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Back-up short circuit protection in underground medium voltage networks

The paper presents issues related to the implementation of back-up short-circuit protection in the final sections of an underground medium voltage distribution network. The difficulties may arise from regulatory requirements regarding the operation time of protection devices in potentially explosive areas and relatively low values of short-circuit currents compared with load currents. Sample calculations results have been presented to illustrate the problems of selecting current settings of short-circuit protection. A method to overcome these problems by using transformer stations with a circuit breaker on the primary side has been shown.

key words: short-circuit protection, electric power networks in mines, electric power systems, electric power engineering in mines, mining power supply networks, protection automation in electric power engineering.

1. INTRODUCTION

Safety and reliability of electric power networks depend, to a large extent, on correct functioning of systems that eliminate disturbance states. Improper functioning of protection devices can result from damages of current transformers, measuring and power supply circuits, transmitters, releases, and switches. These damages can cause the failure of the protection to work and, as a consequence, a disturbance state to persist. Such a situation may have very serious consequences, such as fire-, explosion-, electric shock-, and burn hazards, let alone costly damages of installation or apparatus and power supply interruptions [3]. Improper functioning of protection devices can also cause unwanted operations that will lower the level of power supply continuity which, in the case of mining facilities, can have a significant impact on their safety.

Proper reliability of protection devices can be achieved by [4, 6]:

– proper selection of particular elements in protection systems,
– periodical check-ups of working efficiency of protection devices,
– local back-ups, i.e. making back-ups of protection system elements (protection devices or switches) in the given facility, e.g. a distribution board,
– remote back-up, i.e. the ability of the given protection system to respond to certain disturbances which occur in the adjacent part of the system.

2. GENERAL RULES AND REQUIREMENTS CONCERNING BACK-UP OF SHORT-CIRCUIT PROTECTION IN UNDERGROUND NETWORKS

Due to the necessity to install extra equipment, it may be difficult, or even impossible, to have local back-up in the conditions of a mining network as there is not enough space to install it. The most commonly used type of back-up (or the only possible one in mines) is remote back-up. Its basic advantage is that it uses the existing apparatus, i.e. short-circuit protection which may act, at the same time, as basic protection of its own zone and back-up protection of the adjacent zone in the direction from the power supply source. The back-up protection should work only if the basic protection does not, after the shortest time necessary to detect the failure of the basic protection. Therefore, the basic principle used to provide back-up is the so called time delay. Time delay is based on different operation times of back-ups in particular sections of the network. It is applied due to the necessity to ensure proper selectivity. In electric power engineering it is assumed that back-up protection is, by definition, slower than basic protection. The above solution is successful in networks whose structure is not too much complicated, e.g. those which work in a radial configuration, just as the majority of mining medium-voltage networks. In the case of older electromechanical protection devices and switches, the used time delay is 0.5 s, while for modern (digital) ones – 0.3 s [4, 5].

According to the requirements of the standard [1], back-up short-circuit protection should be used in mining networks with the nominal voltage above 1 kV. Table 1 features the longest admissible delay in short-circuit relay protection stipulated by the standard, depending on the network element under protection and the methane hazard level of the protected zone.

Table 1.

The longest admissible delay (in seconds) of short-circuit relay protection [1]

Protected element of the network	Longest admissible delay of short-circuit relay protection, [s]			
	Basic protection		Back-up protection	
	Safe room	Unsafe room	Safe room	Unsafe room
Shaft lines (cables) and lines (cables) in the distribution network	1.6	0	2.0	0.5
Lines supplying motors	0	0	1.6	0.5
Lines supplying transformers	0.6	0	1.6	0.5

In real underground medium-voltage distribution networks the problems with back-up may result from the requirements related to the operation time of the protection device and difficulties in selecting the setting value of current. If the basic protection zone is located in a safe room, it is possible to provide back-up with the use of time delay, even if the back-up zone is located in an unsafe room. However, if the basic zone is located in a room with explosion hazards, then, due to the necessity to cut off short circuits immediately, full remote back-up with time delay is not possible. Such a situation may cause non-selective operation of protection devices. Partial selectivity can be ensured here by using two-stage short-circuit protection devices. With proper selection of current settings, the first (instantaneous) stage can serve as the basic protection, while the second stage – as the back-up one (e.g. with time delay 0.3÷0.5 s).

Difficulties in the selection of back-up protection current settings arise when the minimum short-circuit current is too small in comparison with the maximum load current. The standard [1] allows to shorten the protected zone by means of back-up protection if this protection cannot switch off the short circuits behind the transformers, on lines equipped with chokes or at the end of the next section. A requirement on back-up can also be found in the standard [2] on installations with the nominal voltage above 1 kV that supply power to coal face systems. Short-circuit protection located at the beginning of the network line (i.e. usually in the transformer station that supplies power with the voltage above 1 kV) should be back-up protection of the protection device whose protected zone is the section of the network that supplies power directly to a mining face machine along with its motors (i.e. protection devices in a mining starter). However, due to the fact that the protection in the transformer station should be instantaneous protection (in compliance with the standard [1]), this back-up does not rest on time delay in the protection operation but on proper selection of the current setting value – such that the protection could respond to disturbances in the adjacent zone. This may cause non-selective operation of protection devices.

While selecting current settings of short-circuit protection devices it is vital to take into account the sensitivity coefficient k_{cz} and safety coefficient k_b. The sensitivity coefficient is defined as a ratio of the smallest value of short-circuit current, which is subject to switch-off, to the setting value of protection current. The value of this coefficient is smaller for back-up protection than for basic protection. Minimum admissible values of sensitivity coefficients stipulated by the standards [1] and [2] are presented in Table 2.

The safety coefficient, i.e. assurance that no unwanted operations occur, is the ratio of the setting value of protection current to the maximum load current (at which the protection should not work). In underground networks the value of the coefficient k_b is assumed to be between 1.2 to 2.0 [1], depending on the type of the protected object.

Table 2.

Values of sensitivity coefficient of short-circuit protection in mining networks [1, 2]

Types of rooms where protected zone is located	Smallest admissible value of sensitivity coefficient k_{cz}	
	of basic protection	of back-up protection
Rooms with no explosion hazards	1.3	1.2
Rooms with explosion hazards	1.5	1.3
Network supplying directly a mining face machine with the voltage above 1 kV	2.0	1.5

3. RESTRICTIONS RELATED TO BACK-UP POSSIBILITIES IN REAL UNDERGROUND NETWORKS

In real underground medium-voltage distribution networks, particularly in their extreme sections, the provision of back-up protection may cause the following problems:

- non-selective operations of protection devices located in rooms with methane explosion hazards, due to the necessity to apply instantaneous protection measures,
- necessity to shorten the operating zone of back-up protection caused by too small minimum value of short-circuit current in relation to the maximum load current in the place where the protection is installed.

Below there are three examples of extreme sections of a medium-voltage distribution network (with nominal voltage U_n=6000 V) which illustrate the above listed problems, along with selected calculation results of short-circuit currents and setting values of protection devices (the provided values are those on the primary side of circuit breakers). To simplify and clarify the analysis, only one or two outlets from distribution boards were taken into account. In real systems, a bigger number of outlets result in bigger values of maximum load currents. This situation reduces the possibilities to select protection settings and makes it even more difficult to solve the described problems with selecting protection devices. In all analyzed cases the following were assumed:

- short circuit power on the distribution board busbars R0 S_z=70 MVA,
- load coefficient of receivers k_o=0,9,
- nominal starting current of motors $I_{rn}=6I_n$,
- safety coefficient (assurance that no unwanted operations occur) k_b=1,2,
- YHKGXSekyn cables were applied in the network with the nominal voltage of 6 kV,
- diagram coefficient k_s=1 (it was assumed that current transformers, which supply short-circuit protection, operate in a star connection),
- transformers are characterized by Yy connections,
- networks are placed in rooms with explosion hazards.

In the first analyzed example the Z0 protection in the R0 distribution board protects the outlet which supplies the R1 distribution board, from which the transformer stations T1 and T2 are supplied through outlets with the Z1 and Z2 protection. These stations supply power to the receiving network with the nominal voltage of 1 kV.

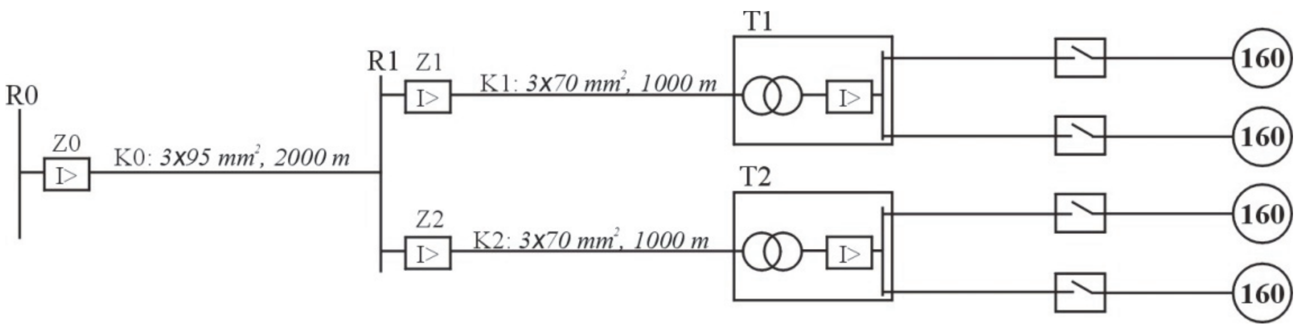

Fig. 1. Sample diagram of an underground network section. Transformer stations with the power of $S_{nT1}=S_{nT2}$=630 kVA and the voltage ratio of 6000/1050 V/V; motors supplied from one transformer are activated simultaneously

The calculation results of short-circuit protection settings are presented in Table 3.

Table 3.

Short-circuit currents and calculation ranges of possible setting values of short-circuit protection devices from Fig. 1.

Protection	Minimum value of short-circuit current in the basic zone [A]	Range of possible settings of [A]		Maximum possible value of sensitivity coefficient of	
		basic short-circuit protection	back-up short-circuit protection	basic protection	back-up protection
Z0	2882	260*) – 1922	260*) – 535	11.08	2.68
Z1	3980**) *(696)*	223 – 464	–	3.12	–
Z2	3980**) *(696)*	223 – 464	–	3.12	–

*) *minimum value; in case of a bigger number of outlets from the R1 distribution board, the bottom limit of the possible settings range will be higher,*
**) *if there is a short circuit on the secondary side of the transformer; the numbers in brackets stand for the current value of the 6 kV side.*

As we can see in the calculations in Table 3, the Z0 protection can function as back-up protection for Z1 and Z2 (in the whole basic zone of these protection devices). However, due to the fact that its basic protected zone is located in a room with explosion hazards, this protection has to be instantaneous. If Z0 is one-stage protection, it may respond non-selectively in case there are short circuits in the outlets supplied from the R1 distribution board. Partial selectivity can be ensured by two-stage protection. Then the current setting of the instantaneous part should be selected from the upper part of the basic protection possible settings range (which means that the value of the sensitivity coefficient will be smaller), while the setting of the delay part (with delay time up to 0.5 s) should be within the range given for the back-up protection. Still, it is necessary to consider the fact that the consequences of non-selective operation of short-circuit protection devices in the extreme sections of an underground electric power supply system will be unsignificant, as the receivers supplied from the terminal distribution board usually carry out the same technological process. If the distribution boards R0 and R1, as well as the K0 line, were placed in a room with no explosion hazards, the delay in the operation of the Z0 protection would ensure its complete selective operation.

In the diagram from Fig. 1 the value of the sensitivity coefficient of Z1 and Z2 results from the necessity to respond to short circuits on the secondary side of the T1 and T2 transformers – the majority of transformer stations exploited in the mining industry do not have switches on the HV side. In some cases this may hamper the selection of a short-circuit protection setting and make it impossible to perform the back-up. Examples of such networks can be seen in Fig. 2 and 3.

In the network section in Fig. 2 the value of the maximum load current in the outlet to the T2 transformer is high. This results from high power of the transformer and the receivers supplied from this transformer. At the same time, the value of the minimum short-circuit current in the outlet to the T1 transformer is low. This limits the back-up zone of the Z0 protection which cannot function as back-up protection for Z1 when there are short circuits on the secondary side of the T1 transformer.

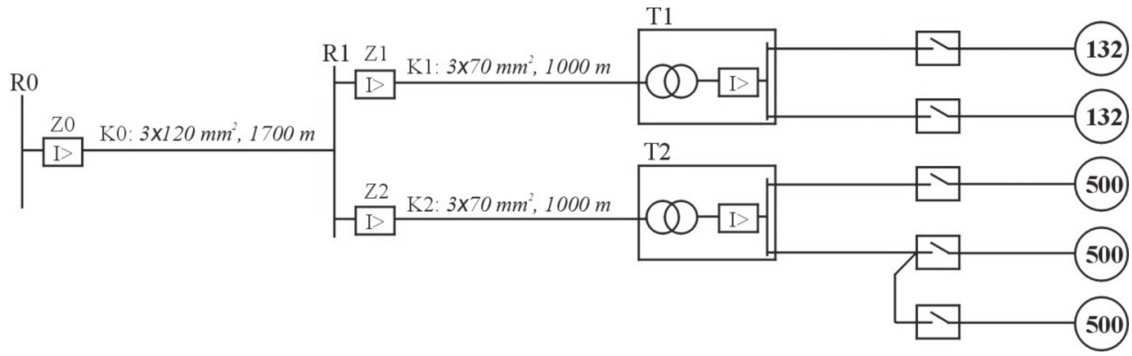

Fig. 2. Sample diagram of an underground network section. Transformer stations: S_{nT1}=400 kVA, 6000/1050 V; S_{nT2}=1750 kVA, 6000/3300 V; 132 kW motors are activated simultaneously, the others in sequence

Table 4.

Short-circuit currents and calculation ranges of possible setting values of short-circuit protection devices from Fig. 2.

Protection	Minimum value of short-circuit current in the basic zone [A]	Range of possible settings of [A]		Maximum possible value of sensitivity coefficient of	
		basic short-circuit protection	back-up short-circuit protection	basic protection	back-up protection
Z0	3202	528 – 2134	***528-1140***)*	6.06	***2.81***)*
Z1	2725**) *(477)*	190 – 318	–	2.51	–
Z2	2697**) *(1483)*	528 – 988	–	2.81	–

**) limitation of back-up protection zone – it does not cover the LV side of the T1 transformer,*
***) value of short-circuit current during a short circuit on the secondary side of the transformer; the numbers in brackets stand for the current value of the 6 kV side.*

In an extreme case, with bus-based power supply to transformer stations (which can be supplied with the use of through connections) it may turn out that it is impossible to select the setting of basic protection. This may happen in a situation when one station has low nominal power and, additionally, high impedance of the transformer limits the value of short-circuit current, while the second station supplies power to receivers with high value of maximum load current. An example of such a network section is presented in Fig. 3.

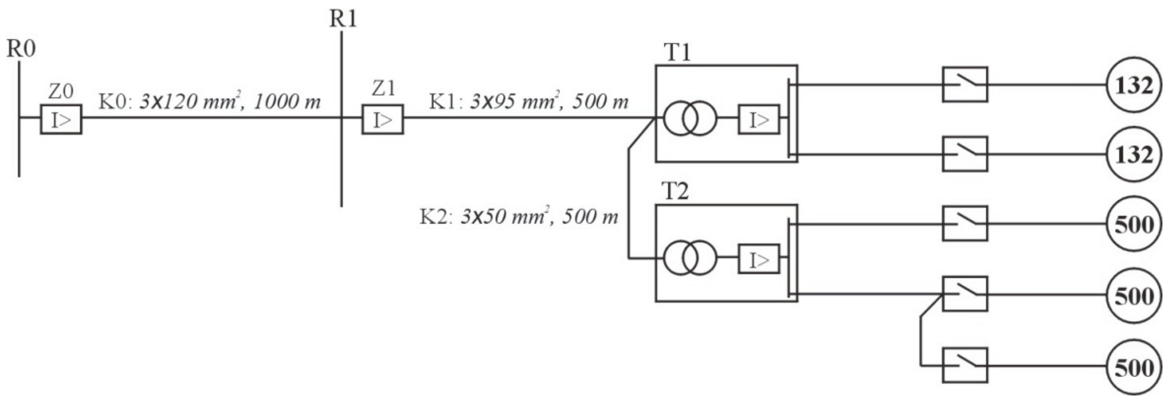

Fig. 3. Sample diagram of an underground network section. Transformer stations: S_{nT1}=630 kVA, 6000/1050 V; S_{nT2}=1750 kVA, 6000/3300 V; 123 kW motors are activated simultaneously, the others in sequence

Table 5.

Short-circuit currents and calculation ranges of possible setting values of short-circuit protection devices from Fig. 3.

Protection	Minimum value of short-circuit current in the basic zone [A]	Range of possible settings of [A]		Maximum possible value of sensitivity coefficient of	
		basic short-circuit protection	back-up short-circuit protection	basic protection	back-up protection
Z0	3728	564 – 2485	***Selection impossible***	6.61	***Selection impossible***
Z1	4322 *(756)*	***Selection impossible***	–	***Selection impossible***	–

As it can be seen from the calculations, the maximum value of load current flowing through the Z1 protection (during the start-up of a 500 kW motor) is 470 A, while the current value during a short circuit on the secondary side of T1 – 756 A. After we take into account the sensitivity and safety coefficients, it is evident that the setting of the Z1 protection is impossible.

The problems related to difficulties in the selection of back-up or short-circuit protection devices can be significantly reduced by using transformer stations equipped with short-circuit protection on the HV side. Then the zone of the protection located in the distribution board does not encompass the side of lower voltage of the transformer. This allows to achieve bigger minimum values of short-circuit currents in the protected zone. Tables 6, 7 and 8 feature the results of calculating short-circuit currents and protection settings for the networks depicted in Fig. 1, 2 and 3 respectively. Yet, the assumption is that the transformer stations are equipped with short-circuit protection devices and switches on the side of the upper voltage.

Table 6.
Short-circuit currents and calculation ranges of possible setting values of short-circuit protection devices from Fig. 1 with transformer stations having switches on the HV side

Protection	Minimum value of short-circuit current in the basic zone [A]	Range of possible settings of [A]		Maximum possible value of sensitivity coefficient of	
		basic short-circuit protection	back-up short-circuit protection	basic short-circuit protection	back-up short-circuit protection
Z0	2882	260 – 1922	260 – 1737	11.08	8.68
Z1	2259	223 – 1506	223 – 535	10.13	3.12
Z2	2259	223 – 1506	223 – 535	10.13	3.12
T1 (GN)	3980 *(696)*	223 – 464	–	2.68	–
T2 (GN)	3980 *(696)*	223 – 464	–	2.68	–

Table 7.
Short-circuit currents and calculation ranges of possible setting values of short-circuit protection devices from Fig. 2 with transformer stations having switches on the LV side

Protection	Minimum value of short-circuit current in the basic zone [A]	Range of possible settings of [A]		Maximum possible value of sensitivity coefficient of	
		basic short-circuit protection	back-up short-circuit protection	basic short-circuit protection	back-up short-circuit protection
Z0	3202	528 – 2135	528 – 1855	6.06	4.63
Z1	2466	190 – 1644	190 – 366	12.98	2.51
Z2	2412	528 – 1608	528 – 1222	4.57	2.81
T1 (GN)	2725 *(477)*	190 – 318	–	2.51	–
T2 (GN)	2697 *(1483)*	528 – 988	–	2.81	–

Table 8.
Short-circuit currents and calculation ranges of possible setting values of short-circuit protection devices from Fig. 3 with transformer stations having switches on the LV side

Protection	Minimum value of short-circuit current in the basic zone [A]	Range of possible settings of [A]		Maximum possible value of sensitivity coefficient of	
		basic short-circuit protection	back-up short-circuit protection	basic short-circuit protection	back-up short-circuit protection
Z0	3728	564 – 2485	564 – 2041	6.61	4.71
Z1	2654	564 – 1769	564 – 582	4.71	1.34
T1 (GN)	4322 *(756)*	210 – 504	–	3.60	–
T2 (GN)	2843 *(1563)*	534 – 1042	–	2.93	–

As we can see from the results of calculations presented in Tables 6-8, the use of transformer stations with switches on the HV side shortens the basic and back-up zones of protection devices in a medium-voltage network. This way it is easier to fulfill the requirements of the standard [3] in the realm of selecting the settings of short-circuit protection.

4. CONCLUSIONS

Based on the calculations and analyses conducted in this article it is possible to formulate the following conclusions:

- in real networks, particularly in situations when back-up protection covers the secondary side of low-voltage/medium-voltage transformers, one has to consider the necessity to shorten the operating zone of the back-up protection. This, in the case when basic protection is damaged, may cause short circuits of long duration,
- when transformer stations are supplied with the use of through connections, particularly when there are big differences in nominal power values of these stations, it may be impossible to select the current setting of basic protection in the distribution board which supplies the stations if the protected zone includes the secondary zone of the transformers,
- the use of transformer stations equipped with short-circuit switches and protection devices on the HV side eliminates the problems described above,
- due to the requirements of the standard [3] concerning the operation time of short-circuit protection devices, providing back-up for the network in a room with explosion hazards is related to the possibility of non-selective operation of protection measures.

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