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Protective and control relays as coal-mine power-supply ACS subsystem

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Abstract. The paper presents instantaneous selective short-circuit protection for the cabling of the underground part of a coal mine and central control algorithms as a Coal-Mine Power-Supply ACS Subsystem. In order to improve the reliability of electricity supply and reduce the mining equipment down-time, a dual channel relay protection and central control system is proposed as a subsystem of the coal-mine power-supply automated control system (PS ACS).

1. Introduction

For coal mines, as dust and gas hazardous areas, the Safety Regulations [1] require installation of instantaneous (non-delayed) short-circuit (SC) protection systems in 3-10 kV lines extending from the Central Underground Station (CUS) and underground distribution hubs (UDHs). In cases of net-work failure, protection enables single-shot automatic reclosing (AR) and automatic transfer switches (ATS) if used with equipment locking voltage supply to power lines and facilities in case of insulation damage caused by SC.

When used, conventional stand-alone digital protective relays, more specifically, overcurrent protection relays (OCP), interrupt SC currents in the power-supply circuit instantaneously and non-selectively by opening all the circuit breakers on the entire SC current path from the CUS to the fault location. Time coordination between protective relays is unacceptable as provided by the require-ments [1], while current coordination between protective relays is impossible due to small lengths (hundreds of meters) of the cable lines in the mine network.

Thus, if short circuit occurs in the power-supply circuit of the underground part of a coal mine, conventional stand-alone overcurrent protection will cause a massive power failure, which signifi-cantly reduces the electricity supply reliability. Recovering power supply by performing immediate switching operations in the power-supply system will result in the increased downtime of mining equipment.

2. Materials and methods

The dual channel protection includes:
1) Logical Protection (LP) as a main protection system;
2) Overcurrent Protection (OCP) as a backup protection system.

The main protection is instantaneous OCP with selectivity provided by blocking signals transmitted between UDHs and the CUS over the communications channels.

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The backup protection is instantaneous OCP non-selectively opening a circuit breaker carrying SC current. The non-selective operation is adjustable by resorting to controlled automatic or automated (by a dispatcher) reclosing (CAR).

In backup systems, following the interruption of SC current, protective relays may provide controlled automatic/automated supply of standby power (CASSP).

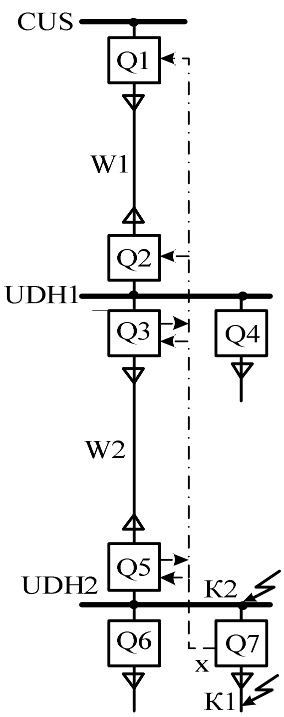

Figure 1. Circuit sector diagram.

The two protective relays and centrally control relays require the creation of channels to transmit data on the status of the circuit breakers, protection operation, and transmission of commands to the circuit breakers. Such equipment was developed and is widely used for state-of-the-art process-control systems. In particular, the power-supply control subsystem of the Energo Mainten-ance Control Automated System [2] uses channeling equipment to create a data network using In-dustrialEthernet, RS485 Interface, or copper or fiber-optic cable dial-up lines.

Let us see how the proposed solutions are applied in the circuit sector shown in Figure 1, which includes CUS (Central step-down substation) busbars and two UDHs (underground distribution substitutions) connected by W cable lines.

Protective Relays

In order to rectify SC, it is recommended to use busbar logical protection (BLP) implemented in up-to-date microprocessor protection relays widely used in substation switchgears.

The BLP operating principle is as follows: the following two kits provide current protection in the switchgear breakers:

- The first, instantaneous kit with a time delay of 0.15 to 0.2 sec is activated when SC current flows through the protective relays unstopped by any blocking signal;
- The second, delayed kit provided with a conventional selective delay of time is designed to back up the first protection.

In substation switchgears, the blocking signal is transmitted from feeder protection to input switch protection kit through the blocking busbar running along all the feeder cells.

As shown in the diagram in Figure 1, in case of feeder failure (K1), the instantaneous protection kit is activated on this line opening the Q7 switch. Input protection is blocked by the x signal (the dashed line in Figure 1); while the second, delayed protection kit, with a conventional selective delay of time, backs up feeder protection.

In case of damage to the busbar (K2 in Figure 1), there is no blocking signal coming from the feeder. In this case, the instantaneous kit for input protection is triggered to open the Q5 switch. The second, delayed protection kit, with a conventional selective delay of time, backs up input protection.

However, the stand-alone use of the BLP feature within every UDH of the mine network will not block the disconnection of the switches of other UDHs. For example, SC at K1 (Figure 1) will cause the opening of the Q1 and Q3 switches resulting in a blackout for all UDH1 and UDH2 con-sumers. In order to prevent the disconnection of the switches, it is advisable to create additional channels transmitting the blocking x signal to the protective relays on the Q1 and Q3 switches (the dashed-dotted line in Figure 1), thus enhancing the capacity of the stand-alone BLP up to the logical protection of the network.

Backup protection is activated in case of main protection failure or used as main protection when there are no communication channels between UDHs and the CUS. However, the direct use of this second, delayed BLP kit provided with a conventional selective time delay is contrary to the requirements [1]. Therefore, backup protection must be operated instantaneously.

In particular, the absence of communication channels between UDHs and the CUS, and the occurrence of short-circuit at K1 (Figure 1) will instantaneously open the Q7, Q5, Q3, Q2 and Q1 switches. The undervoltage protection relays will disconnect the remaining switches. All UDH1 and UDH2 consumers will be left without electricity. SC at K2 (Figure 1) will instantaneously open the Q5, Q3, Q2 and Q1 switches. The undervoltage protection relays will open the remaining switches. As in the first case, all UDH1 and UDH2 consumers will be left without electricity.

It is advisable to recover the system using the CAR and CASSP algorithms described below.

Thus, for reliable, instantaneous, and selective short-circuit breaking and reduced downtime of the mining equipment, it is appropriate to use the dual channel protective relays interacting properly. See the circuit sector (Figure 1) for the options of such interaction.

Two protection kits, LP and OCP, are installed on all the circuit breakers. The blocking x signal channels are laid between the CUS and UDH1 and UDH2 (the dash-dotted line in Figure 1).

In the event of short circuit occurrence at K1 (Figure 1), fault current will flow through the Q1, Q2, Q3, Q5, and Q7 switches. The blocking x signal will keep the Q1, Q2, Q3, and Q5 switches closed. Consequently, in the event of short circuit occurrence at K1 (Figure 1), logical protection will open the Q7 switch only.

In the event of short circuit occurrence in UDH busbars (K2 in Figure 1), logical protection (LP) is expected to open the Q5 switch and transmit the blocking x signal to the Q1, Q2, and Q3 switches.

In case of logical protection failure, backup OCP is activated on any of the switches to instantaneously disconnect the switch.

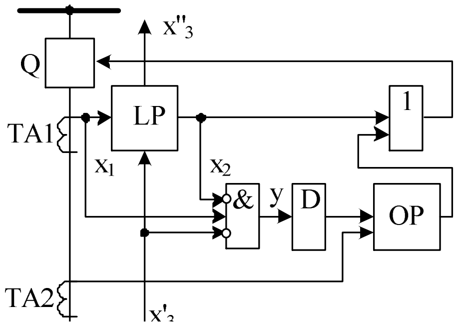

Figure 2. Schematic diagram of dual channel.

The logic of the protective relays on the Q switch is demonstrated through the diagram in Figure 2 accompanied by the following legend: LP, logical protection (main); OCP, overcurrent protection (backup); x1, the connection SC current signal; x2, the connection breaking signal, x’3, the blocking signal coming from the protective relays below; x’’3, the blocking signal transmitted to the protective relays above; & and 1, the logic elements (conjunctor and disjunctor); y, the output conjunctor signal; TA1 and TA2, current transformers, and D, signal delay required to set off the time of the tripping of the logical protective relays.

In order to improve the reliability, the LP and OCP kits must receive signals from different current transformers.

The main channel of protection (LP) provides instantaneous selective tripping of the Q switch. The backup channel of protection (OCP) provides instantaneous tripping of the Q switch in case of main protection channel failure.

The logic of the OCP activation is described by the Boolean expression:

$$y = x_1\bar{x}_2\bar{x}'_3 \ . \qquad (1)$$

The *y* conjunctor output signal is sent to the OCP unit input through the D delay, being a sig-nal activating such protection. OCP is activated and operated when the y conjunctor output signal equals to 1.

The truth table (Table 1) prepared for the expression (1) demonstrates that any combination of input signals (1, 2, 3, 4, 6, 7, and 8), other than combination 5, does not activate OCP. In all cases except case 5, LP will be activated. LP failure is characterized by state 5, which has a SC current signal (x1=1), no blocking signal (x’3=0), and no LP activation signal (x2=0). The conjunctor output signal (y=1) enables OCP.

Table 1. Output signals

State Number	1	2	3	4	5	6	7	8
x_1	0	0	0	0	1	1	1	1
x_2	0	0	1	1	0	0	1	1
x'_3	0	1	0	1	0	1	0	1
y	0	0	0	0	1	0	0	0

The General-Purpose System for the Representation of an Electrical Circuit

The correct operation of the protection and control system is only possible if the topology of the original circuit diagram is represented properly. Such representation is designed to both achieve general purposes and provide an accurate reflection of the circuit structure.

In order to obtain an adequate representation, all switches should be divided into structural switches and feeder breakers. Structural switches determine the architecture of the circuit including the CUS/UDHs connections. These are the head switches of the CUS/UDH connectors and UDH input switches.

Feeder breakers represent how individual consumers get connected to CUS/UDH busbars.

As shown in Figure 1, Q1, Q2, Q3, and Q5 are the structural switches, and Q4, Q6, and Q7 are the feeder breakers.

In addition, all the switches are divided by level of connection (CUS, UDH1, UDH2 ...).

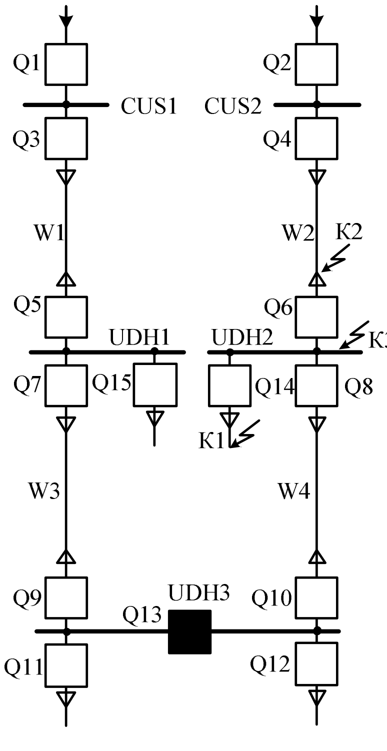

Figure 3. Circuit diagram

CAR Algorithm

Automatic reclosing is widely used in power systems to improve the electricity supply reliability. For a mining cable network with its own unique features, it is recommended to use the reclosing of the switches in order to adjust the non-selective short-circuit breaking by protective relays.

As noted above, in the event of short circuit occurrence in the power-supply circuit of the underground part of a coal mine, the use of conventional stand-alone OCP relays will cause a massive power failure, which significantly reduces the electricity supply reliability. Recovering power supply by performing immediate switching operations in the power-supply system increases the downtime of mining equipment.

In order to reduce the downtime of mining equipment, it is recommended to perform all switching operations under the control of a power dispatcher operating an automated workstation (AWS), as it is required, for example, by the power-supply control subsystem of the Energo MCAS [2] reflecting the status of all CUS/UDH switches and protection activation control on the screen of the AWS host computer.

Switches can be closed remotely under central control or, with the permission of the dispatcher, automatically, by a given algorithm. In the latter case, CASSR features are implemented concurrently with blocking the closing of the switches of the affected component of the power supply system.

It should be noted that reclosing can be an unacceptable option for certain coal-mine consumers. In particular, startup of a loaded conveyor may lead to increased inertial efforts and overloaded traction chains and the drive. This is especially important for long-distance conveyors running the risk of slipping and the oscillations of the slack strand of the belt. Such situations require blocking the closure of relevant switches as well as conveyor inspection and adjustment.

The algorithm for circuit recovery after its collapse resulting from short-circuit breaking by OCP kits can be described by a matrix of signals from switch protection relays (xi=0, protection was not activated, xi=1, protection was activated.) This matrix contains m columns and n rows, where the m is the number of switches in the circuit running from the CUS to where SC occurred, and the n is the number of the states of the field of signals sent from the protective relays.

The controlled AR possibility is determined by the y signal (if y=1, AR is possible, if y=0, AR is not possible) in accordance with the Boolean expression:

$$y = x_1 x_2 x_3 \dots x_m \vee \bar{x}_1 x_2 x_3 \dots x_m \vee x_1 \bar{x}_2 x_3 \dots x_m \vee x_1 x_2 \bar{x}_3 \dots x_m \vee \dots \vee x_1 x_2 x_3 \dots \bar{x}_m . \quad (2)$$

Expression (2) allows for a possible failure in the activation of any of the protective relays. If y=1, CAR is activated: all structural switches, except for the last Qm switch, are closed under central control. Expression (2) implies that "incomplete" CAR is only enabled in case of failure of the protective relay nearest to where short circuit occurred.

As for the feeder breakers opened due to no voltage present on UDH busbars, they also will be closed under central control based on the specific nature of the electrical receivers.

To clarify the above-mentioned, let us have a look at the 3-10 kV circuit diagram (Figure 3) implementing the stand-alone OCP and CAR features. Power is supplied by different bus sections of the CUS (CUS1 and CUS2) powering three UDHs. The Q13 switch on UDH3 is normally opened. The circuit structure is determined by switches Q1, Q3, Q5, Q7, Q9, Q13, Q10, Q14, Q6, Q4, and Q2. The remaining switches are feeder breakers.

In case of short circuit after the feeder breaker (K1), the Q14, Q6, Q4, and Q2 switches are instantaneously opened. Signals coming from the protective relays on these switches will form the following protection signal matrix (Table 2).

Table 2. Protection signal matrix

№	$Q2(x_2)$	$Q4(x_4)$	$Q6(x_6)$	$Q14(x_{14})$	y
1	1	1	1	1	1
2	0	1	1	1	1
3	1	0	1	1	1
4	1	1	0	1	1
5	1	1	1	0	1

The ones in the matrix cells indicate the presence of a protection signal, whilst the zeros indicate no signal. The rows show the possible combinations of signals in case of an error (failure of one protective relay).

The possibility of controlled AR is determined by the y signal (if y=1, AR is possible, if y=0, AR is not possible) in accordance with the Boolean expression:

$$y = x_2 x_4 x_6 x_{14} \vee \bar{x}_2 x_4 x_6 x_{14} \vee x_2 \bar{x}_4 x_6 x_{14} \vee x_2 x_4 \bar{x}_6 x_{14} \vee x_2 x_4 x_6 \bar{x}_{14} . \quad (3)$$

If y=1, the Q2, Q4, and Q6 switches are expected to be closed under central control. However, in case 5 (switch Q14 protection failure), it is recommended to close the Q2 and Q4 switches only.

CASSP Algorithm

Automated supply of stand-by power is widely used in substation switchgears for electricity supply to key consumers with two or more independent power sources.

Let us delve into the centrally controlled activation of such control relays used for cable distribution network of the mine.

The CASSP algorithm depends on where SC occurs in the mine power supply circuit and the location of the breaker of the circuit providing two sources to power its consumers. [1] prohibits the subsurface use of loop power systems.

CASSP is expected to be activated following such short circuit leaving several UDHs without power after SC rectification and even after AR, i.e., in the event of SC on the lines connecting stand-alone UDHs, or SC on UDH busbars (e.g. K2 and K3 in Figure 3).

The standard algorithm for supply of stand-by power in case of SC at K2 (Figure 3) is as follows: opening Q10 in case of no voltage present on the busbars and closing the Q13 bus-section switch will leave UDH2 consumers without power. Therefore, it is feasible to adjust the CASSP algorithm to the CAR algorithm in respect of closing all switches, except the last one near the fault location. However, the switch-closing direction will be different. If CAR first closes structural switches nearest to the power source (CUS busbars) proceeding towards the fault location, CASSP first closes the switch normally breaking the circuit proceeding towards the fault location.

As shown in the diagram in Figure 3, in case of SC at K2, after relay protection is activated (the Q4 switcher is opened) without voltage, the Q6, Q8 and Q10 structural switches are opened. In this case, close the Q13, Q10, and Q8 switches under central control and do not close the Q6 switch nearest to the fault location.

In case of SC at K3, after the Q6 switch is closed, close the Q13 and Q10 switches under central control and do not close the Q8 switch.

Close the feeder breakers open without voltage as in AR based on the specific nature of the electrical receivers.

3. Conclusion

A dual channel SC protection system is proposed for the underground part of the power supply system of a coal mine, including logical and overcurrent protection, and providing instantaneous selective disconnection of the affected component.

In order to reduce the mining equipment downtime due to power system failures, centrally controlled relay algorithms have been developed to enable automatic reclosing and stand-by power supply. It is shown that centrally controlled relays continue operating even in case of failure of one protective relay of a coal mine power-supply circuit.

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