https://doi.org/10.33271/nvngu/2023-6/086

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STUDY OF LEAKAGE CURRENT IN UNDERGROUND MINE POWER NETWORK: A CASE STUDY IN MINING IN VIETNAM

Purpose. To determine DC leakage current in mine power network with long DC power transmission.

Methodology. Nowadays, the increase in capacity and working depth leads to the use of DC power transmission, which has many benefits both economically and technically in mining. However, the appearance of DC power transmission changes the structure of the network. In the underground mine power network, there will be electrical networks with industrial frequency 50 Hz, DC power networks, and power networks after variable frequency inverters. The correlation of these network parameters complicates leakage protection in the mine power network. For DC power transmission in mining, the DC network parts have a large length, so during the working process, electricity leakage in these parts of the network often occurs. Leakage current in a DC network depends not only on DC network parameters but also on AC network parameters. The article uses analytical methods and simulation methods on Matlab/Simulink software to determine leakage currents in underground mine power networks with DC transmission when there is a change in power network parameters.

Findings. The research results show that the leakage current value of the DC network is greatly affected when the insulation parameters of the electrical network change, 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.

Originality. Calculation model and simulation of DC leakage current in underground mine power networks with long DC transmission in mining in Vietnam

Practical value. 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, DC transmission, mine power network, leakage protection, leakage current, underground mining*

Introduction. Vietnam's economic growth rate is superior to that of other Asian countries, which can be explained by the fact that industrial growth mainly takes place in the energy sector, which supports all sectors of the national economy [1]. As of the first 7 months of 2022, the share of electricity generation from coal in Vietnam accounted for 40.5 % [2]. This encourages Vietnam's coal mines to operate with high frequency.

In Vietnam, coal has many types and large reserves, mainly in Quang Ninh (90 % of the country's coal reserves) [3]. Vietnam's coal reserves are estimated at more than 6.6 billion tons, of which the exploitable reserve is 3.6 billion tons (ranked in Southeast Asia) [4]. Coal production and exports have increased rapidly in recent years. Underground mining in harsh environments such as high fine dust, high humidity, a high risk of fire, and tight spaces poses a risk to electrical safety for operators [5, 6]. Mining safety regulations mandate that the power network be an isolated neutral network and be equipped with a leakage protection relay [7].

The study of DC power transmission is interesting for researchers in the field of power transmission [8–10]. Nowadays, mining capacity is getting bigger and bigger, the mining depth is increasing, this leads to the use of DC power transmission in network mining with many benefits both in terms of economy and technique [11–13]. For long cable networks, the DC power transmission brings many benefits such as reducing the influence of harmonics, reducing voltage loss, power loss in the power network, and reducing cable costs [14–16].

The solution of using the above-mentioned power electronic converters is that power electronics can be used to transmit DC power in mining. That means separating the AC-DC rectifier from the DC-AC inverter with a DC cable segment, this solution brings a lot of economic efficiency and reduces the unwanted consequences caused by inverters in mining [17, 18].

According to the research works by Marek [19, 20], for DC power transmission network, the value of leakage current is highly dependent on the insulation parameter of the DC network. However, the appearance of DC power transmission changed the structure of the network. In the underground mine power network, there will appear electrical networks with industrial frequency 50 Hz, DC power networks, and power networks after variable frequency inverters. The parameters and configuration of the rectifier greatly affect the mains voltage. 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 [21, 22].

The calculation and selection of leakage protection devices in the electrical network of the DC power network depend heavily on the calculation and determination of the dependent relationship of the leakage current with the parameters of the electrical network [23]. However, the investigation and construction of the correlation relationship between leakage current and the parameters of the power network in the mining power network have not been studied or mentioned. The content of the article is to build the correlation of leakage current in DC power networks with the parameters of the power network. The research results are proved on the Matlab-Simulink simulation model.

Determination of leakage currents in mine power networks with DC power transmission. ***Model of the underground mine power network with DC power transmission.*** The electrical network in underground mining with DC power transmission has the structure shown in Fig. 1, in which the AC power source V-AC (f = 50 Hz) is from the transformer, then through the rectifier (AC-DC) to be able to supply power to the DC machines M(DC), or through the DC-AC inverter to supply power to the AC machines M(AC) [24].

In the underground mine power network, there will appear power networks with industrial frequency 50 Hz, DC power network, and power network after variable frequency inverters (DC-AC). With the above DC transmission structure, the AC-DC rectifiers have been separated from the DC-AC inverter by a DC power network, where R, C are the resistance and capacitance to ground of the AC and DC power network parts.

According to studies [17, 18], in order to reduce power loss and improve the quality of power supply with mining power networks with DC transmission, AC-DC rectifiers are often located near power transformers, DC-AC inverters are usually located near M(AC) AC machines. With such a structure, the AC cable in before the inverter (BI) and after the inverter (AI) has a short length, so there is little leakage in the AC cables, the length of the DC cable for power transmission is large, so electrical leakage often occurs in the DC power cables (Fig. 2).

Thus, with the increased DC length, electrical leakage often occurs in these cable segments. DC leakage current depends not only on DC network parameters but also on AC power network parameters. Therefore, it is necessary to identify DC leakage detectors for mining enterprises to improve the reliability of leakage protection and safety in mining.

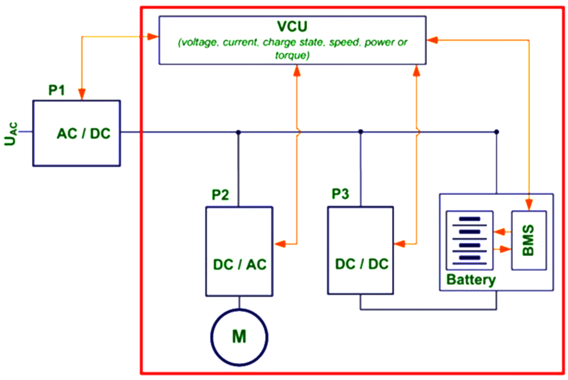

Fig. 1. The underground mine power network with DC power transmission [24]

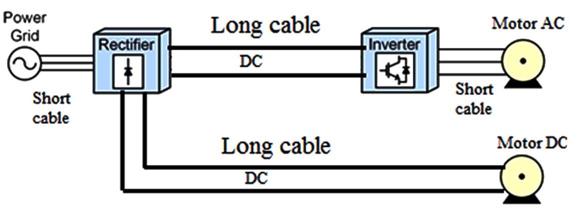

Fig. 2. Model of DC power transmission in mine power network

Determination of leakage current in DC power network. In the DC power network, leakage may occur from the positive (+) or negative (–) poles of the electrical network. Assuming that the case of leakage occurs at the negative (+) pole to ground, assuming the network has centralized parameters, ignoring the impedances of transformers and cables, the equivalent diagram is given in Fig. 3.

In the diagram (Fig. 3): R_A, R_B, R_C, C_A, C_B, C_C are insulation phase resistance and phase capacitance of the network before the inverter (BI); R_{Af}, R_{Bf}, R_{Cf}, C_{Af}, C_{Bf}, C_{Cf} – insulation phase resistance and phase capacitance of the network after the inverter (AI); R_+, R_-, C_+, C_- – insulation resistance and capacitance between positive pole (+) and negative pole (–) with respect to ground of the DC power network; U_f – secondary winding phase voltage of transformer; U_0 – average value of three-phase bridge rectifier voltage; R_{ro} – leakage resistance.

When there is a leakage from the positive pole of the DC source, the leakage current includes two components: current i_1 caused by the insulation resistance of the power frequency AC network part (BI) and current i_2 caused by the negative insulation resistance of the DC power network R_- (DC).

The calculation of the component i_1^+: The rectifier current due to the positive 3 phase half wave rectifier compared to the ground and the average value is determined according to the following expression

$$I_1^+ = \frac{1.17U_f}{R+(R_+//R_{ro})}(R_+//R_{ro})\frac{1}{R_{ro}} = \frac{1.17U_f}{R_{ro}(R+R_+)+R.R_+}R_+.$$

The calculation of the component i_2^+: The rectifier current due to the negative 3 phase half wave rectifier compared to the ground and the average value is determined according to the following expression

$$I_2^+ = \frac{U^+}{R_{ro}} = \frac{U_0}{R_- + (R_+//R_{ro})}(R_+//R_{ro})\frac{1}{R_{ro}} = \frac{2.34U_f}{R_{ro}(R_+ + R_-) + R_+R_-}R_+.$$

Determination of leakage current I_{ro} from the positive pole of DC power network is

$$I_{ro}^+ = I_1^+ + I_2^+ = U_f\left(\frac{1.17R_+}{R_{ro}(R+R_+)+R.R_+} + \frac{2.34R_+}{R_{ro}(R_+ + R_-) + R_+R_-}\right). \quad (1)$$

According to the working principle of the inverter, at each time, the phases of the AC network part after the inverter (AI) will be controlled by connecting to the positive or negative pole of the DC network part. If we consider the influence of the insulation impedance of the power network AI on the leakage, then the current i_2 will have its maximum value at the time when all three phases of the power network AI are connected to the positive pole of the DC power network. Therefore, the leakage current i_2 in the most dangerous case has a value determined by the expression

$$I_{2\max}^+ = \frac{2.34U_f}{R_{ro}(R_+ + R_-) + R_+R_-}R_+.$$

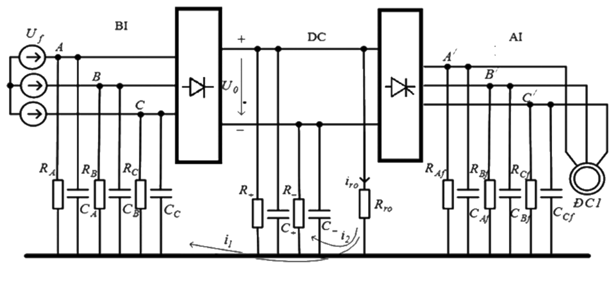

Fig. 3. Calculation diagram for leakage current in DC power network

Similarly, when leakage of negative pole (–) in the DC network to ground occurs, the leakage current is determined by the expression

$$I_{ro}^{-} = U_f\left(\frac{1.17R_-}{R_{ro}(R+R_-)+RR_-}+\frac{2.34R_-}{R_{ro}(R_+ + R_-)+R_+R_-}\right); \quad (2)$$

$$I_{2\max}^{-} = \frac{2.34U_f}{R_{ro}(R_+ + R_-)+R_+R_-}R_-.$$

From formulas (1, 2), it can be seen that the DC leakage current depends not only on the parameters of the DC network, but also on the parameters of the AC network. In the mining process, in case the length of the AC network (BI) is changed, then the network parameter changes can increase or decrease, which will change the leakage value.

Simulation modeling of leakage currents in the underground mine power network. Research has been conducted to build the simulation modeling on Matlab-Simulink (Fig. 4). The parameters of the underground mine power network are suitable for mining in Vietnam, with the initial set of numbers as follows: $U = 1140$ V; $C = 0.2$ mF/phase; $R = 150$ kΩ/phase; insulation resistance of DC power network: $R_+ = R_- = 200$ kΩ; leakage resistance $R_{ro} = 1$ kΩ. The inverter in this case uses an uncontrollable 3-phase rectifier bridge with a filter capacitor and a long DC cable, the inverter uses I GBT valves controlled by a PWM control pulse generator. The load of the system is a 3-phase induction motor with a rated load.

Fig. 5 shows that, with a three-phase input voltage of 1140 V, the motor is started stably and works after 0.3 s, the starting current after passing through the inverter is equal to 2 times the rated current value, this current has harmonic

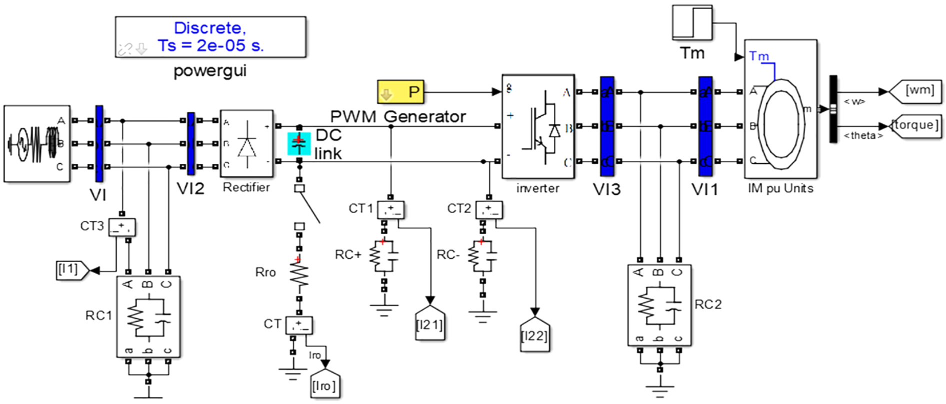

Fig. 4. Simulation model to determine leakage current in DC power network

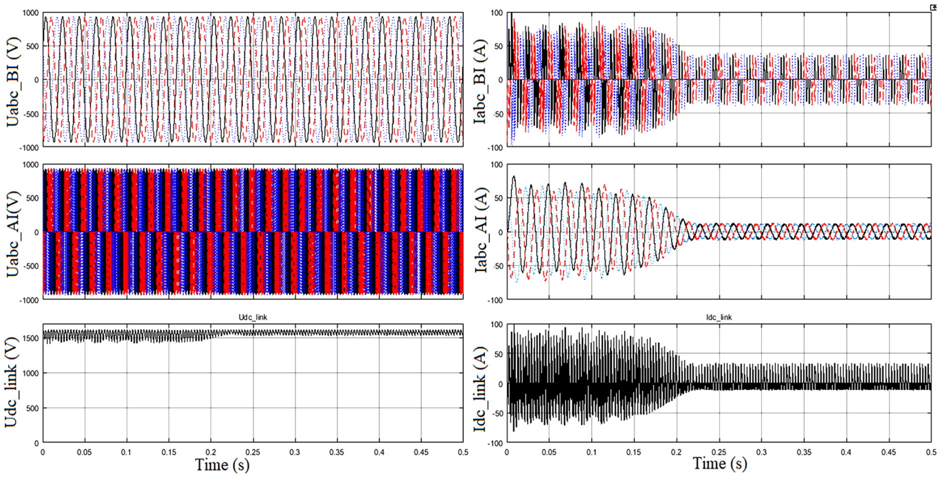

Fig. 5. Network working parameters

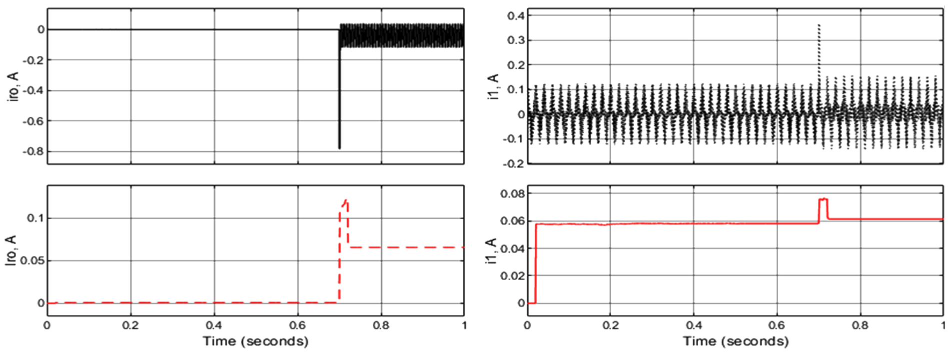

Fig. 6. Result leakage current in standard case

components. Thus, the simulation model works normally with the mine power network parameters with DC transmission.

In the standard case, when the network parameters are the same as described above, and leakage occurs from 0.7 s at the negative terminal of the DC power network. The results of the standard case simulation study are shown in Fig. 6. It is clear that when a leakage occurs at the negative terminal of the DC power network at time $t = 0.7$ s, the leakage current suddenly jumps with the peak amplitude of the leakage current $i_{ro\ max} = 120$ mA, this value may cause tripping of the leakage protection relays. When stabilizing the value of leakage current $i_{ro} = 52$ mA, value of leakage current through the resistors and reactances of the AC network $i_1 = 60$ mA, value of leakage current through the DC resistors of the positive and negative poles respectively $i_2^+ = 7.8$ mA, $i_2^- = 0.2$ mA. Realizing that, when in steady state, the value of leakage current on the BI side of the network is equal to the total current on the DC side of the network. This is completely consistent with the theo-

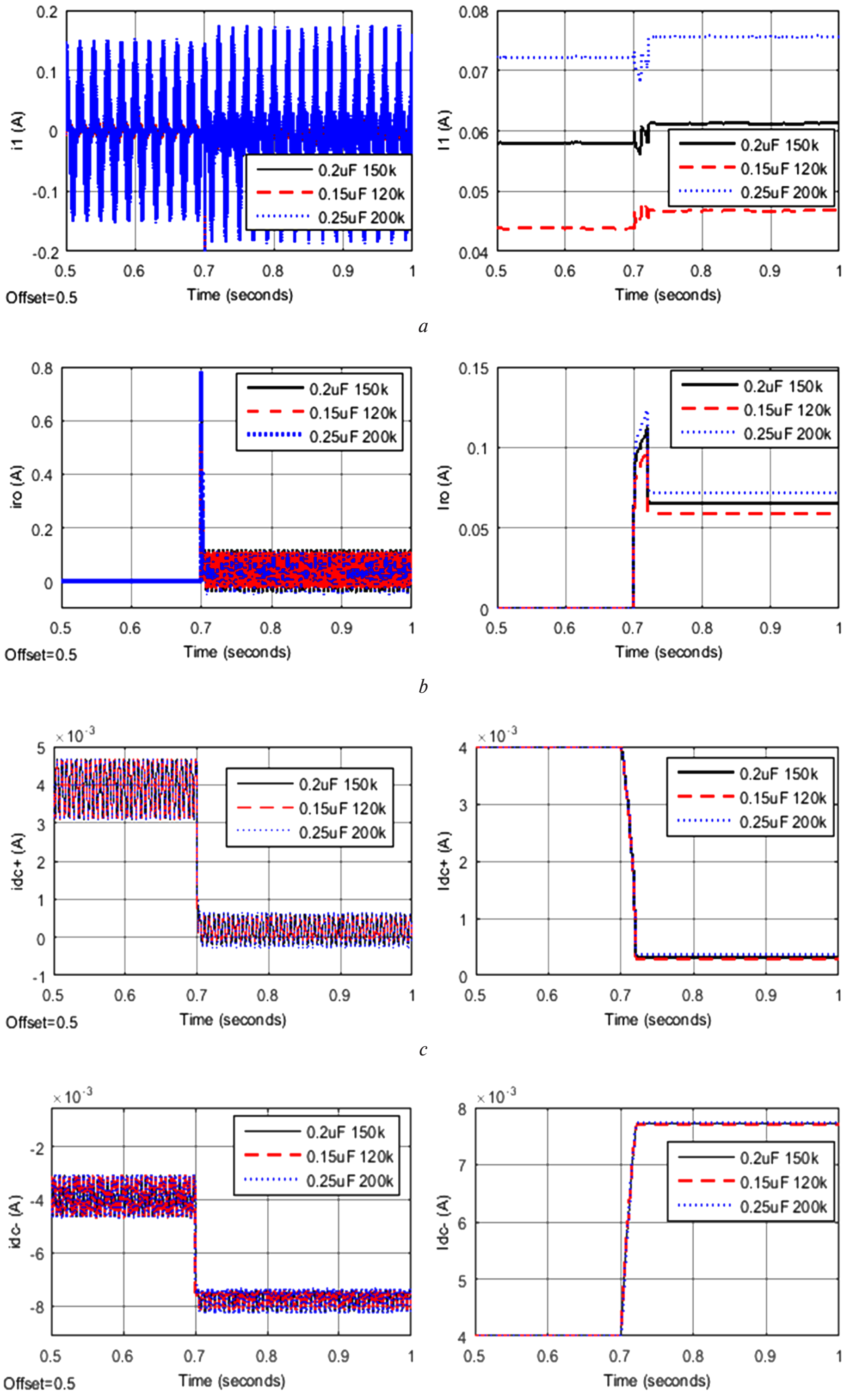

Fig. 7. Effect of AC network BI on DC network leakage current:

a – leakage current at power network BI and its RMS value; b – leakage current at the leakage location and its RMS value; c – leakage currentat positive pole of DC power network and its RMS value; d – leakage current at negative pole of DC power network and its RMS value t retical basis for determining the leakage current built in (1, 2). The leakage current components through the resistors on the network side *BI*, *AI* and leakage through the resistors R_+ and R_- are also varied, the variation of other leakage current components can be observed in Fig. 6.

In the case of considering the influence of power network parameters on the BI side to the leakage current on the DC side, with the assumption that during mining, the electrical network parameters have resistance and reactance change corresponding to two pairs of values ([C_1 = 0.15 mF/phase; R_1 = = 120 kΩ/phase], [C_2 = 0.25 mF/phase; R_2 = 200 kΩ/phase]) and keep other parameters of the power network unchanged. In the case of electrical leakage at the negative pole of the DC power network, the survey results are shown in Fig. 7.

The research results in Fig. 7 show that, when the insulation parameters of the 50 Hz AC network (BI) are changed,

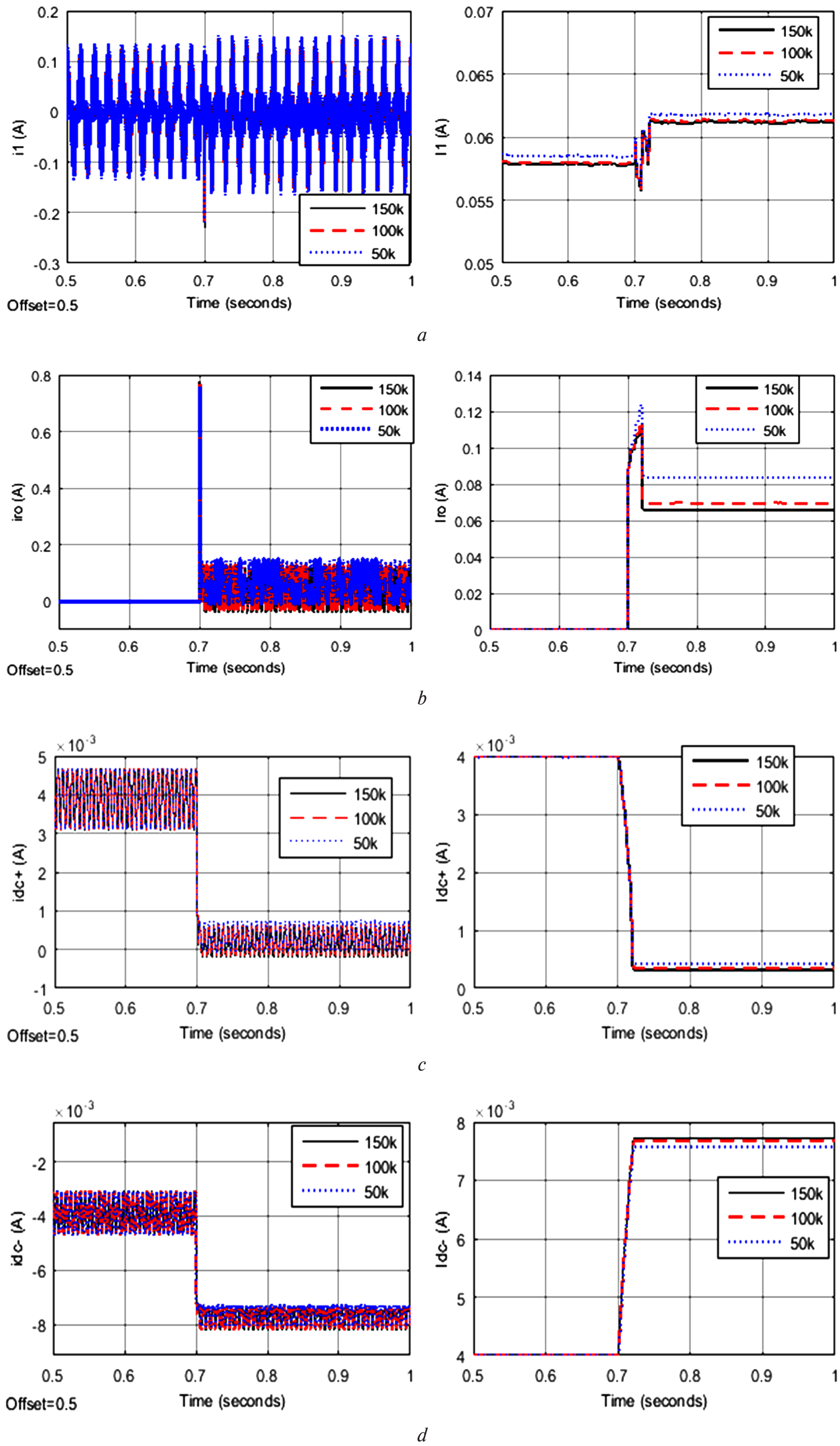

Fig. 8. Effect of AC network AI on DC network leakage current:

a – leakage current at power network BI and its RMS value; b – leakage current at the leakage location and its RMS value; c – leakage currentat positive pole of DC power network and its RMS value; d – leakage current at negative pole of DC power network and its RMS value the value of the DC network leakage current is changed. It is clear that, in all three cases, the corresponding steady-state DC leakage current value is [$I_{ro1} = 52$; $I_{ro2} = 53$; $I_{ro3} = 54$ mA]. In addition, at the time of leakage, the surge leakage current value tends to increase, corresponding to the maximum value of respectively [$I_{ro\text{-max}1} = 99$; $I_{ro\text{-max}2} = 115$; $I_{ro\text{-max}3} = 130$ mA], this value may cause tripping of the leakage protection relays. The leakage current components through the network side resistors BI, AI and the leakage current through the resistors R_+ and R_- are also varied, the variation of other leakage current components can be observed in Fig. 7.

The case of considering the effect of the network insulation parameter AI on the leakage current of the DC power network, with the assumption that the parameters of the network are stable during long-term operation, the network segments after the inverter are changed corresponding to the insulation values (50, 100 kΩ). The results of the DC side leakage current survey are shown in Fig. 8.

The research results in Fig. 8 show that, when the insulation parameters of the AI power network are changed, the value of the leakage current of the DC power network changes. In the above 3 case studies, with the insulation parameters of the power network AI corresponding to the values [$R_1 = 150$; $R_2 = 100$; $R_3 = 50$ kΩ/phase], the corresponding DC leakage current value when steady is [$I_{ro1} = 64$; $I_{ro2} = 67$; $I_{ro3} = 82$ mA]. In addition, at the time of leakage, the surge leakage current value tends to increase, corresponding to the maximum value of respectively [$I_{ro\text{-max}1} = 109$; $I_{ro\text{-max}2} = 114$; $I_{ro\text{-max}3} = 122$ mA]. This value may cause false protection for leakage protection relays. The leakage current components through the network charge resistors BI, AI and the leakage current through the resistors R_+ and R_- are also varied, the variation of other leakage current components can be observed in Fig. 8.

The research results from the theory according to the formulas (1, 2) and the experimental simulation results show that in mining, when using DC power transmission, the insulation resistance and reactance values of the BI and AI power networks will also greatly affect the leakage current value in the DC power network part. In addition, at the time of leakage, there is a surge current, and the maximum jump value is 2–2.5 of the stable value. This value can cause the wrong protection effect for the leakage protection relays.

Complex variations in leakage current in the power network can lead to unreliable operation of electrical leakage equipment in underground mine power networks, increasing the risk of losing electrical safety and fire safety in underground mines. Subsequent research focuses on developing experimental models to study the possibility of explosions in mine power networks caused by leakage currents, in addition to focusing on building smart algorithms to quickly and accurately protect electric leakage in electrical networks with DC power sources. Through this, smart electric leakage protection relays are formed to protect the safety of the mine power network and, more importantly, human safety against the risk of "electric shock".

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 to transmit DC power in underground mining will be a trend in the following years when the mine capacity is increasing, and the mining depth is large.

However, the use of DC power transmission will affect leakage protection in mining. The research results show that the leakage current value is affected by the insulation parameter 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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Дослідження блукаючих струмів у мережі енергопостачання шахти: за матеріалами гірничої промисловості В'єтнаму

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Мета. Визначити витоки постійного струму в електромережі шахти з протяжною лінією передачі постійного струму.

Методика. У теперішній час унаслідок збільшення виробничих можливостей і робочої глибини використовується передача електроенергії постійним струмом, що має багато переваг у гірничій промисловості як з економічної, так і з технічної точки зору. Однак у результаті впровадження електропередачі постійного струму змінюється структура мережі. У підземній електромережі шахти наявні електричні мережі промислової частоти 50 Гц, мережі постійного струму, інверторні перетворювачі й мережі змінної частоти, що живляться від інверторів. Взаємозв'язок параметрів у шахтній мережі ускладнює забезпечення захисту від струму витоку. Частина мережі постійного струму має значну протяжність, тому у процесі роботи на цих ділянках мережі часто трапляються витоки струму. Струми витоку в мережі постійного струму залежать не тільки від параметрів цієї мережі, але й від параметрів мережі змінного струму. У роботі використовуються аналітичні методи та методи моделювання з використанням програмного забезпечення Matlab/Simulink для визначення струмів витоку в підземних електромережах шахт із передачею електроенергії постійним струмом при зміні параметрів електромережі.

Результати. Результати дослідження показують, що значення витоку струму в мережі постійного струму значною мірою залежить від зміни параметрів ізоляції цієї частини мережі, але й мережі змінного струму до та після інвертора. Це призводить до ненадійної роботи пристроїв захисту від витоку струму у мережі передачі постійного струму.

Наукова новизна. Побудована розрахункова модель і проведене моделювання витоку постійного струму в підземних електромережах шахт з протяжною лінією передачі постійного струму в умовах гірничодобувної промисловості В'єтнаму.

Практична значимість. Результати дослідження є основою для розрахунку й вибору обладнання для захисту від витоку струмів з метою підвищення безпеки підземної роботи в гірничій промисловості В'єтнаму.

Ключові слова: *електробезпека, передача постійного струму, мережа енергопостачання шахти, захист від витоку, витік струму, підземний видобуток корисних копалин*

The manuscript was submitted 10.08.23.