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**THE EFFECT OF POWER PROTECTION EQUIPMENT ON EXPLOSION HAZARDS
AND ON THE RELIABILITY OF POWER SUPPLY TO LONGWALL SYSTEMS****WPLYW ZABEZPIECZEŃ ELEKTROENERGETYCZNYCH NA ZAGROŻENIE WYBUCHOWE
I PEWNOŚĆ ZASILANIA INSTALACJI PRZODKOWYCH**

Operational safety of electrical machines and equipment depends, *inter alia*, on the hazards resulting from their use and on the scope of applied protective measures. The use of insufficient protection against existing hazards leads to reduced operational safety, particularly under fault conditions. On the other hand, excessive (in relation to existing hazards) level of protection may compromise the reliability of power supply. This paper analyses the explosion hazard created by earth faults in longwall power supply systems and evaluates existing protection equipment from the viewpoint of its protective performance, particularly in the context of explosion hazards, and also assesses its effect on the reliability of power supply.

Keywords: methane hazard, power cables, protection equipment, power supply reliability

Bezpieczeństwo eksploatacji maszyn i urządzeń elektrycznych zależy m.in. od zagrożeń powodowanych ich użytkowaniem oraz od zakresu działania stosowanych środków ochronnych. Zastosowanie niewystarczających środków ochrony wobec istniejących zagrożeń prowadzi do obniżenia bezpieczeństwa eksploatacji, szczególnie w stanach zakłóceń. Z drugiej strony, nadmiernie wysoki (w stosunku do istniejących zagrożeń) poziom ochrony może prowadzić m.in. do obniżenia niezawodności zasilania. W artykule dokonano analizy zagrożenia wybuchowego powodowanego zwarciami jednofazowymi w instalacjach zasilających kompleksy ścianowe oraz dokonano oceny istniejących zabezpieczeń z punktu widzenia ich działania ochronnego, szczególnie wobec zagrożenia wybuchowego, a także ich wpływu na niezawodność zasilania.

Słowa kluczowe: zagrożenie metanowe, kable elektroenergetyczne, zabezpieczenia, pewność zasilania

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1. Introduction

The purpose of using protection means in power networks of mining facilities is to minimize hazards resulting from fault conditions. The risk associated with the power network operation should be assessed before specific protection means are selected for application. Special hazards are associated with the probability of methane explosion initiated by an electrical factor in an underground working, especially at the coal face. Although factors of electrical nature are not listed as the foremost cause of potential methane ignition (Cioca, 2012), such risk can by no means be underrated. The level of protection provided by safety systems should be a compromise between the actual hazards (risk) and the required reliability of power supply, with account taken of the characteristics of electrical equipment operation in underground mines.

2. Risk of methane explosion caused by an electrical factor

Risk may be defined as a combination of the probability of occurrence of harm and the severity of that harm (PN-EN ISO 12100:2012). Risk assessment is made using both quantitative and qualitative methods. Development of quantitative methods requires the knowledge of sufficient number of data of high confidence that can, for instance, be applied to determine the probability of an event or of the severity of the consequences of an accident. At the same time the lack of such data (resulting, for instance, from non-occurrence of accidents or from small number thereof) should not be treated as a sufficient condition to assess the risk as low. One of the risk factors of methane explosion is a stimulus (ignition source) of electrical origin which comes into contact with an explosive atmosphere. Some of the possible causes of the occurrence of such a stimulus include:

- phenomena related to the operation of normally sparking equipment (e.g. switches, slipping motors) with damaged enclosures,
- line-to-line short-circuits inside explosion proof devices resulting in the release of an ignition factor,
- internal line-to-line short-circuits in power cables (it should be noted that in areas classified as having „b“ or „c“ degree of methane explosion hazard, the cables used are provided with insulation screens, where line-to-line short-circuiting during operation is unlikely),
- earth faults in cables caused by mechanical damage, where conductors become exposed and the spark (arc) created comes into direct contact with the surrounding atmosphere,
- earth faults in cables accompanied by release of high energy at the point of fault causing a breakout of sparks or of an arc.

The probability of electric factors participating in the initiation of a methane explosion should nowadays be described as minor. According to the State Mining Authority, 34 methane ignition events were reported in the years 2002-2013 in coal mines. None of these incidents has been clearly associated with an electrical factor as the cause of an explosion. Compared to that, in the years 1960-1980 electricity was found to be the cause of 11.3% of methane explosions (Krasucki, 1984).

Factors of electrical nature are not listed among the main factors affecting the level of methane explosion hazard (Cioca, 2012). However, in addition to the response time of methane measuring de-energizing protective devices, important is also the technical condition of electrical equipment and systems and the level of explosion safety afforded by protection means listed in Table 1.

TABLE 1

Selected protection means used in longwall power supply systems

Protection means	Location (system) type		
	Explosion-safe location, voltage up to 1 kV	Explosion-unsafe location, voltage up to 1 kV	Longwall supplied with voltage above 1 kV
Equipment enclosures	protection level at least IP54	protection level at least IP54, required explosion proof design	depending on methane hazard
Cable screening	not required	required insulation screens	required insulation screens and common control shields
Sensitivity coefficient of fault protection	≥ 1.3	≥ 1.5	≥ 2.0
Fault protection response time	permissible delay 1.6 s	instantaneous	instantaneous
Earthing capacitance of insulation	unlimited	unlimited	$\leq 2.5 \mu\text{F}$
Insulation condition check	Tripping leakage protection	Tripping and locking leakage protection	Tripping and locking leakage protection, system for earth insulation test prior to energizing

The use of higher rated voltage in power supply systems for longwall machinery (3.3 kV instead of 1 kV), resulting from increased power rating of that machinery, is a factor that can increase the risk of electric shock and explosion. This is due to the higher values of touch voltages and earth fault currents, as well as to possible higher concentration of methane resulting from increased rate of longwall progress (Szlązak & Kubaczka, 2012). Rules of design, selection and operation of higher voltage systems should ensure proper level of operational reliability of the network, and at the same time maintain hazards at a level corresponding to that of low voltage networks. For this reason, 3.3 kV systems require the application of stricter or additional protective measures (in addition to those listed in Table 1, other protective measures of organizational nature are applied in these systems).

Insufficient protection measures may reduce the level of safety in these systems, especially under fault conditions. On the other hand, excessive (in relation to existing hazards) level of protection may lead to deterioration of network performance and to unjustified cost increase, as well as to reduced power supply reliability due to unnecessary tripping.

The above statements are reflected in recommendations (PN-EN ISO 12100:2012) that specify that in the case of a machine „*the protective measures allow its easy use and do not hinder its intended use. Not doing this could lead to protective measures being bypassed in order to achieve maximum utility of the machine*”. Difficulties in maintaining a protective means in proper condition during operation can “*induce to prevent or bypass its operation in order to maintain the continuity of machinery operation.*” These remarks can also be applied to protective measures used in power networks. It is therefore important to seek a compromise between real hazards (risk) and the level of protection provided by protective and safety systems. When establishing the level of protection, one should also consider the requirements on the reliability of power supply as well as the characteristics of electrical equipment operation in underground

mines. Lack of such compromise may result in the conviction of the uselessness of a protective measure which prevents effective operation of a system due to unjustified tripping. This conviction may entail inappropriate behaviour of electrical maintenance staff and bypassing of protective measures and underestimating the role thereof. As a result, such behaviour may eventually become a habit leading to a disregard of other rules. This may further be compounded by other factors that shape the attitude of employees, for instance by pressure exerted by superiors, atmosphere among colleagues, work culture and other (Moraru, 2010).

3. Hazards resulting from the use of power cables

The most crucial component of the electric power network are the cables that supply power to longwall machinery. This is due to the fact that the wires are not protected against mechanical damage with sufficiently strong enclosures, and the manner of their operation (arising from the need to power mobile, portable etc. equipment) makes them highly susceptible to mechanical damage. The main hazard associated with the use of cables in underground workings results from the possibility of an electric arc formation in the case of damage to the cable, which creates a risk of ignition or explosion of methane and/or coal dust. Damaged cables may also pose an electric shock hazard and, to a lesser degree, a fire hazard. These hazards are particularly apparent in longwall excavations and gateroads, where adverse environmental conditions and increased methane and dust hazards normally prevail. The above-mentioned hazards are the result of the possibility of damage to cable insulation, leading to an earth fault or to a line to line short-circuit or to a voltage leakage. The principal method of mitigating these hazards is the use of an effective earth fault protection system, one of the basic elements of which are cables with insulation screens connected to a system of protective earthing conductors.

The basic task of insulation screens in mining power cables is to reduce the possibility of line to line short circuits (virtually every such short circuit may be accompanied by an outbreak of an electric arc or of sparks). Any damage to the insulation of a screened cable, before it produces a line to line short circuit, causes an earth fault. In isolated neutral system power networks of underground mines, the amount of energy released at the point of earth fault usually does not cause any significant explosion, electric shock or fire hazard.

The condition for the insulation screens to be effective is to use appropriate safety devices (e.g. leakage or earth fault protection units) able to de-energize the circuit in a sufficiently short time. This follows from the fact that both the energy released at earth fault point, which determines the probability of an explosion, as well as the possible effects of an electric shock depend on the time elapsed from the moment of damage to the moment of tripping.

3.1. Hazards caused by earth faults

The discussion presented above shows that the most significant hazards associated with the use of power cables at coal faces result from the possibility of a line to line short circuit or of a voltage leakage, while the hazards posed by earth faults are much less severe. However, the risks associated with earth faults, especially under adverse environmental conditions prevailing at coal faces, must be taken into consideration. One of the protective measures introduced for use in the networks supplying power to longwalls at voltages above 1 kV are common control

shields in power cables. One of the reasons given for making such shields obligatory was the desire to reduce the possibility of earth faults occurring after mechanical damage (Boron, 1996). The control shield de-energizes the cable when earthing resistance of the control shield (resistance between the control shield and the earthed protective screen) is decreased as a result of mechanical damage, for example due to crushing. Explosion hazard during an earth fault depends in this case mainly on the possibility of the explosion initiating factor (electric arc, sparks, hot particles, etc.) being released outside the cable. For this reason we analyze here the explosion hazard from the point of view of energy released at the point of the earth fault.

In a mine medium-voltage network the value of an earth fault current I_s , when the earth fault across resistance R_f is given by the following formula (Krasucki, 1984):

$$I_s = \frac{U_0}{\sqrt{R_f^2 + \frac{R_i^2 + 6R_i R_f}{9(1 + \omega^2 C_0^2 R_i^2)}}} \quad (1)$$

where:

- C_0 — earthing capacitance of a single phase of the network, F,
- U_0 — phase voltage, V,
- R_i — insulation resistance, Ω ,
- ω — angular frequency of the power voltage, $\text{rad} \times \text{s}^{-1}$.

The relationship between the earth fault current and insulation resistance for various values of earthing capacitance and transfer resistance at the point of damage is shown in Figs. 1 and 2.

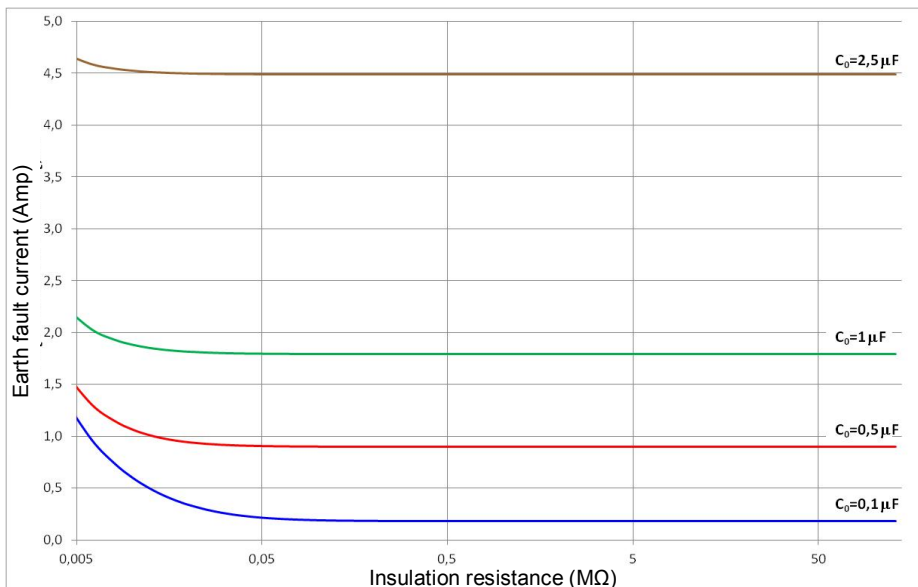


Fig. 1. Earth fault current vs. insulation resistance for various values of earthing capacitance in a 3.3 kV network. Fault resistance $R_f = 0 \Omega$

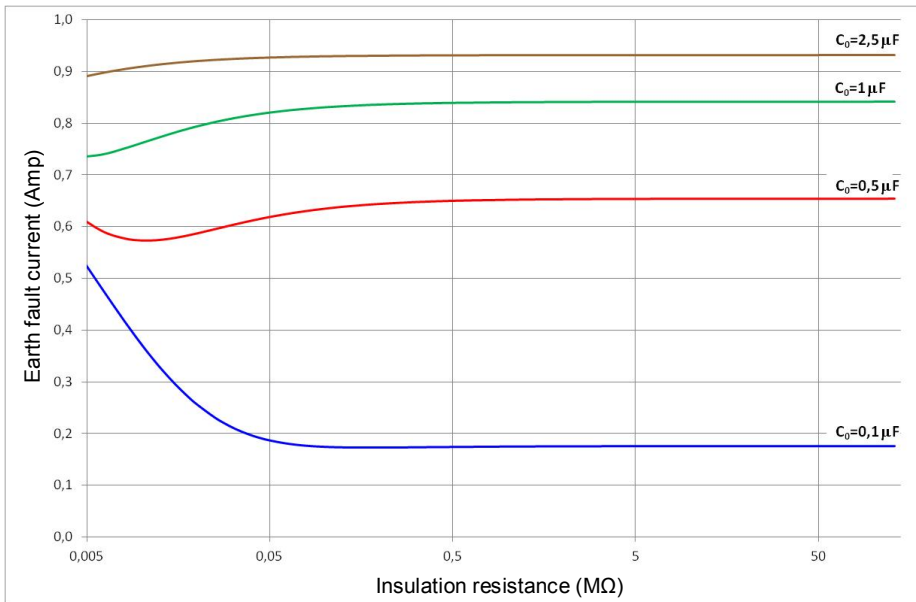


Fig. 2. Earth fault current vs. insulation resistance for various values of earthing capacitance in a 3.3 kV network. Fault resistance $R_f = 2 \text{ k}\Omega$

Power P_s released at earth fault point may be calculated from:

$$P_s = I_s^2 \cdot R_f = \frac{U_0^2 \cdot R_f}{R_f^2 + \frac{R_i^2 + 6R_i R_f}{9(1 + \omega^2 C_0^2 R_i^2)}} \quad (2)$$

Equation (1) shows that fault current attains its highest value when the fault resistance R_f is 0:

$$I_{s0} = 3U_0 \sqrt{\frac{1 + \omega^2 C_0^2 R_i^2}{R_i^2}} \quad (3)$$

and at the same time, as shown by equation (2), the power released at the point of fault is equal to zero. The probability of generating an ignition factor depends on the energy released at the point of fault, wherein that energy is equal to fault duration time multiplied by power P_s . The maximum value of that power can be determined for the steady state parameters of the network (U_0 , R_i and C_0) by calculating the derivative of the function of P_s vs. fault resistance R_f and equating it to zero:

$$\frac{\partial P_s}{\partial R_f} = 0$$

Hence

$$R_{f \max} = \frac{R_i}{3\sqrt{1 + \omega^2 C_0^2 R_i^2}} \quad (4)$$

$$P_{\max} = \frac{3U_0^2 (1 + \omega^2 C_0^2 R_i^2)}{2R_i \left(1 + \sqrt{1 + \omega^2 C_0^2 R_i^2}\right)} \quad (5)$$

The value of the fault current is thus equal to:

$$I_{s \max} = \frac{3U_0 (1 + \omega^2 C_0^2 R_i^2)}{\sqrt{2} R_i \sqrt{\left(1 + \omega^2 C_0^2 R_i^2\right) + \sqrt{\left(1 + \omega^2 C_0^2 R_i^2\right)}}} \quad (6)$$

The value of the insulation resistance R_i depends on the condition of the insulation, on the extent of the network and on the temperature of the cables, and it should not be less than the tripping resistance of the central leakage protection unit – for a 3.3 kV network the resistance set in that protection unit is 85 k Ω . Fig. 1 shows that insulation resistance higher than 85 k Ω has a negligible effect on the value of the earth fault current and can therefore be assumed to be infinite. Under this simplifying assumption the relationships (1) to (6) take on the following forms:

$$I_s = \frac{U_0}{\sqrt{R_f^2 + \frac{1}{9\omega^2 C_0^2}}} \quad (7)$$

$$P_s = \frac{9U_0 R_f \omega^2 C_0^2}{1 + 9U_0 R_f^2 \omega^2 C_0^2} \quad (8)$$

$$I_{s0} = 3U_0 \omega C_0 \quad (9)$$

$$R_{f \max} = \frac{1}{3\omega C_0} \quad (10)$$

$$P_{\max} = \frac{3\omega C_0}{2} U_0^2 \quad (11)$$

$$I_{s \max} = \frac{3U_0 \omega C_0}{\sqrt{2}} \quad (12)$$

The graphs below show current I_s (Fig. 3) and power P_s (Fig. 4) as functions of the fault resistance R_f in a 3.3 kV network for different values of earthing capacitance.

Table 2 shows values calculated from formulas (1), (4) and (5): of the fault resistance $R_{f \max}$ at which the power released at the point of fault is the highest, of that maximum power $P_{f \max}$ and the maximum earth fault current I_{s0} (calculated assuming that the fault resistance R_f is zero).

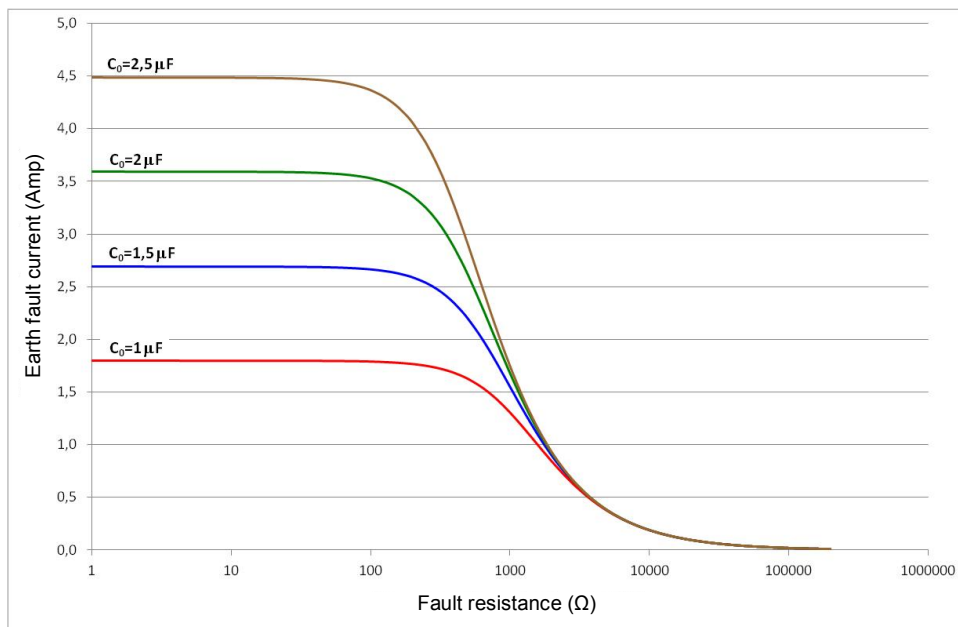


Fig. 3. Earth fault current vs. fault resistance in a 3.3 kV network for various values of earthing capacitance (assuming that $R_i = \infty$)

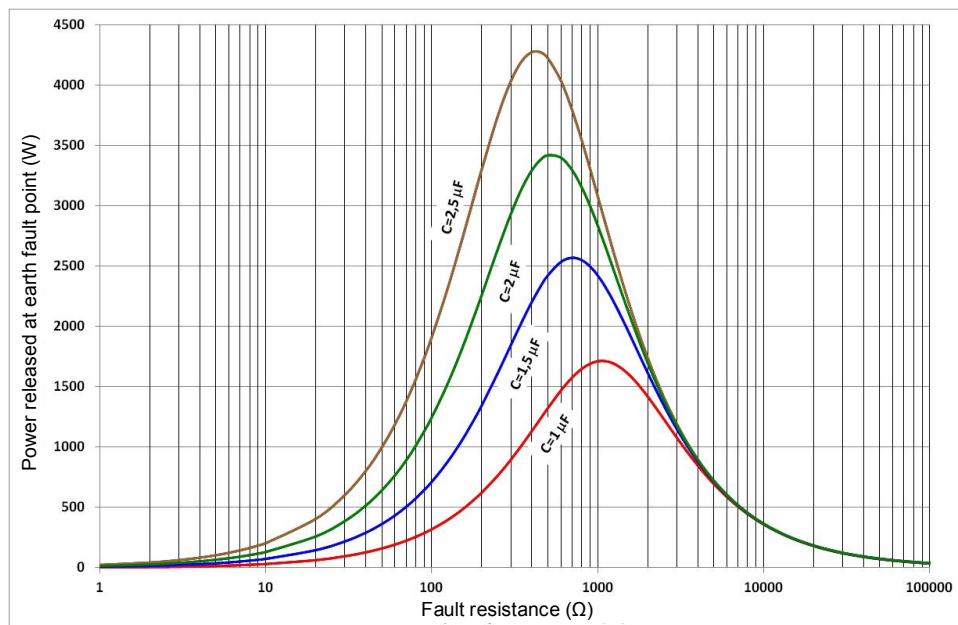


Fig. 4. Power released at the point of damage vs. fault resistance in a 3.3 kV network for various values of earthing capacitance (assuming that $R_i = \infty$)

Calculations were performed for networks with rated voltages of 3.3 kV and 6 kV for various values of earthing capacitance (the overall extent of the actual systems powered from a single transformer varies usually in the range of from 2 to 4 km, which corresponds to an earthing capacitance within the range of 1.0 to 2.0 μF).

TABLE 2

Earth fault parameters vs. earthing capacitance for various rated voltages

$C_0, \mu\text{F}$	$R_{f \max}, \text{W}$	$U_n = 3300 \text{ V}$		$U_n = 6000 \text{ V}$	
		$P_{s \max}, \text{W}$	I_{s0}, A	$P_{s \max}, \text{W}$	I_{s0}, A
1.0	1061	1710	1.27	5655	2.31
1.5	707	2566	1.90	8482	3.46
2.0	530	3421	2.54	11310	4.62
2.5	424	4276	3.17	14137	5.77

Conducted tests and studies (Krasucki, 1984; Boron, 2006) show that the approximate minimum critical thermal energy E_{cr} released at the point of fault, at which arc discharge is possible, is ca. 4000 J. That value has been determined for cables with paper insulation and lead sheath. Similar studies with power cables of rubber insulation and sheath have not been performed, but upon comparison of the mechanical properties of insulating and sheath materials, one may assume that such cables are characterized by comparable E_{cr} energy value. Under that assumption, the maximum earth fault duration time at which there will still be no arc discharge will be equal to:

$$t_{\max} = \frac{E_{kr}}{P_{s \max}} \quad (13)$$

The results of t_{\max} calculations for the maximum power released at the point of earth fault are presented in Table 3.

TABLE 3

Maximum earth fault duration t_{\max} , during which the energy released at the point of earth fault does not exceed the critical value E_{cr}

Earthing capacitance of a single phase $C_0, \mu\text{F}$	Maximum earth fault duration t_{\max}, s	
	network voltage 3.3 kV	network voltage 6 kV
1.0	2.34	0.71
1.5	1.56	0.47
2.0	1.17	0.35
2.5	0.94	0.28

According to requirements, power networks at coal faces with voltage of above 1 kV should be provided with central leakage protection units with a response time (for fault resistance of 1 k Ω) of no more than 0.07 second. Longer response time of the leakage protection unit is admissible when an earth-fault protection unit with response time of no more than 0.1 second is in place. Calculations show that, upon taking into account the response time of the protection unit, the opening time of the switching device and other factors that could affect the tripping time, an

earth fault the cause of which is not related to the damage of the cable sheath, will not result in an external discharge of an electric arc.

3.2. Effect of protective measures on the reliability of power supply

As mentioned before, protective measures should not affect proper operation of the network. Most of the protective measures listed in Table 1 meet this requirement. Some problems may only arise in the case of systems with common control shields, which are in fact used only in longwall power supply networks with voltages above 1 kV. These systems should trip and lock off the circuit in the event of a break in the protected circuit, or in the case of a drop in insulation resistance between the control (common) shield and the earthed insulation screen to less than a set value of at least 1 k Ω . This solution provides the highest level of protection currently attainable. Tripping occurs already when the inner sheath of a cable is damaged (due to, for instance, crushing) and the resistance between the common shield and earth is lowered. This protection means provides an advance switch off which reduces the probability of an earth fault. However, as has been shown earlier in this paper, such an earth fault does not pose any explosion or fire hazard, and it can therefore be concluded that the contribution of such protection means to the mitigation of the risk of methane explosion is insignificant. The main disadvantage of the described means of protection is its very high susceptibility to nuisance tripping. Under the environmental conditions prevailing in underground mines, a drop in the earthing resistance of a common shield of a cable, and consequently the de-energizing of that cable, may be caused by a slight abrasion of the outer sheath, by water absorption, by a rock splinter penetrating the cable, etc. For this reason, particularly in the case of cables supplying power to moving machinery, there are trips regarded by the users as unnecessary. Moreover, finding the point of decreased resistance may prove extremely troublesome. In these circumstances, the operators seek to ensure uninterrupted power supply and eliminate the protective means that are regarded unnecessary. At the same time the employees start to adopt an attitude of limited confidence towards the requirements of valid regulations. This can lead to a dangerous situation, wherein the wrong attitudes affect also the approach to protective measures that are critical to the safety of network operation.

One of the additional problems associated with the use of common control shields is the occurrence of switching surges causing the appearance of voltages of up to several hundred volts in the intrinsically safe control circuit (Marek, 2010). These surges lead to damage to relays. Emergence of an explosion hazard is also possible due to sparks caused by these surges (observed during laboratory tests).

4. Summary

Protection means used nowadays in power supply networks warrant proper level of explosive, fire and electric shock safety. As follows from the calculations and graphs presented in this paper, the energy of a spark produced in a longwall power system at the point of an earth fault inside a cable is too low to cause rupture of the cable and to initiate a methane gas explosion. It is also worth noting that such earth fault may not only be caused by mechanical damage resulting from the action of an external factor, but also be due to ageing, moisture absorbed by insulation,

factory defect, surge or penetration of the insulation by a cracked conductor wire. In view of the above the use of common control shields in cables in order to prevent earth faults is not justified, the more so as it significantly affects the reliability of network operation. Higher voltage systems (3300V) use a number of additional protective measures (of technical and organizational nature) to ensure appropriate level of network operation safety. These measures provide at least the same level of safety as in low voltage systems, which is evidenced by the fact that during the period of nearly twenty years of the 3.3 kV systems operation, not a single accident was reported the cause of which could be attributed to the increased supply voltage. This statement is further confirmed by the often observed greater care that personnel is exercising when operating higher voltage electrical equipment and by the absence in mining regulations of other countries (e.g. UK) of similar requirements regarding the use of control shields.

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