Research on Electric Leakage Protection to Improve Electrical Safety in Underground Mining in Vietnam

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Abstract

To ensure safety in underground mining, it is imperative to equip yourself with electric leakage protection. Today, underground mines are gaining a high degree of mechanization and using more power electronics to enhance the operation and organization of power supplies, including the application of power electronics for DC power transmission in mining. i.e., separate the rectifier (AC-DC) from the inverter (DC-AC) with a long DC cable. The transmission of DC power changes the structure of the mine power network; then there will appear a power network with an industrial frequency of 50 Hz, a DC power network, and a power network after the variable frequency inverter. Due to the mutual interaction between DC power networks and AC power networks, leakage protection devices are unreliable, causing unsafe conditions in mining. The content of the article is to determine the leakage current in the power network when using converters in DC power transmission in mining. The research results are the basis for calculating and selecting leakage protection equipment for the purpose of improving safety in underground mining in Vietnam.

Keywords: *electrical safety, conversion devices, mine power network, leakage protection*

1. Introduction

Underground mining in Vietnam has a harsh environment, such as 100% humidity, a high risk of fire, and tight spaces, leading to a risk of electrical safety for operators. According to Vietnam's regulations on safety in mining, it is mandatory that the electrical network be an isolated neutral network, and it is mandatory to equip the leakage protection relay [1].

Today, underground mines are gradually putting mechanized complexes to use to replace human power. With the increasing degree of mechanization, power electronic converters are gradually being used at all stages of underground mining. They are responsible for regulating the working process of the motor or improving the power quality of the mine power network [2–4].

The use of power electronics for motor drive systems creates harmonics in the mine power network [5–7]. Harmonics generated from power electronic devices confuse leakage protection relays and cause power loss in mine electrical network [8–10]. In order to minimize the influence of power electronic devices and improve the reliability of leakage protection in the underground mine power network, the solution to eliminating harmonics is mentioned in many works [11–13]. However, the use of harmonic filtering equipment increases the costs incurred, increasing the loss of the power network [14, 15].

To reduce power loss and avoid unwanted high-frequency phenomena, power electronics with DC power transmission are used in mining, i.e., separating the AC-DC rectifier from the DC-AC inverter with a DC cable. This solution brings a lot of economic efficiency and reduces the unwanted consequences caused by inverters in mining [15, 16].

Thus, the solution of using power electronics to transmit DC power in mining brings many benefits. However, due to the correlation between the currents in the networks of different frequencies, it causes the unreliable operation of the leakage protection device, causing unsafety in underground mining [19, 20]. In the harsh environmental conditions of underground mines in Vietnam, it is necessary to research solutions to ensure electrical safety in underground mines using power electronic converters to transmit DC power. The content of the article is to build a model to calculate leakage current in an electrical network containing converters to transmit DC power, thereby improving electrical safety in underground mining in Vietnam.

2. Determination of leakage currents in mine power networks using DC power transmission

2.1. Model of underground mine power network with DC power transmission

The underground mine power network using power electronic converters to transmit DC power has a diagram as shown in Figure 1 [14–16].

In which the AC power source V-AC (f=50Hz) is supplied by the regional distribution transformer, through the rectifier, DC power is supplied to the equipment using DC power, and through the inverter, the AC voltage with adjustable frequency is supplied to the working AC motors. For simplicity, it is possible to assume that the network has centralized parameters, ignoring the reactance of transformers and cables and not taking into account the insulation resistance between the phases of the network. The equivalent diagram for the underground mine power network using semiconductor converters is shown in Figure 2 [19].

In equivalent diagram: R_A, R_B, R_C, C_A, C_B, C_C – insulation resistance and phase-to-ground capacitance of the network before the inverter (BI); R_{Af}, R_{Bf}, R_{Cf}, C_{Af}, C_{Bf}, C_{Cf} – insulation resistance and phase-to-ground capacitance of the inverter (AI);

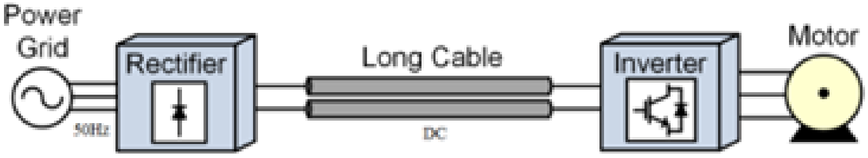

Fig. 1. Underground mine power network using power electronic converters to transmit DC power

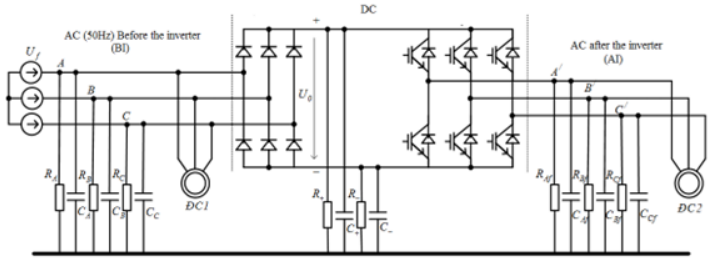

Fig. 2. Equivalent diagram for the underground mine power network using semiconductor converters

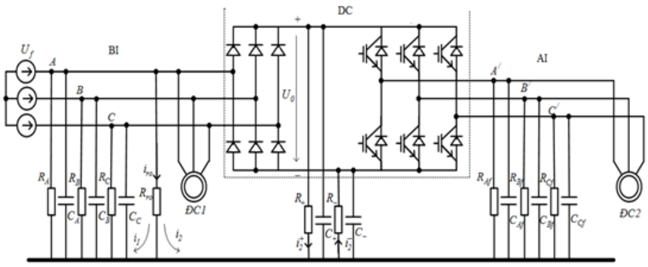

Fig. 3. Diagram of calculating leakage current with case of leakage in the power network BI

R_+, R_-, C_+, C_- – insulation resistance and capacitance between the anode (+) and cathode (-) of the DC network part relative to earth; U_f – secondary winding phase voltage of area transformer; U_0 – average value of three-phase bridge rectifier voltage.

2.2. Leakage current in the power network before the inverter (BI)

In case of electric leakage in the power network BI (power network with industrial frequency), the calculation diagram has the form as shown in Figure 3. In which, R_{ro} is the single-phase leakage resistance, when there is a single-phase leakage, i_{ro} – leakage current through the leakage resistor will consist of two components: The AC component i1 caused by the insulation resistance and capacitance of the AC network part BI and the DC component i_2 has a value depending on the asymmetry of the insulation resistance of the part of the DC network.

The RMS value of the AC component is determined by the formula:

$$I_1 = U_f \frac{\sqrt{R^2 + X_C^2}}{\sqrt{R^2 R_{ro}^2 + X_C^2 (R + R_{ro})^2}} \tag{1}$$

where: R, X_C – resistance and reactance total three-phase insulation of part BI to earth; U_f – network phase voltage.

In the case of ignoring the influence of the insulation impedance of the AI part, the current generated by positive and negative 3 phase half wave rectifier is calculated as follows:

$$I_2^- = \frac{1{,}17 U_f}{R_{ro}(R + R_-) + RR_-} R \tag{2}$$

$$I_2^+ = \frac{1{,}17 U_f}{R_{ro}(R + R_+) + RR_+} R \tag{3}$$

The DC current component i_2 is determined:

$$i_2 = I_2 = I_2^- - I_2^+ = 1{,}17 U_f \left(\frac{1}{R_{ro}(R + R_-) + RR_-} - \frac{1}{R_{ro}(R + R_+) + RR_+} \right) R \tag{4}$$

The RMS value of leakage current in case of leakage in part BI according to expression:

$$I_{ro} = \sqrt{I_1^2 + I_2^2} = U_f \sqrt{\frac{R^2 + X_C^2}{R^2 R_{ro}^2 + X_C^2 (R + R_{ro})^2} + 1{,}17^2 R^2 \left[\frac{1}{R_{ro}(R + R_-) + RR_-} - \frac{1}{R_{ro}(R + R_+) + RR_+} \right]^2} \tag{5}$$

From expression (5), it can be seen that the external leakage current depends on the resistance and reactance of the network (BI) also depends on the insulation resistance of the DC-side electrical network. When the DC power network is symmetrical ($R_+ = R_-$), then the leakage current only has an ac component, when the network loses symmetry ($R_+ \neq R_-$), the leakage current in the network increases by an amount i_2.

2.3. Leakage current in DC power network

2.3.1. Case of electric leakage from the negative terminal of the DC power network

In case of electric leakage from the negative terminal of the DC power network leakage current also has two components: The current i1 is caused by the insulation resistance of the power network BI and the current i_2 is caused by the insulation resistance of the positive terminal of the DC power network (R_+), the calculation diagram is as shown in Figure 4.

The leakage current component i_1 is the rectifier current due to the negative 3 phase half wave rectifier compared to the

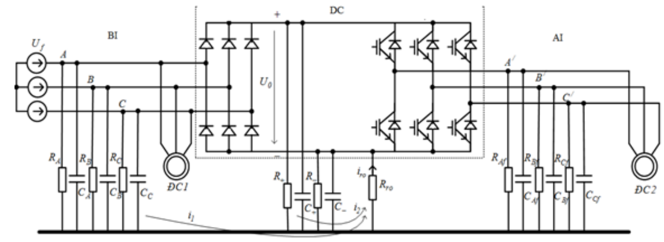

Fig. 4. Diagram of calculating leakage current with case of leakage from the negative terminal of the DC power network

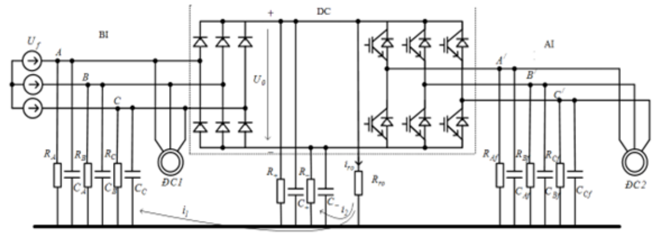

Fig. 5. Diagram of calculating leakage current with case of leakage from the positive terminal of the DC power network

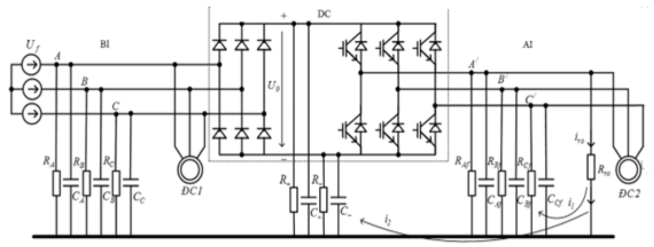

Fig. 6. Diagram of calculating leakage current with case of leakage in the power network AI

ground and the average value is determined according to the following expression:

$$I_1 = \frac{1{,}17U_f}{R_{ro}(R + R_-) + RR_-} R_- \tag{6}$$

The leakage current component i_2 is the DC current caused by the negative polarity voltage of the DC power source relative to the ground and the average value is determined by the following expression:

$$I_2 = \frac{U^-}{R_{ro}} = \frac{2{,}34U_f}{R_{ro}(R_+ + R_-) + R_+R_-} R_- \tag{7}$$

The leakage current in case of leakage from the negative terminal of the DC power network is determined by the following equation:

$$I_{ro} = I_1 + I_2 = U_f \left(\frac{1{,}17}{R_{ro}(R + R_-) + RR_-} + \frac{2{,}34}{R_{ro}(R_+ + R_-) + R_+R_-} \right) R_- \tag{8}$$

2.3.2. Case of electric leakage from the positive terminal of the DC power network

In case of electric leakage from the positive terminal of the DC power network leakage current also has two components: The current i_1 is caused by the insulation resistance of the power network BI and the current i_2 is caused by the insulation resistance of the negative terminal of the DC power network (R_-), the calculation diagram is as shown in Figure 5.

Similar to the case in Section 2.3.1, the leakage current in case of leakage from the positive terminal of the DC power network is determined by the following formula:

$$I_{ro} = I_1 + I_2 = U_f \left(\frac{1{,}17}{R_{ro}(R + R_+) + RR_+} + \frac{2{,}34}{R_{ro}(R_+ + R_-) + R_+R_-} \right) R_+ \tag{9}$$

From expression (8) and (9), it can be seen that, in the case of leakage in the DC power network, the leakage current depends on the resistances R+, R- of the DC power network and also on the resistance R of the BI power network.

2.3. Leakage current in the network after the inverter (AI)

In case of electric leakage in the power network AI (variable frequency AC power network), the calculation diagram has the form as shown in Figure 6. In this case, the leakage current consists of two components: the AC component i'_1 caused by the insulation impedance of the AI part and the DC component i'_2 caused by the insulation impedance of the DC part.

The AC current component is determined by the formula:

$$I_1^{/} = U_f^{/} \frac{\sqrt{R_f^2 + X_{Cf}^2}}{\sqrt{R_f^2 R_{ro}^2 + X_{Cf}^2 \left(R_f + R_{ro}\right)^2}} \tag{10}$$

where R_f, X_{Cf} is the total resistance and reactance of the three-phase insulation of the AI part relative to earth; $U_f^{/}$ is the phase voltage of the power network AI.

DC current component is determined by the expression

$$I_2^{/} = \frac{2{,}34U_f}{R_-R_+R_f + R_-R_+R_{ro} + R_-R_fR_{ro} + R_+R_fR_{ro}} R_+R_f \tag{11}$$

The leakage current in case of leakage in the power network AI is determined by the following formula:

$$I_{ro} = \sqrt{I_1^{/2} + I_2^{/2}} = \sqrt{\frac{U_f^{/2}\left(R_f^2 + X_{Cf}^2\right)}{R_f^2R_{ro}^2 + X_{Cf}^2\left(R_f + R_{ro}\right)^2} + \frac{2{,}34^2 U_f^2 R_+^2 R_f^2}{\left(R_-R_+R_f + R_-R_+R_{ro} + R_-R_fR_{ro} + R_+R_fR_{ro}\right)^2}} \tag{12}$$

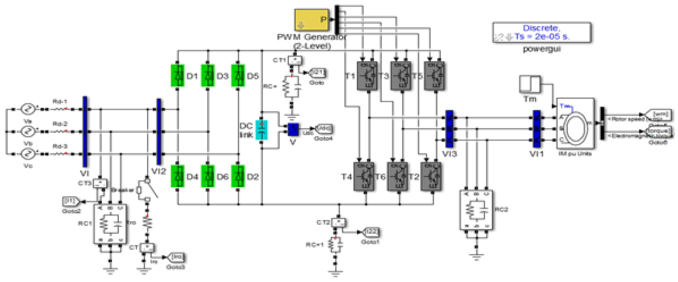

Fig. 7. Simulation model of mine power transmission network DC

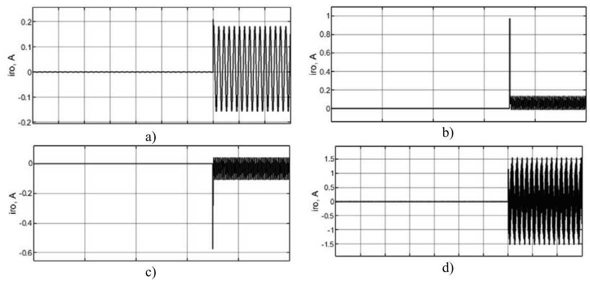

Fig. 10. Leakage current value in higher asymmetry of the DC power network insulation. a – Case of electric leakage before the inverter; b – Case of electric leakage in positive DC terminal; c – Case of electric leakage in negative DC terminal; d – Case of electric leakage after the inverter

From formula (12) it is found that, in this case, the leakage current depends on the parameters of the electrical network after the inverter and also on the resistances R_+, and R_- of the DC network.

3. Research results and discussion

3.1. Simulation modeling of leakage currents in the underground mine power network

Modeling on Matlab – simulink software is presented in Figure 7, with underground mine power network parameters suitable for mining in Vietnam: U=1140V, C=0,19uF/ phase; R=168kΩ/ phase; leakage resistance R_{ro}=1kΩ. Conduct a survey of leakage currents in the case of a DC network with symmetrical insulation $R_+ = R_- = 300k\Omega$, and in the case of a DC network with reduced insulation in the negative circuit (R_-=150 kΩ và 50 kΩ).

3.2. Case of electric leakage with symmetrical DC network insulation

The study conducts survey of electric leakage model with symmetrical DC network insulation resistance value $R_{d+}=R_{d-}$ =300kΩ. The analysis results of leakage current in the case BI, AI and in the DC power network are shown in Figure 8.

From the results in Figure 8a, it can be seen that with the same leakage resistance value, leakage current in the network AI is the highest, near 0.6A, leakage current in DC power network is the lowest about 0.08A, leakage current in the power network BI is 0.11A.

With symmetric DC network insulation, the AC component leakage current in the power network BI tends to decrease, in the DC power network and in the power network AI tends to increase (Figure 8b). Leakage current components to the positive and negative DC terminal in case of leakage in the power network BI and AI appears the process of oscillation before reaching the steady state (Figures 8c, 8d).

3.3. Case of electric leakage with asymmetrical DC network insulation

Assume that the DC network resistance on the negative DC terminal has an insulation loss corresponding to the values R_-=150kΩ, 50kΩ. Leakage survey at the positions before the inverter (BI), after the inverter (AI) and the DC network gives the results as shown in Figure 9.

From the research results in Figure 9 it can be seen that, when the DC network has reduced insulation (300kΩ, 150kΩ, 50kΩ) leakage current increases as insulation R- decreases in cases of electric leakage before the inverter, in positive DC terminal and after the inverter (hình 9a, b, d). However, the growth rate of leakage current is highest in the case of electric leakage in positive DC terminal, followed by in case of electric leakage before the inverter, and almost unchanged in the case of electric leakage after the inverter. Leakage current decreases as the insulation resistance decreases in case of electric leakage in negative DC terminal, this is because part of the leakage current value has passed through the insulation R_- itself (figure 9c).

The result of Figure 9 shows that the larger asymmetry of the DC power network insulation, the greater the change in leakage current. The investigation of the leakage current value in higher asymmetry of the DC power network insulation is shown in figure 10.

The results shown in Figure 10 indicate that, at the time of leakage t = 0.7s, the leakage current at any position in the network will fluctuate before reaching steady state. However, the amplitude of oscillation in the DC network is the largest and the oscillation time is the longest. In addition, the leakage current on the AC power network BI can cause unreliable operation of the leakage protection relay when leakage occurs on the power network AI and DC power network.

4. Conclusions

To ensure safety in underground mining, where there is a harsh environment, it is imperative to equip electric leakage protection. Today, underground mines are increasing their level of mechanization by using a variety of power electronics to enhance the operation and organization of their power supplies. The use of converters for DC power transmission in underground mining will be a trend in the following years when

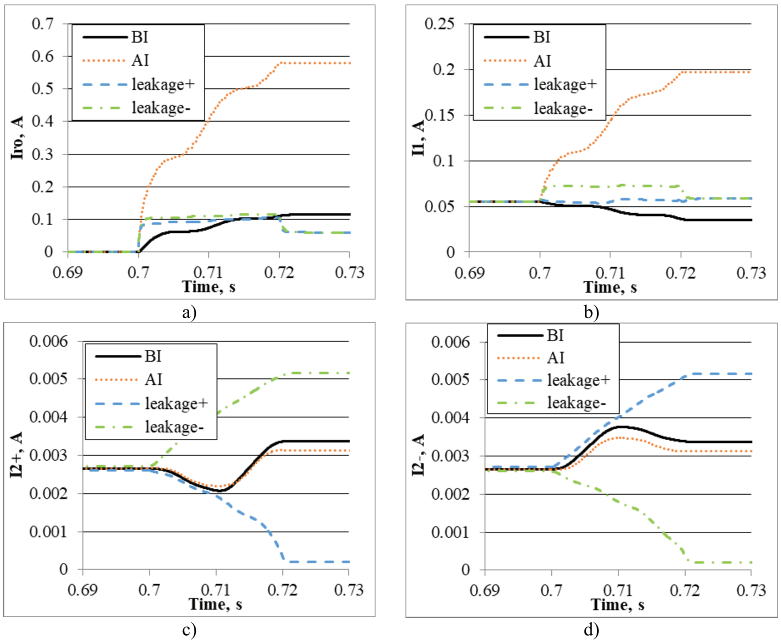

Fig. 8. Leakage current with symmetrical DC network insulation resistance value. a – Leakage current through leakage resistor; b – Leakage current through AC component; c – leakage current to the positive DC terminal; d – leakage current to the negative DC terminal

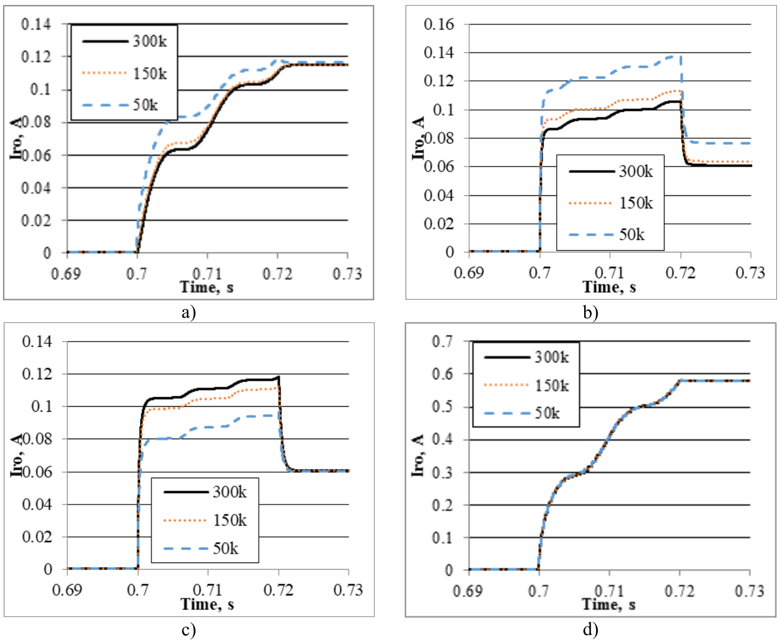

Fig. 9. Leakage current with asymmetrical DC network insulation resistance value. a – Case of electric leakage before the inverter; b – Case of electric leakage in positive DC terminal; c – Case of electric leakage in negative DC terminal; d – Case of electric leakage after the inverter

the mine capacity is increasing and the mining depth is large.

However, the use of DC power transmission will affect leakage protection in mining. Research results show that changing the parameter of the DC network will greatly affect the leakage current value not only in the DC power network but also in the AC network before and after the inverter. This causes the unreliable operation of the leakage protection device in this DC transmission network.

Research results in the article have built the dependent relationship between leakage current and network parameters for underground mine power networks with DC power transmission. The dependency relationship has been verified on the Matlab-Simulink simulation model. Research results are the basis for calculating and selecting leakage protection equipment for the purpose of improving safety in underground mining in Vietnam.

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