SHORT-CIRCUIT PROTECTION OF INTERCOMPONENT CABLES ON 3 PHASE, ALTERNATING CURRENT, PERMISSIBLE MINING) EQUIPMENT

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Abstract-Magnetic and thermal magnetic circuit breakers are used to provide short-circuit protection for intercomponent cables on permissible mining equipment. Limits are needed for the circuit breaker settings which will adequately protect intercomponent cables under a short-circuit fault condition. Calculations reveal that the maximum allowable settings for large capacity power cables are limited by the minimum available short-circuit currents while the maximum settings for small control cables are limited by the amount of current the cable can withstand. When the available short-circuit current is greater than the current the cable can withstand, no circuit breaker setting is practical. The use of some small control cables with large trailing cables will be eliminated from future approvals due to large available short-circuit currents. Present approvals would not be affected. A computer program is available from the Approval and Certification Center to calculate circuit breaker settings.

I. INTRODUCTION

Title 30 Code of Federal Regulations (30CFR) part 18 [1] contains the requirements for Mine Safety and Health Administration approval of electrically operated mining equipment. Section 18.36(a)(2) states that cables between machine components shall have short-circuit protection. Magnetic and thermal magnetic circuit breakers and single or dual element fuses have been used to provide short-circuit protection. The circuit breaker not only

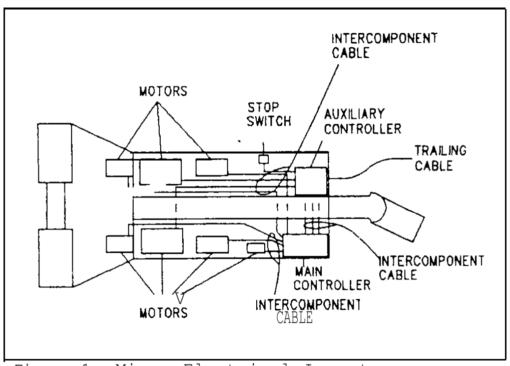


Figure 1. Miner Electrical Layout

provides short-circuit protection, but also a means by which power conductors can be de-energized at the machine. Enclosure covers which provide access to fuses, other than headlight, control circuit, or hand-held tool fuses must be interlocked with a circuit-interrupting device (Section 18.52); making fuses less desirable than circuit breakers for short-circuit protection. This report will deal with magnetic and thermal magnetic circuit breakers because they are most widely used. The report addresses intercomponent cable where no voltage transformation on the machine with corresponding reduction of available current is involved. Figure 1 is a typical electrical layout of a continuous miner with its intercomponent cables and trailing cable. The trailing cable supplies power to the machine. Figures 2 and 3 are the power and control schematic diagrams for this machine.

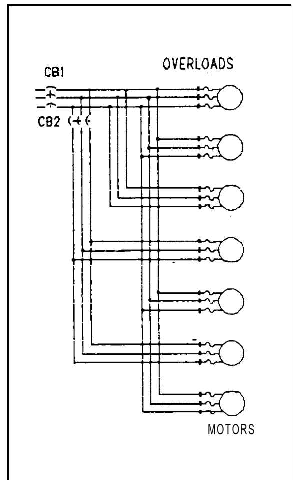
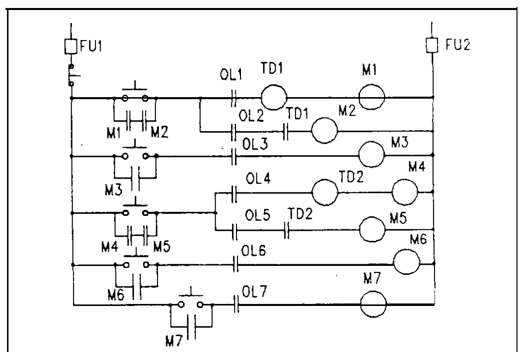


Figure 2. Miner Power Schematic

No guidelines are given in Part 18 for the setting of circuit breakers on-board a machine. Table 8, "Fuse Ratings or Instantaneous Setting of Circuit Breakers for Short-Circuit Protection of Portable Cables and Cords,." has been used as a guide for the setting of on-board circuit breakers. This



igure 3. Miner Control Schematic

table was compiled by calculating the line-to-line short-circuit current in a 500 foot length of two conductor trailing cable with an infinite capacity 250 volt dc power supply. A 50 percent safety factor was applied to the calculated currents. These settings are listed in Table I.

TABLE I		
INSTANTANEOUS SETTING OF CIRCUIT BREAKERS FOR SHORT-CIRCUIT PROTECTION OF PORTABLE CABLES AND CORDS, 30 CFR PART 18, TABLE 8		
Conductor size-AWG or MCM	Ohms/1000 feet at 25 °C	Maximum Allowable Circuit Breaker Instantaneous Setting (Amperes)[1]
14	2.62	50
12	1.65	75
10	1.04	150
8	0.654	200
6	0.41	300
4	0.259	500
3	0.205	600
2	0.162	800
1	0.129	1000
1/0	0.102	1250
2/0	0.081	1500
3/0	0.064	2000
4/0	0.051	2500
250	0.043	2500
300	0.036	2500
350	0.031	2500
400	0.027	2500
450	0.024	2500
500	0.022	2500

[1]Higher circuit-breaker settings may be permitted for special applications when justified.

When intercomponent cables are connected to a trailing cable of larger size than the intercomponent cable, more short-circuit current will be available than with a trailing cable of the same size. The minimum available short-circuit current for 500 feet of No. 4/O trailing cable and 25 feet of No. 4/O intercomponent cable is only 10 percent higher than the minimum available short-circuit current for 500 feet of No. 4/0 trailing cable and 25 feet of No. 6 intercomponent cable. The impedance of 25 feet of intercomponent cable is very small when compared with the impedance of 500 feet of trailing cable. When intercomponent cables are used with trailing cables of larger size, the settings of circuit breakers for intercomponent cables can be higher than those for trailing cables of the same size due to the increased available short-circuit current.

In order to determine that a circuit is adequately protected under a short-circuit condition, it must first be determined how much current the cable can withstand in the time required for the protective device to open (withstand current). The maximum available short-circuit current is then calculated. The maximum available short-circuit current must be less than the withstand current. The minimum available short circuit current is then calculated and the circuit breaker is set at a reduced value of this minimum current to account for circuit breaker tolerances.

II. WITHSTAND CURRENT

The withstand current, IW, is calculated using the equation:

$$IW = A\sqrt{\frac{.0297}{t}\log_{10}\frac{(T_2+234)}{(T_1+234)}}\quad (amperes)\qquad (1)$$

Where: A = conductor cross-sectional area (circular mils)
t = duration of short-circuit (seconds)
T_1 = initial conductor temperature ('C) (insulation rating)
T_2 = final conductor temperature ('C) (insulation damage rating)

The final conductor temperature is the temperature at which insulation damage will occur. For cables with insulation (rubber) rated 60°C, 75°C, and 85°C, T_2 is 200°C. For cables with insulation (EPR or XLPE) rated 90°C, T_2 is 250°C. For cables with insulation (AMA) rated 130°C, T_2 is 300°C. In 46 tests of mine duty circuit breakers where the circuit breaker setting was no more than 70% of the trip current, the circuit breakers tripped in less than two cycles. A worst case circuit breaker trip time of 6 cycles (.1 second) is substituted for t.

III. MAXIMUM AVAILABLE SHORT-CIRCUIT CURRENT

The maximum available short-circuit current, IMAX, is calculated using the equation:

$$IMAX = \frac{V}{\sqrt{3}\, ZMIN}\quad (amperes)\qquad (2)$$

Where: V = Machine voltage (480, 600, 1040, 2400, or 4160)

$$ZMIN = \sqrt{RMIN^2 + XMIN^2}\ (ohms)\qquad (3)$$

$$RMIN = TCRMIN + MCRMIN + PCRMIN + SSRMIN\ (ohms)\qquad (4)$$

TCRMIN = Minimum Trailing Cable Resistance (ohms)
MCRMIN = Minimum Intercomponent Cable Resistance (ohms)
PCRMIN = Minimum Power Center Resistance (ohms)
SSRMIN = Minimum Supply System Resistance (ohms)

$$XMIN = TCX + MCX + PCXMIN + SSXMIN \text{ (ohms)} \quad (5)$$

TCX = Trailing Cable Reactance (ohms)
MCX = Intercomponent Cable Reactance (ohms)
PCXMIN = Minimum Power Center Reactance (ohms)
SSXMIN = Minimum Supply System Reactance (ohms)

Equation (2) is for a three-phase bolted fault which would yield the highest short-circuit current. Figure 4 is a schematic diagram of a mine power system.

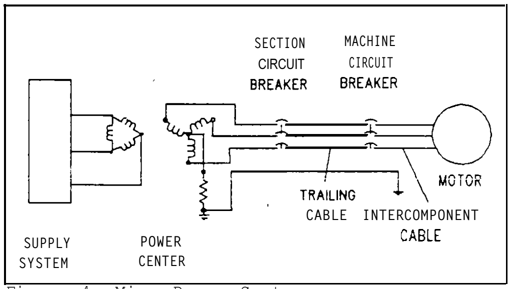


Figure 4. Mine Power System

The minimum power center resistance and reactance at 480, 600, and 1040 volts are calculated for a 2000 KVA power center with 1.0 percent resistance and 4.9 percent reactance. This is the maximum size power center with minimum impedance expected to be found in mines at these voltages. A review of approved 2400 volt longwalls indicated that at this voltage, 2500 KVA power centers with 811% minimum resistance and 3.5% minimum reactance are standard. The minimum values of power center resistance and reactance are listed in Table II.

TABLE II

ARCING FAULT FACTOR, PHASE-TO-PHASE VOLTAGE, MAXIMUM SUPPLY SYSTEM IMPEDANCE, AND POWER CENTER IMPEDANCE

Voltage	Arcing Fault Factor - K_1	Phase-to-Phase Voltage-$E_{\phi\phi}$ (Volts)
480	.85	456
600	.90	570
1040	.95	988
2400	1.00	2280
	Maximum Supply System Impedance (ohms)	
Voltage	Resistance	Reactance
480	.0121	.0139
600	.0189	.0217
1040	.0568	.0653
2400	.1590	.1990
	Minimum Power Center Impedance (ohms)	
Voltage	Resistance	Reactance
480	.00115	.00564
600	.00180	.00882
1040	.00541	.02650
2400	.01870	.07830
	Maximum Power Center Impedance (ohms)	
Voltage	Resistance	Reactance
480	.0046	.0226
600	.0072	.0353
1040	.0144	.0707
2400	.0240	.1010

If a specific power center is specified, its size can be entered in the computer program. A specific power center must be specified for 4160 volts since limited data is available from approved systems. An infinite supply system is used to calculate MAXIMUM available current resulting in supply system impedance being equal to zero.

The DC resistances of rope-lay concentric member, coated copper conductors at 25°C are listed in [2]. Rope-lay concentric member construction is most common for mining cables. Nos. 14 through 9 cables are Class G stranded, Nos. 8 through 500 MCM cables are Class H stranded. The resistance at 60 hertz is equal to the DC resistance. The resistance of the cables at 20°C, R_2, was calculated from the resistance at 25°C, R_2, using the equation:

$$R_2 = R_1 \frac{(234.5 + T_2)}{(234.5 + T_1)} \quad \text{(ohms)} \quad (6)$$

Where: R_1 = Resistance at Temperature T_1 (ohms)
T_1 = 25°C
T_2 = 20°C

Cable resistances are calculated at 20°C. This simulates a short-circuit occurring upon start-up, when the cables are cold. The reactance for Nos. 8 through 500 MCM cables are listed in [3]. The reactance of Nos. 10, 12, and 14 cables are listed in [4]. The reactance of No. 9 cable was interpolated from the combined tables of the above sources. All cables were assumed to be of round construction since this is the most common construction for intercomponent cables. Resistances and reactances are listed in Tables III and IV. An average length for intercomponent cable is 25 feet. Five hundred feet is the maximum length of trailing cable allowed by Part 18, with certain exceptions and is the standard length used on a typical mining machine. These lengths can be used as defaults in the computer program.

TABLE III

NOMINAL DIRECT CURRENT RESISTANCE IN OHMS PER 1000 FEET FOR ROPE-LAY, CONCENTRIC MEMBER, COATED COPPER CONDUCTORS AT 25-C

AWG or MCM	Resistance	AWG or MCM	Resistance
14	2.81	1	.140
12	1.77	1/0	.109
10	1.11	2/0	.0863
9	.884	3/0	.0685
8	.708	4/0	.0543
7	.561	250	.0462
6	.445	300	.0385
5	.353	350	.0330
4	.280	400	.0289
3	.222	450	.0257
2	.172	500	.0231

TABLE IV

REACTANCE OF CABLES AND CORDS IN OHMS PER 1000 FEET

AWG or MCM	Reactance	AWG or MCM	Reactance
14	.041	1	.030
12	.038	1/0	.029
10	.035	2/0	.029
9	.034	3/0	.028
8	.034	4/0	.027
7	.033	250	.028
6	.032	300	.027
5	.032	350	.027
4	.031	400	.027
3	.031	450	.026
2	.029	500	.026

IV. MINIMUM AVAILABLE SHORT-CIRCUIT CURRENT

The minimum available short-circuit current, IMIN, is calculated using the equation:

$$IMIN = \frac{K_A E_{\phi\phi}}{2\ ZMAX}\ (amperes)\ (7)$$

Where: K_A = Arcing Fault Factor
$E_{\phi\phi}$ = Phase-to-Phase Voltage (Volts)

$$ZMAX = \sqrt{RMAX^2 + XMAX^2}\ (ohms)\ (8)$$

$$RMAX = TCRMAX + MCRMAX + PCRMAX + SSRMAX\ (ohms)\ (9)$$

TCRMAX = Maximum Trailing Cable Resistance (ohms)
MCRMAX = Maximum Intercomponent Cable Resistance (ohms)
PCRMAX = Maximum Power Center Resistance (ohms)
SSRMAX = Maximum Supply System Resistance (ohms)

$$XMAX = TCX + MCX + PCXMAX + SSXMAX\ (ohms)\ (10)$$

TCX = Trailing Cable Reactance (Ohms)
MCX = Intercomponent Cable Reactance (ohms)
PCXMAX = Maximum Power Center Reactance (ohms)
SSXMAX = Maximum Supply System Reactance (ohms)

Cable resistances were calculated from equation (6) at operating temperature; i.e. at 90°C for the trailing cable, and at the insulation rating for intercomponent cables. Equation (7) is for a phase-to-phase arcing fault which would yield the least short-circuit current. The arcing fault factor relates arcing fault current to bolted fault current.

Typical arcing fault factors, phase-to-phase voltages, maximum power center impedances, and maximum supply system impedances are listed in Table II. Phase-to-phase voltages are 95% of nominal voltage to account for power line voltage fluctuations. 480, 600, and 1040 volt arcing fault factors, maximum power center impedances, and maximum supply system impedances are found in [4]. Arcing fault current and bolted fault current were considered equal for 2400 and 4160 volts. Maximum power center impedance at 2400 volts was calculated using a 2500 KVA power center with 1.04% maximum resistance and 4.5% maximum reactance. These values were found in a review of approved 2400 volt longwalls which also revealed maximum supply system impedance.

V. CIRCUIT BREAKER SETTINGS

The maximum available short-circuit current is compared with the withstand current. If the maximum available short-circuit CURRENT is greater than the withstand current, no circuit breaker setting will protect the cable, and use of the cable is prohibited for intercomponent wiring. If the maximum available short-circuit current is less than the withstand current, the circuit breaker is set at 70 percent of the minimum available short-circuit current. The 30 percent reduction is due to the 25 percent tolerance on the circuit breaker and a 5 percent tolerance on the visual setting. The 25 percent tolerance is the worst case tolerance specified by mining circuit breaker manufacturers.

VI; EXAMPLE

No. 6, 90°C, 600 volt, intercomponent cable
No. 1 trailing cable

Withstand Current

$$IW = A\sqrt{\frac{.0297}{t}\log_{10}\frac{(T_2 + 234)}{(T_1 + 234)}}\ (amperes)$$

A = 26240 circular mils
t = .1 second
T_2 = 250°C
T_1 = 90°C

IW = 5970 amperes

Maximum Available Short-Circuit Current

$$IMAX = \frac{V}{\sqrt{3}\ ZMIN}\ (amperes)$$

V = 600 volts

$$ZMIN = \sqrt{RMIN^2 + XMIN^2}\ (ohms)$$

$$RMIN = TCRMIN + MCRMIN + PCRMIN + SSRMIN\ (ohms)$$

TCRMIN = .137 ohms/1000 feet
X 500 feet
= .0686 ohms
MCRMIN = . 436 ohms/1000 feet
X 25 feet
.0108 ohms
PCRMIN = .0018 ohms
SSRMIN = 0 ohms

RMIN = .0813 ohms

$$XMIN = TCX + MCX + PCXMIN + SSXMIN\ (ohms)$$

TCX = .030 ohms/1000 feet
X 500 feet
= .015 ohms
MCX = .032 ohms/1000 feet
X 25 feet
= .0008 ohms

PCXMIN = .00882 ohms
SSXMIN = 0 ohms

XMIN = .02462 ohms

ZMIN = .0849 ohms

IMAX = 4080 amperes

Minimum Available Short-Circuit Current

$$IMIN = \frac{K_1 E_{11}}{2\ ZMAX}\ (amperes)$$

K_1 = .90
E_{11}= 570

$$ZMAX = \sqrt{RMAX^2 + XMAX^2}\ (ohms)$$

$$RMAX = TCRMAX + MCRMAX + PCRMAX + SSRMAX\ (ohms)$$

TCRMAX = .0875 ohms
MCRMAX = .0139 ohms
PCRMAX = .0072 ohms
SSRMAX = .0189 ohms

RMAX = .1275 ohms

XMAX = TCX + MCX + PCXMX + SSXMAX (ohms)

TCX = .015 ohms
MCX = .0008 ohms
PCXMAX = .0353 ohms
SSXMAX = .0217 ohms

XMAX = .0728 ohms

ZMAX = . 147 ohms

IMIN = 1750 amperes

IW > IMAX

Circuit Breaker Setting = .7 X IMIN
= 1220 amperes

VII. CONCLUSION

Three currents must be evaluated to determine that an intercomponent cable is adequately protected against a short-circuit: withstand current, maximum available short-circuit current, and minimum available short-circuit current. The consideration of maximum available short-circuit current eliminates the use of many combinations of smaller size intercomponent cables with larger size trailing cables. This does not eliminate the use of control cables. Available current to control cables is reduced by control transformers. Control cables should continue to be protected by protective devices with settings or ratings which are no higher than the cables' ampacity.

REFERENCES

[1] Office of the Federal Register, National Archives and Records Service, General Services Administration, Title 30 Code of Federal Regulations, Washington, DC, 1990.

[2] National Electrical Manufacturers Association, Ethylene-Propylene-Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy, Washington, DC, 1988.

[3] The Anaconda Company, Wire and Cable Division, Mining Cable Engineerins Handbook, Greenwich, Connecticut, 1976.

[4] G. Fesak, W. Vilcheck, W. Helfrich, D. Deutsch, "Instantaneous Circuit Breaker Settings for the Short-Circuit Protection of Three-Phase 480, 600, and 1040 Volt Trailing Cables." IAS '77 Annual.