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

Wayne L. Carey, P.E.
Approval and Certification Center
RRL, Box 251
Triadelphia, WV 26059

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.

1. 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 or dual element fuses have been used to provide short-circuit protection. The circuit breaker not only 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 18.32); 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. 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 other circuit breakers. This 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 current. 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

<table>
<thead>
<tr>
<th>Conductor size-AMG</th>
<th>Ohms/1000 feet at 25°C</th>
<th>Maximum Allowable Circuit Breaker Instantaneous Setting (Amperes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>1.65</td>
<td>75</td>
</tr>
<tr>
<td>10</td>
<td>1.04</td>
<td>150</td>
</tr>
<tr>
<td>8</td>
<td>0.654</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>0.41</td>
<td>300</td>
</tr>
<tr>
<td>4</td>
<td>0.259</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>0.205</td>
<td>600</td>
</tr>
<tr>
<td>2</td>
<td>0.162</td>
<td>800</td>
</tr>
<tr>
<td>1</td>
<td>0.129</td>
<td>1000</td>
</tr>
<tr>
<td>1/0</td>
<td>0.102</td>
<td>1250</td>
</tr>
<tr>
<td>2/0</td>
<td>0.081</td>
<td>1500</td>
</tr>
<tr>
<td>3/0</td>
<td>0.064</td>
<td>2000</td>
</tr>
<tr>
<td>4/0</td>
<td>0.051</td>
<td>2500</td>
</tr>
<tr>
<td>500</td>
<td>0.022</td>
<td>2500</td>
</tr>
</tbody>
</table>

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


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:

\[
IW = A \sqrt{\frac{t}{T_1 + T_2}}
\]

Where:
- A = conductor cross-sectional area (circular mils)
- t = duration of short-circuit (seconds)
- T1 = initial conductor temperature (°C) (insulation rating)
- T2 = 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, T2 is 200°C. For cables with insulation (EPR or XLPE) rated 90°C, T2 is 250°C. For cables with insulation (AMA) rated 130°C, T2 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 (0.1 second) is substituted for t.

III. MAXIMUM AVAILABLE SHORT-CIRCUIT CURRENT

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

\[
IMAX = \frac{\sqrt{3} \times V}{ZM} \text{ (amperes)}
\]

Where:
- V = Machine voltage (480, 600, 1040, 2400, or 4160)
- ZMIN = \sqrt{ZMIN_T + ZMIN_M + ZMIN_P + ZMIN_S} \text{ (ohms)}
- ZMIN_T = Minimum Trailing Cable Resistance (ohms)
- ZMIN_M = Minimum Intercomponent Cable Resistance (ohms)
- ZMIN_P = Minimum Power Center Resistance (ohms)
- ZMIN_S = Minimum Supply System Resistance (ohms)
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.

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, R₂, was calculated from the resistance at 25°C, R₁, using the equation:

\[ R₂ = \frac{R₁ (234.5 + T₂)}{(234.5 + T₁)} \text{ (ohms)} \]

Where: \( R₁ \) = Resistance at Temperature \( T₁ \) (ohms)
\( T₁ = 25°C \)
\( T₂ = 20°C \)

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

<table>
<thead>
<tr>
<th>Voltage (Volts)</th>
<th>Arcing Fault Factor ( K₁ )</th>
<th>Phase-to-Phase Voltage ( E_{p} ) (Volts)</th>
<th>Maximum Supply System Impedance (ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>480</td>
<td>0.85</td>
<td>456</td>
<td>0.0121</td>
</tr>
<tr>
<td>600</td>
<td>0.90</td>
<td>570</td>
<td>0.0189</td>
</tr>
<tr>
<td>1040</td>
<td>0.95</td>
<td>988</td>
<td>0.0217</td>
</tr>
<tr>
<td>2400</td>
<td>1.00</td>
<td>2280</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage (Volts)</th>
<th>Resistance (ohms)</th>
<th>Reactance (ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>480</td>
<td>0.0121</td>
<td>0.0139</td>
</tr>
<tr>
<td>600</td>
<td>0.0189</td>
<td>0.0217</td>
</tr>
</tbody>
</table>
TABLE III
NOMINAL DIRECT CURRENT RESISTANCE IN OHMS PER 1000 FEET FOR ROPE-LAY, CONCENTRIC MEMBER, COATED COPPER CONDUCTORS AT 25-C

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

TABLE IV
REACTANCE OF CABLES AND CORDS IN OHMS PER 1000 FEET

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

IV. MINIMUM AVAILABLE SHORT-CIRCUIT CURRENT

The minimum available short-circuit current, \( I_{MIN} \), is calculated using the equation:

\[
I_{MIN} = \frac{K_f E_{pp}}{2 R_{MAX}} \quad \text{(amps.)} \quad (7)
\]

Where:
- \( K_f \) = Arcing Fault Factor
- \( E_{pp} \) = Phase-to-Phase Voltage (Volts)
- \( R_{MAX} \) = Maximum Reactance (ohms) \quad (8)

\( K_f \) and \( E_{pp} \) are taken from Table II. \( R_{MAX} \) is the maximum reactance of the system.

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.

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

\[
IW = A \sqrt[3]{\frac{V}{2.57}} \cdot \frac{\log (T_2 + 234)}{T_1 + 234} \quad \text{(amperes)}
\]

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

\[IW = 5970 \text{ amperes}\]

Maximum Available Short-Circuit Current

\[IMAX = \frac{V}{\sqrt{ZMIN}} \quad \text{(amperes)}\]

\[V = 600 \text{ volts}\]

\[ZMIN = \sqrt{RMIN^2 + XMIN^2} \quad \text{(ohms)}\]

\[RMIN = TCRMIN + MCRMIN + PCXMIN + SSXMIN \quad \text{(ohms)}\]

\[TCRMIN = .137 \text{ ohms/1000 feet} \times 500 \text{ feet} = .0686 \text{ ohms}\]
\[MCRMIN = .036 \text{ ohms/1000 feet} \times 25 \text{ feet} = .0093 \text{ ohms}\]
\[PCXMIN = .0018 \text{ ohms}\]
\[SSXMIN = 0 \text{ ohms}\]

\[RMIN = .0813 \text{ ohms}\]

\[XMIN = TCR + MCX + PCXM + SSXM \quad \text{(ohms)}\]

\[TCX = .030 \text{ ohms/1000 feet} \times 500 \text{ feet} = .015 \text{ ohms}\]
\[MCX = .032 \text{ ohms/1000 feet} \times 25 \text{ feet} = .0080 \text{ ohms}\]
\[PCXM = .00882 \text{ ohms}\]
\[SSXM = 0 \text{ ohms}\]

\[XMIN = .02462 \text{ ohms}\]

\[ZMIN = .0849 \text{ ohms}\]

\[IMAX = 4080 \text{ amperes}\]

Minimum Available Short-Circuit Current

\[IMIN = \frac{K_1 \cdot E_{IN}}{ZMAX} \quad \text{(amperes)}\]

\[K_1 = .90\]
\[E_{IN} = 570\]

\[ZMAX = \sqrt{RMAX^2 + XMAX^2} \quad \text{(ohms)}\]

\[RMAX = TCRMAX + MCRMAX + PCXMAX + SSXMAX \quad \text{(ohms)}\]

\[TCRMAX = .0875 \text{ ohms}\]
\[MCRMAX = .0139 \text{ ohms}\]
\[PCXMAX = .0072 \text{ ohms}\]
\[SSXMAX = .0189 \text{ ohms}\]

\[RMAX = .1275 \text{ ohms}\]

\[XMAX = TCR + MCX + PCXMAX + SSXMAX \quad \text{(ohms)}\]

\[TCX = .015 \text{ ohms}\]
\[MCX = .0008 \text{ ohms}\]
\[PCXMAX = .0353 \text{ ohms}\]
\[SSXMAX = .0217 \text{ ohms}\]

\[XMAX = .0728 \text{ ohms}\]

\[ZMAX = .147 \text{ ohms}\]

\[IMAX = 4080 \text{ amperes}\]

\[IW > IMAX\]

Circuit Breaker Setting = \(.7 \times IMIN = 1220 \) 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


