняння струму протікання, а також метод імітаційного моделювання в середовищі Matlab/Simulink для визначення значень струму протікання в кожному випадку мерехтіння напруги.

Результати. Окрім теоретичного аналізу моделі шахтної електромережі, у роботі також проведене оцінювання моделі мережі із перетворювачем у середовищі Matlab/Simulink із такими параметрами моделі: U = 1140 В, C = 0,19 мкФ/фаза, R = = 168 кОм/фаза. Результати дослідження показують, що у випадку флікера зниження напруги, коли амплітуда напруги становить менше 50 % від номінального значення протягом половини періоду мережі, струм протікання до інвертора зменшується максимум на 19,7 %, а після інвертора – максимум на 5,2 % у порівнянні зі струмом протікання за нормальної напруги. У випадку флікера перенапруги, коли амплітуда напруги перевищує 150 % від номінального значення протягом половини періоду мережі, максимальний струм протікання до інвертора зростає на 33,6 %, а після інвертора – на 47,4 % у порівнянні із нормальним режимом. Це явище може призводити до помилкової роботи реле захисту від струмів протікання, що створює небезпечні умови експлуатації в шахті.

Наукова новизна. Полягає у введенні моделі струму протікання в мережі змінного струму шахти, що містить силові електронні пристрої, а також у проведенні імітаційного моделювання для визначення впливу флікера напруги на струм протікання у цій електромережі із використанням програмного середовища Matlab/Simulink.

Практична значимість. Результати дослідження вказують на необхідність упровадження заходів щодо зменшення флікера напруги, що, у свою чергу, сприятиме підвищенню надійності захисту від струмів протікання й покращенню безпеки ведення гірничих робіт.

Ключові слова: *якість напруги, флікер напруги, силова електроніка, струм протікання, шахтна електромережа*

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