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MANAGEMENT OF POWER NETWORK OPERATION SAFETY IN MINING

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Abstract:
The paper characterizes hazards resulting from the use of power networks in underground workings of mines, with particular emphasis placed on electric shock and explosion hazards. Protection measures that mitigate hazards caused by network failures are presented. These measures are related to the proper design of equipment and cable lines, network arrangement and principles of selecting adequate protection equipment. The vast majority of electrical accidents are caused by the incorrect behaviour of people, mostly intentional (resulting from not respecting the rules). For this reason, particular attention should be paid to the level of skills and awareness of the risks of electrical personnel, especially for junior employees. The article presents selected safety rules when working on electrical equipment.

Key words: *electrical safety, power networks*

INTRODUCTION

Cable lines should be considered one of the most important components of the power supply system for mining machinery and equipment. The reasons for this are the following:

- cables are a crucial factor that determines the reliability of power supply to the current-using equipment which is important from the point of view of production effects and personnel safety,
- due to the nature of their construction, cables are particularly subject to environmental hazards (mechanical and others), which results from the lack of an enclosure that would protect cables against damage (electrical mining equipment is provided with enclosures of high mechanical strength).

The above considerations make the following properties of primary importance for cables used in the mining industry:

- failure-free operation to ensure the required continuity of power supply, which is particularly important for cables feeding power to basic facilities of a mine,
- the capacity to reduce hazards caused by the use of cables, particularly explosive, electric shock and fire hazards.

The paper discusses major hazards associated with the use of power supply cables in underground mines and the principles of the design and use of these cables and the protective measures applied to ensure appropriate level of safety.

IDENTIFICATION OF HAZARDS

Electric shock hazard

Analyses of the causes of accidents that occur in mining show that electric shocks, which are included in the statistics, are relatively rare [13]. By way of an example: in the years 2007-2012 there were 40 cases of electric shock recorded in underground mining, 3 of them fatal. Whereas in the years 2005-2011 electric factors were the cause of 2.8% of fatal accidents and of 1.6% of severe injuries. This is mainly due to the fact that power networks in underground mines are those operating in a system with an isolated neutral point of the transformer, which should be considered safer than earthed networks, commonly used in low voltage industrial systems. In isolated networks the earth fault current is low, therefore the touch voltages (which determine the severity of electric shocks) that occur as a result of damage to exposed conductive parts, are limited. In isolated networks one of the protection means against electric shock is the protective earthing system. The standard [3] requires that this system should be designed in such manner as to limit the touch voltage to a value not higher than the conventional touch voltage limit U_{TL}:

$$U_{TL} \geq R_E \cdot I_S \tag{1}$$

where:
R_E – earthing resistance (total resistance of the protective earthing system),
I_S – earth-fault current of the network, A.

The adopted touch voltage limit U_{TL} is 25 V when assessing the efficiency of the protective earthing system in low voltage networks, or it depends on the duration of the earth fault in a medium voltage distribution network (not higher than 50 V in any case). Due to the fact that in real low-voltage networks the earth fault current is usually no more than 1 A, the prospective touch voltage is much lower than the permissible touch voltage, and the condition defined by relation (1) is easily satisfied. The earth fault current in large medium voltage distribution networks may attain values in excess of 100 A, and the resistance to earth R_{ws} must therefore be sufficiently low for the condition (1) to be satisfied. That resistance is the total of the resistances of the (main and local) earth electrodes and of the PE conductors. To take an example, when the earth fault current is 180 A at fault duration of less than 1.2 s, the touch voltage limit is 50 V [3], and the maximum earthing resistance is then:

$$R_{E\max} = \frac{U_{TL}}{I_S} = \frac{50}{180} = 0{,}28\,\Omega \qquad (2)$$

This condition can be difficult to satisfy, especially in dry mines, where providing earth electrodes of sufficiently low resistance is often impossible. In such cases, in addition to the proper installation of earth electrodes, it is important to ensure low resistance of PE conductors. The role of PE conductors is now taken on by the earth conductors of power supply cables. These earth conductors are most often in the form of insulation screens (copper tapes applied helically over the insulation of each live conductor) or, in the case of cables without insulation screens, in the form of a common shield (tapes applied over the cable sheath). The nominal cross section of the earth conductor in the case of unscreened cables is less than in screened cables (up to three times less, depending on the cross section of live conductors [11]), which adversely affects the resistance of the protective earthing system. This shows that the use of cables with conductor insulation screens is advantageous to reducing the electric shock hazard when insulation is damaged and an earth fault occurs.

However, it must be emphasized that virtually all fatal accidents and severe injuries resulting from electric shocks in mines are the effect of direct contact, that is of touching a live part. The most common cause of these accidents is the improper operation of equipment and networks by operators, in particular live working (access to the interior of enclosures of live electrical equipment) [12]. It should be emphasized that, in accordance with the regulations, "live working in underground headings is permitted only on electrical circuits and systems of the SELV or PELV type" [1]. Frequent disregard of this regulation cannot be justified by the lack of knowledge or by shortage of electrical maintenance personnel, although it is a fact that the level of professional qualifications of that personnel in the mines is often insufficient, and the number of electricians and electrical maintenance supervisors remains at a low level 12]. It is not rare that experienced electricians, among whose responsibilities is to provide guidance to junior employees, become victims of electric shock injuries. It should be emphasized that the proper conduct of employees, especially those with long employment history, appreciation of safety regulations and rejection of risky behaviour has a direct impact on the development of safety culture in the workplace [10].

Direct contact may also occur due to accidental contact of the body with a damaged cable. Damage may be the result of cable insulation abrasion or of puncture of the cable by a conductive object, which brings the live voltage outside. In these situations electric shock hazard can be dramatically reduced through the use of screened cables (with earthed conductor insulation screens). In such cables any insulation damage causes connection of the live conductor with the earthed screen and de-energizes the cable after a trip action of appropriate earth fault or leakage protection device. For this protection means to be effective, it is necessary to use cut off protection devices (regulations allow the use of warning protection devices in specific cases).

In order to reduce the electric shock hazard it is therefore advisable to replace unscreened cables with cables with conductor insulation screens. An additional advantage of screened cables is the uniform distribution of electric field and temperature in the insulation, which is beneficial for their durability.

Explosion hazard

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 number of risks, including the risk of inflammation or explosion of methane and/or coal dust. This hazard exists mainly in longwalls, development headings and adjacent workings, principally due to increased release of methane in these areas, and also because of the intensity of operations conducted there, which increases exposure to mechanical damage. In the underground workings mentioned above, it is the low voltage (up to 1000 V) and medium voltage (3.3 kV) systems that are used. The level of explosion hazard created during an earth fault depends in the first place on the amount of energy dissipated in the fault location. This energy determines the possibility of cable bursting and generating an explosion initiating factor (spark or electric arc). Conducted tests show that the approximate minimum critical heat energy E_{CR} dissipated at the fault location, at which arc discharge is possible, is ca. 4000 J [7].

Observations indicate that virtually any phase-to-phase short in a cable may lead to an electric arc escaping the cable. According to laboratory tests the arc (spark) discharge can occur within 5 to 20 ms from the moment of the fault [8]. Therefore the applied overcurrent protection means cannot effectively prevent this (fault clearance time is usually longer). In addition to explosion hazard, phase-to-phase shorts are also a source of fire hazard, and in the case of human occupancy, there is also the risk of burns. The hazards mentioned may to a large extent be reduced by using screened cables and by de-energizing them during the first moments of fault development, whereas the de-energizing mechanism is identical to the one described earlier. In cables with earthed insulation screens, an earth fault (which poses a much smaller hazard than a phase-to-phase short) occurs at the moment of phase insulation damage, where that fault should be cleared as a result of tripping earth fault or leakage protection before any damage is done to the insulation of a second phase and before a phase-to-phase short occurs.

As indicated before, the level of explosion hazard created by an earth fault depends on the energy evolved at the fault location. The earth fault current I_S in an isolated neutral system is given by the relation:

$$I_S = \frac{U_0}{\sqrt{R_f^2 + \dfrac{R_i^2 + 6R_iR_f}{9\left(1+\omega^2 C_0^2 R_i^2\right)}}} \qquad (3)$$

where:

C_0 – earth capacitance of one phase of the network, F,
U_0 – line-to-earth voltage, V,
R_i – insulation resistance, W,
R_f – fault resistance, W,
w – pulsatance of supply voltage, rad×s^{-1}.

The power generated at the earth fault location depends on the value of the short-circuit current I_s and on the fault resistance R_f :

$$P_S = I_S^2 \cdot R_f = \frac{U_0^2 R_f}{R_f^2 + \frac{R_i^2 + 6R_i R_f}{9\left(1+\omega^2 C_0^2 R_i^2\right)}} \tag{4}$$

Calculation results show [7] that in real underground heading systems with a voltage of 3300 V or less, the maximum power that can evolve at an earth fault location is ca. 4.2 kW, which implies that in order to satisfy the condition to limit the maximum energy evolved at the fault location, the fault duration time should be limited to less than 1 s. According to the standards [2, 5], in networks with a voltage of up to 1 kV, and in networks feeding power to heading machines with a voltage exceeding 1 kV, the response time of leakage or earth fault protection should not be longer than 0.1 s, which effectively mitigates the explosion hazard caused by earth faults.

In 6 kV distribution networks, due to their large area coverage, and consequently their earthing capacitance, the energy evolved at the fault location is much higher, reaching up to several dozen kilowatts. The explosion hazard in such networks can be reduced if fast earth fault clearance is attained (according to the standard [4], instantaneous earth-fault protection with trip time no longer than 0.1 s should be used in rooms where explosion hazard exists). In addition, cables with crosslinked poyethylene (XLPE) insulation are recommended for new or upgraded networks. The relative permittivity of insulation, which is one of the factors determining the earthing capacitance of a cable, is ca. 2.4 in the case of XLPE, which is more than twice less than in the case of PVC, the latter being also an insulation material for cables used in mining. As a result, the earth fault current for cables with polyethylene insulation is almost two times lower than in the case of PVC insulation, which translates into two times lower values of maximum power and energy dissipated at the fault location.

WORK ORGANIZATION DURING REPAIRING OR CONNECTING CABLES

Another factor that significantly affects the safety of power networks operation is the manner of performing work when repairing or connecting cables and conductors at the place of their installation. This is due to the following reasons:

- cable joints are the only components of power networks in underground mines that are fabricated at the place of their installation,
- connections and repairs are often made in adverse ambient and technical conditions (high humidity, dripping water, dust, confined space, poor lighting, pressure placed on electric maintenance personnel), which can have an impact on the quality of installation work,
- insulation removal operations generate the risk of electric shock which can occur in the case of wrong cable identification or accidental energizing of the cable.

Therefore, performing cable repair and connection operations should be ruled by regulations aimed at minimizing the possibility of mistakes during installation work. Regulations [1] stipulate that such work should be done in accordance to a manual based on rules defined by an expert body. The status of an expert body in this area has been granted to ITI (Institute of Innovative Technologies) EMAG, which has developed the rules to be followed when performing such activities [14]. The major factors affecting the quality of repair and connections include:

- qualifications of the personnel that make repairs and connections, acquired by completing appropriate training courses (including those organized by the expert body),
- quality of the materials and tools used (complete repair kits are available for specific cable types),
- clear and detailed description of the operations to be performed,
- quality control schemes (technical acceptance inspections).

When discussing the factors determining the safety of work performance, particular attention should be paid to identification of the cable on which a task, e.g. cutting, is to be performed. Such tasks should be regarded as work performed under the conditions of particular threat to health and life, and may only be carried out upon receiving a written instruction. The cable and conductors must also be protected against accidental energizing.

NETWORK PROTECTION EQUIPMENT

The purpose of using protection equipment in power networks is to reduce the effects of failures by preventing or eliminating such conditions (in most cases by shutting down the part of network where failure had occurred). Due to the increased level of hazard caused by failures in underground workings, the requirements set for such protection means should be higher than those for other industrial networks. Such requirements include:

- reliability, meaning that on the one hand in case of a failure the protection device will definitely respond, and on the other hand, when a failure does not occur, or when it occurs in an object assigned to another protection device, it will not respond. Lack of necessary response from the protection device may lead to material losses (mainly thermal damage to equipment and cables) and a number of hazards [6, 9]. Unnecessary response, on the other hand, may lead to the shutdown of equipment which is important for maintaining continuous production or for the safety of operations (e.g. main fans, pumps, etc.).
- speed of action, which determines failure duration and, in the case of fault protection, determines the amount of energy evolved at failure location and the temperature reached by network components. These factors determine the explosion and fire hazards, therefore the response of the device that protects an object (e.g. a cable) situated in an explosion hazard zone should be instantaneous. Standards place tight requirements in this respect [2, 4, 5]. Meeting them may be difficult in technical terms (e.g. in the case of networks with frequency converters).
- selectivity, that is the ability of the protection device to act only with respect to the object (part of a power supply system) assigned to that device. The basic method of ensuring selectivity of protection equipment is the introduction of a time delay, which is only possible in areas with no explosion hazard (as mentioned before, hazardous zones require the use of instantaneous protection). For this reason it is often impossible to provide full selectivity of protection in

hazardous areas, which in turn may lead to unnecessary shutdowns.
- sensitivity, that is ability to detect a failure even when there is only a small change in the measured parameter (e.g. current, resistance, etc.) Sensitivity is determined quantitatively by sensitivity factor which is defined as the ratio of the lowest measured value that trips the protection device to the setting value of the protection device. Higher value of this factor means that the certainty of the protection device to respond to a failure is higher, and that at the same time it is more difficult to specify the setting value. In the case of fault protection in underground mines, the value of the sensitivity factor depends on the level of hazard and is equal to 1.3 for areas with no methane explosion hazard, 1.5 for hazardous areas, 2.0 for 1 kV+ power supply systems for heading equipment.

Given the very important role of protection means in ensuring safe operation of power networks, which in particular applies to fault protection, it is very important that the rules of selecting such means and the level of protection afforded by them be proportional to the existing hazards. The effects of applying insufficient protective means are obvious – increased hazards leading to accidents or damage to property. But the opposite situation, when protective measures are excessively strict as related to actual hazards, is also undesirable. It may result in a significant number of shutdowns considered (often rightly) by the user to be unnecessary. This leads to a specific conflict of interests, wherein on the one hand there is the desire to attain a higher level of safety by implementing extensive protection means, and on the other hand there is the need to ensure proper operating conditions, including uninterrupted power supply to machinery. As a result the following effects may be observed [7]:
- intentional elimination of protection means considered by the users to be unnecessary and to be a source of problems,
- formation and spreading of the attitude of low confidence in regulatory requirements.

Particularly dangerous is the adoption of wrong attitudes with regard to other protection systems and means that are critical to safety issues.

CONCLUSION

Technical means of protection applied in power networks of mines provide proper level of safety, the evidence of which may be the low percentage of electricity-related accidents not caused by the human factor. Such technical means include, for instance:
- use of networks with an isolated neutral point of the transformer,
- the requirement to use cables with individual screens in systems located in methane explosion hazard areas,
- tight requirements on protection equipment performance specifications,
- protective earthing system which reduces the touch voltages down to permissible levels.

During the recent 10-20 years there has been a very rapid technological progress in the furnishing of machinery and equipment with electrical instruments, automation devices, monitoring, surveillance and data transfer systems, etc. Irrespective of the obvious benefits of this process, we must see its potential adverse effects, such as insufficient experience of the personnel in operating the equipment, growing number of technical devices, limited space in underground workings [15]. Given these considerations, and the fact that the vast majority of electricity-related accidents are caused by wrong human acts, mostly intentional (resulting from disregard of regulations), special attention should be paid to the level of skills and hazard awareness of the electrical personnel, particularly of junior employees. Difficult economic situation of coal mining companies may push them to look for savings in training courses (reduced number of courses, low-skilled instructors, etc.), which in the near future may lead to an increased accident rate.

The electrical safety level is also affected by the shortage of electrical personnel and often low technological culture of non-electrical personnel.

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