# INSTANTANEOUS CIRCUIT BREAKER SETTINGS FOR THE SHORT-CIRCUIT PROTECTION OF DIRECT CURRENT 300 AND 600 VOLT TRAILING CABLES

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## ABSTRACT

Present Federal regulations which specify maximum instantaneous circuit breaker settings for the short-circuit protection of coal mine trailing cables are discussed. Characteristics of mine power systems, which limit short-circuit current in dc trailing cables and minimum expected short-circuit currents for dc 300 and 600 V trailing cables, are analyzed. New maximum instantaneous circuit breaker settings, based on minimum expected short-circuit currents and typical circuit breaker tolerances, are proposed with emphasis on safety and field tests are cited.

## INTRODUCTION

Trailing cables on electric face equipment in underground coal mines undergo more severe service than most other cables in industrial applications. During normal operation, a unit of self-propelled mining equipment subjects its trailing cable to extreme tensile forces, abrasion, and frequent flexing, twisting, and crushing. As a result, electrical faults are much more prevalent in working sections of a coal mine than in stationary industrial applications. One of these faults, the short circuit, has proven to be one of the most hazardous in that the energy expended is capable of igniting loose coal and coal dust on the mine floor, as well as hydraulic oil and other combustible materials on board a mining machine. Between 1952 and 1969, there were 265 mine fires caused by short circuit in trailing cables resulting in 13 fatalities and 50 injuries.

If the arc from a short circuit is not contained within the trailing cable jacket, and the short circuit occurs where an explosive mixture of methane and air is present, an ignition is likely to occur. From 1952 to 1968, 21 methane ignitions and explosions were caused by electrical faults in trailing cables and accounted for nine fatalities and 18 injuries [1]. Other hazards initiated by short circuits include dense smoke and noxious fumes generated by cable insulation combustion and flash burns of miners near the fault area.

The frequency of short circuits in trailing cables, coupled with the potential hazards associated with their occurrence, make adequate trailing cable short-circuit protection extremely important. The enactment of the Federal Coal Mine Health and Safety Act of 1969 (Coal Act) required short-circuit protection of all trailing cables by Federal statute.

This resulted in a significant reduction of mine fires and reported methane ignitions. Since 1969 there have been no injuries or fatalities caused by short circuits. However, 1972 and 1973 accident data [1] indicate that electrical faults are still responsible for a significant number of serious flash burn and electrical burn injuries to miners' hands and eyes.

Perhaps one reason for the continued occurrence of electrical accidents from trailing cables is because the requirements for maximum instantaneous circuit breaker settings, as developed and promulgated by the Coal Act, have not recently been reexamined. These settings were determined by applying a 50% safety factor to the line-to-line short-circuit current calculated by assuming an infinite capacity 250 V dc power source and 500 feet of 2-conductor trailing cable. The 50% safety factor was included to account for voltage dips, power-system impedance, circuit breaker tolerances, etc. In addition, a maximum circuit breaker setting of 2500 A was established. Section 75.601-1 of Title 30, Code of Federal Regulations (30 CFR 75), also contains provisions for allowing higher circuit breaker settings when special applications justify them.

In recent years, the mining industry has progressed toward the use of ac equipment and reference [2] gives proposed standards for the maximum instantaneous settings for circuit breakers protecting three-phase trailing cables. Attention must now be given to dc trailing cable protection. This paper will attempts to meet the need for a new table of maximum instantaneous circuit breaker settings for protection of 300 and 600 V dc trailing cables based on an analysis of the minimum expected fault current and the characteristics of the circuit breakers commonly used to provide trailing cable short-circuit protection. This paper, however, will not discuss protection afforded by fuses nor protection for trailing cables that supply power to equipment from generators.

## MINIMUM EXPECTED SHORT-CIRCUIT CURRENT

Safety considerations demand that the circuit breaker trip whenever the minimum value of short-circuit current flows through the trailing cable. Consequently, the maximum setting must be chosen to account for the many factors which limit fault current including: fault type and location, circuit voltage, power-system impedance, section transformer and rectifier impedance, and trailing cable impedance. The maximum specified setting must also be based on circuit breaker tolerances.

Safety cannot be compromised. However, the short operating time of an instantaneous trip circuit breaker requires that it be set to trip at a current greater than the peak starting and/or operating current of the machine connected to the trailing cable. Otherwise, nuisance circuit breaker tripping would require a larger trailing cable than necessary for ampacity considerations alone. Therefore, any tabulation of maximum allowable circuit breaker settings should account for sufficient parameters to assure that for the majority of situations encountered, the specified settings will provide the necessary protection without being overly restrictive.

## Rectifier Configuration

When calculating minimum expected short-circuit current, the rectifier configuration and type of ground play an important role in determining the maximum allowable circuit breaker settings. Three cases will be considered.

Case 1 occurs when the mining equipment is grounded by a means other than a ground wire. Since the trailing cable does not contain a frame ground, the only type of electrical fault within the cable would be a line-to-line. Fault voltage would be at system voltage less the voltage drop of the trailing cable.

Case 2 occurs when the mining equipment is grounded by a separate wire. The possibility now exists for a line-to-ground fault. For most trailing cable, the ground fault will produce less current than the line-to-line because the ground wire is only required to be one-half the size of the conductor for cables No. 6 AWG and larger. For this type of grounding, the circuit breaker must be set low enough to protect against a line-to-ground fault unless a ground-fault-interrupter is provided in the circuit.

Case 3 occurs when the rectifier is center tap grounded. In a center tap rectifier, the ground wire has equal potential to each conductor, at one-half the system voltage. To provide adequate protection, the circuit breaker must be set to trip during a line-to-ground fault. Since fault voltage is nearly one-half the system voltage, the fault current is one-half that of a line-to-line fault, and adequate protection would probably result in nuisance tripping during normal operation. In such cases it is necessary that a ground-fault-interrupter be used in conjunction with short-circuit protection to provide maximum safety without nuisance trippings.

## Calculation of Faults

When calculating minimum expected short-circuit current, the fault location and fault condition yielding the minimum current flow was used as the basis for the calculation. All faults were calculated at the machine end of the trailing cable and rectifier grounding and configuration were reflected in the maximum allowable instantaneous settings.

The calculation of fault current in dc circuits is treated extensively elsewhere; therefore, only the general equation is presented here:

$$I_F = \frac{0.95\ K_A\ V_{dc}}{R_{source} + 1.05\ R_c}$$

where:

$I_F$ = minimum expected fault current

$V_{dc}$ = rated dc output voltage of rectifier

$K_A$ = arcing fault factor

$R_{source}$ = equivalent resistance of power system and transformer/rectifier combination at section

$R_c$ = resistance of trailing cable

It should be pointed out that an arcing fault factor ($K_A$) has been applied to the equation for bolted fault current to account for reduced fault current due to the voltage developed across an arcing fault. Also, the commutating reactance of the power system and section transformer/rectifier combination have been included in the calculation even though their values can be neglected for smaller size cables.

## Base Voltages

The standard nominal secondary voltage ratings of section transformers used in conjunction with rectifiers are 240 V ac for 300 V dc rectifiers and 480 V ac for 600 V dc rectifiers. These voltages were used as a base to calculate the supply system commutating reactance. Also, no-load dc voltages which were 95% of the rated rectifier output, were used to calculate minimum expected short-circuit current, thus accounting for reductions in section transformer no-load voltages not uncommon in operating mine power systems.

## Impedances Which Limit dc Fault Current

The model of a typical mine power system shown in Figure 1 illustrates the impedances which limit fault current: supply system impedance, section transformer/rectifier impedance, and trailing cable impedance.

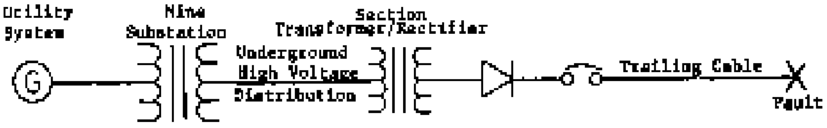

Figure 1. Simplified Model of Typical Mine Power System

The supply system impedance includes the total power impedance from the generating stations to the primary of the section transformer. This is equivalent to a 2 MVA substation transformer supplying power at 4.16 kV to a section transformer through approximately 14,000 feet of No. 4/0 AWG, 5 kV SHD-GC cable [2]. From the commutating reactance of the supply system, the equivalent dc resistance was combined with the section transformer/rectifier combination impedance. The impedance of the supply system calculated at the section transformer secondary base is as follows:

| $V_{base}$ (volts) | $X_{supply}$ (ohms) | $R_{supply}$ (ohms) | $L_{supply}$ ($\mu$h) |
|---|---|---|---|
| 240 | 0.0035 | 0.0030 | 9.28 |
| 480 | 0.0139 | 0.0121 | 36.87 |

Direct-current power may be supplied to the section from silicon rectifiers, mercury arc rectifiers, motor-generator sets, or synchronous converters. This paper will treat rectifiers supplying power through trailing cables to portable or mobile equipment. In general, two different rectifier circuits are used; the three- phase bridge and the six-phase double wye. The operation of both rectifiers is equivalent. A detailed description of their operation can be found in reference [3].

The resistance of the transformer/rectifier combination is not constant. The source resistance is greater for a bolted fault at the rectifier than for regular operation because the commutating angle exceeds the conduction angle. Short-circuit calculations for a three-phase bridge rectifier indicate that the source impedance increases at a current in excess of 25% of the bolted fault current at the rectifier terminals. Thus, if the minimum expected theoretical short-circuit current exceeds 25% of the maximum bolted fault current, the minimum expected fault current must be recalculated with the short-circuit source resistance.

The regular-operation and short-circuit resistances were calculated from the per unit resistance and reactances of the section transformer/rectifier. Typical values were obtained from various dc supply manufacturers. Total equivalent resistances of a three-phase bridge rectifier and power supply for regular and short circuit operation are as follows:

| Voltage (volts) | KW Rating | Overload $R_{source}$ (ohms) | Short-Circuit $R_{source}$ (ohms) |
|---|---|---|---|
| 300 | 150 | 0.0645 | 0.0766 |
| 300 | 300 | 0.0250 | 0.0282 |
| 600 | 150 | 0.2575 | 0.3069 |
| 600 | 300 | 0.1000 | 0.1118 |

With a three-phase bridge connection, the transformer can have the minimum power rating for a six-pulse rectifier. This low rating and the simplicity of the connection make the three-phase bridge connection an extremely economical circuit and one widely used for power supplied with a three-phase input.

Many power center combinations have both ac and dc outputs. Direct current outputs usually service shuttle cars or smaller equipment and, thus, a small rectifier is installed in the power center. In calculating minimum expected fault current, a 150 kW rectifier was assumed for cables No. 2 AWG and smaller for both 300 and 600 V systems. For large-size cables, a 300 kW rectifier was assumed.

Direct-current resistances for trailing cables were taken from Insulated Power Cable Engineers Association Standards Publication No. S-68-516 [4]. Because minimum expected fault current must be determined, maximum resistance values were of interest. Therefore, dc resistance values were based on a conductor temperature of 90°C.

In equation (2) a factor ($K_A$) was applied to account for reduced current flow due to an arcing fault. Although considerable theoretical as well as experimental work had been done to determine the factor relating probable minimum arcing fault current to bolted fault current in ac systems, little had been done to determine an arcing fault factor for low voltage dc systems. The Mine Safety and Health Administration (MSHA) had done experiments to simulate arcs on 300 V dc systems. From these results a graph was developed relating arc voltage to line current as seen in Figure 2.

These preliminary tests indicate that for a gap of 3/8 inch, currents above 600 A produce relatively constant arc voltages, but for smaller currents, arc voltage variations are large for small changes in current. An arc gap of 3/8 inch was used to determine the arcing fault factor because trailing cable geometry and test results indicate that 3/8 inch is the maximum distance to sustain an arc of significant duration.

The curve in Figure 2 can be described by a constant for values greater than 600 A and by a logarithmic function for values less than 600 A. Arc voltage was calculated from the equation fitting the curve of Figure 2 and was determined to be 60 V for currents greater than 600 A. The arcing fault factor ($K_A$) can be determined from supply voltage and arc voltage as follows:

$$V_{\mathrm{arc}} = e \, \frac{1842 - I_F}{303} \qquad for \; I_F < 600 \; A$$

$$K_A = \frac{0.95 \; V_{dc} - V_{\mathrm{arc}}}{0.95 \; V_{dc}}$$

where $V_{arc}$ = voltage developed across the arc
= 2.71828

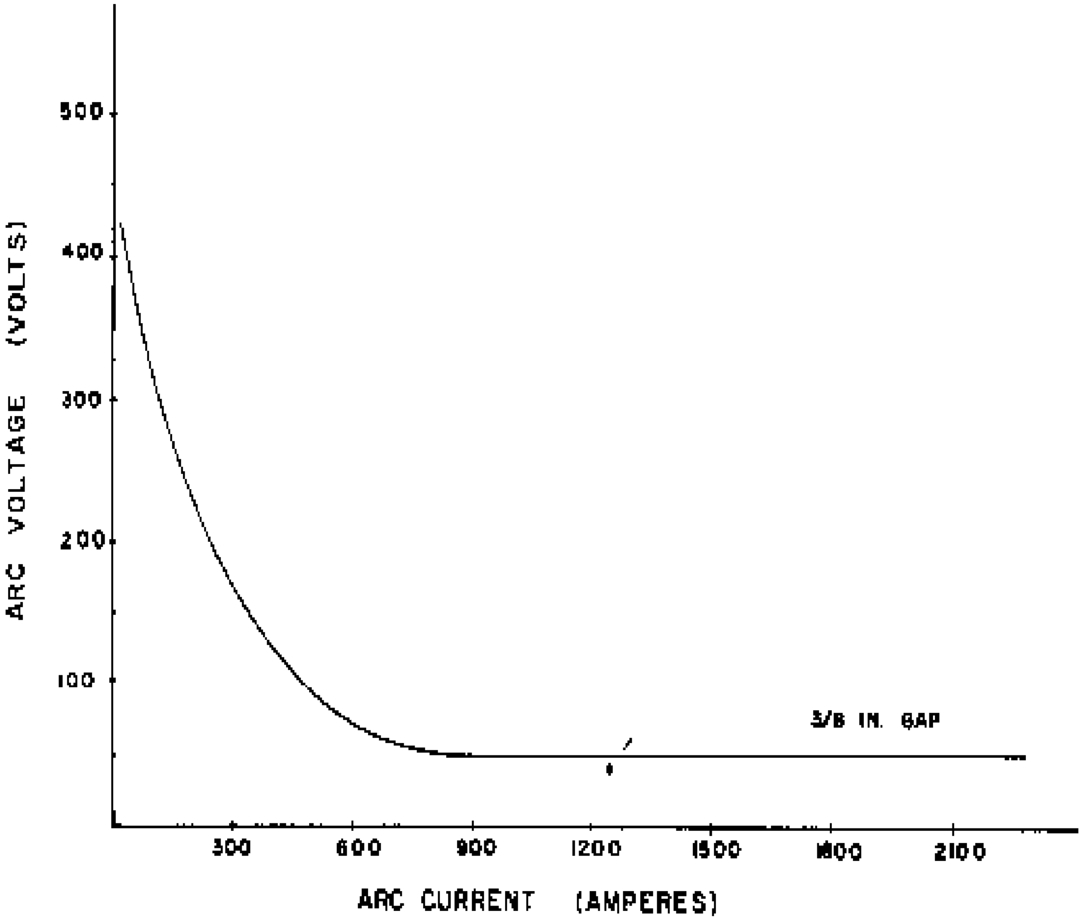

Figure 2. Relation Between Arc Voltage and Arc Current

If the available fault current $I_F$ at the machine end of the trailing cable is less than that current necessary to sustain an arc $I_{arc}$, then the maximum allowable circuit breaker setting will be determined from $I_F$ with no applied arcing fault factor. If available fault current $I_F$ is greater than $I_{arc}$, then the appropriate $K_A$ will be applied to $I_F$, and the circuit breaker setting will be determined from $K_AI_F$ or $I_{arc}$, which ever is larger. For $I_F$ greater than 600 A, $K_A$ = 0.789 for 300 V systems and $K_A$ = 0.895 for 600 V systems. These factors were based on preliminary tests and are subject to change as research progresses.

## Short-Circuit Calculations

Once the arcing fault factor, line-to-line voltage, supply system impedance, section transformer impedance, and trailing cable impedance were determined, equation (1) was used to determine minimum expected trailing cable short-circuit current. Since trailing cable length has a significant effect on the magnitude of short-circuit current, calculations were made for each of the common lengths of trailing cables up to the maximum length permitted for permissible equipment by Section 18.35 of Title 30, Code of Federal

Regulations. A factor of 1.05 was applied to the calculated trailing cable impedance to allow for possible errors in determining trailing cable length.

## MAXIMUM ALLOWABLE CIRCUIT BREAKER SETTINGS

Many 300 and 600 Vdc trailing cables in the coal mining industry are protected against short circuit by molded case circuit breakers equipped with magnetic-only or thermal-magnetic trip units. In either case, the magnetic trip unit operates instantaneously, without intentional time delay and typically is adjustable over a range of at least 2:1. Consequently, the worst case tolerances of adjustable magnetic trip units in molded case circuit breakers must be considered when determining maximum allowable circuit breaker settings for the short-circuit protection of dc trailing cables.

Reference [2] describes circuit breaker tolerances in detail and a summary is presented. The maximum allowable instantaneous circuit breaker settings were based on a 25% circuit breaker tolerance. An additional +5% factor was included in the circuit breaker tolerance factor to allow for trip setting drift with aging, nonlinearity in the trip setting scale, and visual error in setting the circuit breaker. Maximum allowable instantaneous circuit breaker settings were then calculated by multiplying the minimum expected short-circuit current by the circuit breaker tolerance factor which is 1/1.3. The resulting maximum allowable circuit breaker settings were rounded off and are presented in Table I.

## DISCUSSION

The remainder of this paper will compare those proposed maximum circuit breaker instantaneous settings with typical operating and starting currents of mine equipment in the field. The proposed settings are very conservative in nature and were developed with the safety of the miner and protection of the trailing cable in mind. Furthermore, the circuit breaker should not be set at the maximum setting if the equipment can be effectively operated at a lower value. If the settings result in nuisance tripping then the total power system should be analyzed before any serious thought is given to altering the setting of the circuit breaker.

### Test Procedure

Several coal mine operators were contacted and tests were made at their mines on various mining machines. These tests were conducted in order to compare the actual peak working current with the proposed maximum current settings. There were six mining machines studied: a loader, a shuttle car, a cutting machine, and three continuous-miners. Recordings of voltage and current were made at the nipping station or power center for each of the machines. Current and voltage were continuously recorded for three hours on the loader, shuttle car, and cutting machine, and for six hours on each of the continuous miners. During the recording, the operator of that machine was asked to load and work the machine to its maximum capacity. The loading machine operator was able to stall his machine several times. These recordings were reviewed and the peak operating currents tabulated.

## TABLE I
## Maximum Allowable Circuit Breaker Settings - dc 300 and 600 V Trailing Cables

| Cond.-Size (AWG, MCM) | Cable Length (Feet) | 300 V Max. Inst. Setting | | 600 V Max. Inst. Setting | |
|---|---|---|---|---|---|
| | | ℓ-ℓ(A) | ℓ-g(A) | ℓ-ℓ(A) | ℓ-g(A) |
| 14 . . . . . . . . | 0 - 500 | 50 | 50 | 50 | 50 |
| 12 . . . . . . . . | 0 - 500 | 75 | 75 | 100 | 100 |
| 10 . . . . . . . . | 0 - 500 | 75 | 75 | 200 | 200 |
| 8 . . . . . . . . . | 0 - 500 | 100 | 100 | 300 | 300 |
| 6 . . . . . . . . . | 0 - 500 | 200 | 100 | 450 | 350 |
| 4 . . . . . . . . . | 0 - 500 | 400 | 250 | 650 | 500 |
| | 501 - 600 | 300 | 150 | 550 | 450 |
| 3 . . . . . . . . . | 0 - 500 | 500 | 350 | 700 | 550 |
| | 501 - 650 | 400 | 250 | 600 | 450 |
| 2 . . . . . . . . . | 0 - 500 | 600 | 400 | 800 | 650 |
| | 501 - 600 | 500 | 350 | 750 | 600 |
| | 601 - 700 | 450 | 300 | 700 | 350 |
| 1 . . . . . . . . . | 0 - 500 | 850 | 600 | 1350 | 1050 |
| | 501 - 600 | 700 | 500 | 1200 | 900 |
| | 601 - 750 | 600 | 400 | 1050 | 750 |
| 1/0 . . . . . . . . | 0 - 500 | 1050 | 750 | 1550 | 1200 |
| | 501 - 600 | 900 | 600 | 1400 | 1050 |
| | 601 - 750 | 750 | 500 | 1200 | 900 |
| | 751 - 800 | 700 | 450 | 1150 | 850 |
| 2/0 . . . . . . . . | 0 - 500 | 1250 | 900 | 1750 | 1400 |
| | 501 - 600 | 1100 | 750 | 1600 | 1250 |
| | 601 - 750 | 900 | 600 | 1400 | 1100 |
| | 751 - 850 | 800 | 550 | 1300 | 1000 |
| 3/0 . . . . . . . . | 0 - 500 | 1500 | 1100 | 1950 | 1600 |
| | 501 - 600 | 1300 | 950 | 1800 | 1450 |
| | 601 - 750 | 1100 | 750 | 1600 | 1250 |
| | 751 - 900 | 950 | 650 | 1450 | 1100 |
| 4/0 . . . . . . . . | 0 - 500 | 1750 | 1350 | 2150 | 1800 |
| | 501 - 600 | 1550 | 1150 | 2000 | 1650 |
| | 601 - 750 | 1350 | 950 | 1800 | 1450 |
| | 751 - 1000 | 1050 | 750 | 1550 | 1200 |
| 250 . . . . . . . | 0 - 500 | 1950 | 1500 | 2300 | 1950 |
| | 501 - 600 | 1750 | 1300 | 2150 | 1800 |
| | 601 - 750 | 1500 | 1100 | 1950 | 1600 |
| | 751 - 1000 | 1200 | 850 | 1700 | 1350 |
| 300 . . . . . . . . | 0 - 500 | 2250 | 1700 | 2400 | 2100 |
| | 501 - 600 | 1950 | 1500 | 2300 | 1950 |
| | 601 - 750 | 1700 | 1250 | 2100 | 1750 |
| | 751 - 1000 | 1400 | 1000 | 1850 | 1500 |
| 350 . . . . . . . . | 0 - 500 | 2450 | 1900 | 2550 | 2250 |
| | 501 - 600 | 2200 | 1650 | 2400 | 2100 |
| | 601 - 750 | 1900 | 1450 | 2250 | 1900 |
| | 751 - 1000 | 1550 | 1150 | 2000 | 1650 |
| 400 . . . . . . . . | 0 - 500 | 2650 | 2050 | 2650 | 2350 |
| | 501 - 600 | 2400 | 1850 | 2500 | 2200 |
| | 601 - 750 | 2050 | 1550 | 2350 | 2000 |
| | 751 - 1000 | 1700 | 1300 | 2100 | 1750 |
| 500 . . . . . . . . | 0 - 500 | 3000 | 2400 | 2750 | 2550 |
| | 501 - 600 | 2750 | 2150 | 2650 | 2350 |
| | 601 - 750 | 2400 | 1850 | 2500 | 2200 |
| | 751 - 1000 | 2000 | 1500 | 2300 | 1950 |
| 600 . . . . . . . . | 0 - 500 | 3250 | 2650 | 2850 | 2650 |
| | 501 - 600 | 3000 | 2400 | 2750 | 2500 |
| | 601 - 750 | 2650 | 2050 | 2650 | 2350 |
| | 751 - 1000 | 2250 | 1700 | 2400 | 2100 |
| 700 . . . . . . . . | 0 - 500 | 3500 | 2900 | 2950 | 2750 |
| | 501 - 600 | 3250 | 2600 | 2850 | 2600 |
| | 601 - 750 | 2900 | 2300 | 2750 | 2450 |
| | 751 - 1000 | 2450 | 1900 | 2550 | 2250 |
| 800 . . . . . . . . | 0 - 500 | 3700 | 3100 | 3000 | 2800 |
| | 501 - 600 | 3450 | 2800 | 2900 | 2700 |
| | 601 - 750 | 3100 | 2500 | 2800 | 2500 |
| | 751 - 1000 | 2650 | 2050 | 2650 | 2350 |
| 900 . . . . . . . . | 0 - 500 | 3900 | 3300 | 3050 | 2850 |
| | 501 - 600 | 3650 | 3000 | 3000 | 2850 |
| | 601 - 750 | 3300 | 2650 | 2850 | 2650 |
| | 751 - 1000 | 2850 | 2250 | 2700 | 2450 |
| 1000 . . . . . . . | 0 - 500 | 4050 | 3450 | 3100 | 2900 |
| | 501 - 600 | 3800 | 3150 | 3000 | 2850 |
| | 601 - 750 | 3450 | 2800 | 2900 | 2700 |
| | 751 - 1000 | 3000 | 2400 | 2750 | 2500 |

Tests on the machines were made with the following equipment. A 60 mV = 600 A shunt was used in all cases to record current to the machine. High voltage dc preamplifiers with a frequency response of 0 to 10 Hz were used to amplify the millivolt signal from the shunt and to attenuate the line-to-line voltage supplied to the machine. The signal from the preamplifiers was supplied to an oscillograph recorder which had a frequency response of 0 to 5000 Hz.

The preamplifiers were used to isolate the oscillograph from the high voltages present at the nipping station or rectifier. Gains on the oscillograph and preamplifiers were adjusted to give adequate trace deflection on the oscillograph.

Current and voltage were also recorded at a 500 KW rectifier. A 100 mV = 3000 A shunt was used to measure current out of the rectifier. Results of all the tests are in Table II.

TABLE II
Test Results

| Type of Machine | Cable Size AWG, MCM | Cable Length (Feet) | Volts at $I_{peak}$ | $I_{peak}$ (A) | Average $I_{peak}$ (A) | $R_{source}$ (ohms) |
|---|---|---|---|---|---|---|
| Rectifier | - | - | 263 | 1367 | 841 | 0.019 |
| Shuttle Car | 2 | 500 | 266 | 375 | 294 | 0.084 |
| Cutting Machine | 2/0 | 367 | 238 | 843 | 563 | 0.057 |
| Loading Machine | 1 | 450 | 213 | 937* | 493 | 0.056 |
| Continuous Miner | 350 | 500 | 282 | 1467 | 1057 | 0.017 |
| Continuous Miner | 350 | 525 | 260 | 1470 | 997 | 0.047 |
| Continuous Miner | 350 | 530 | 140 | 1640 | 1397 | 0.090 |

*Stall-out. Next highest peak was 672 A.

These results indicate that none of the above equipment should have any problems operating with the proposed settings for a line-to-ground fault, which is the lower of the settings. Only the current to the loading machine exceeded the proposed setting, but the operator stalled the loader and blew a fuse in doing so. The second highest peak of 672A was less than the line-to-line proposed setting but greater than the line-to-ground proposed setting. A ground-fault-interrupter would eliminate the need for the circuit breaker to protect for a line-to-ground fault and allow the higher setting for line-to-line protection.

## Power System Impedance

The power system impedance as seen by the trailing cable is an important factor in determining maximum allowable cable breaker settings. Figure 3 illustrates an example of nipping off the trolley wire and the effect its impedance has on the circuit breaker setting. The power system impedance includes the total resistance of a 500 KW rectifier feeding a length of No. 9 section trolley wire with 1000 MCM feeder and 90 lb./yd. track return up to the nipping station. The x-axis was labeled in units of trolley wire length instead of resistance to give the reader a better feel for the problem.

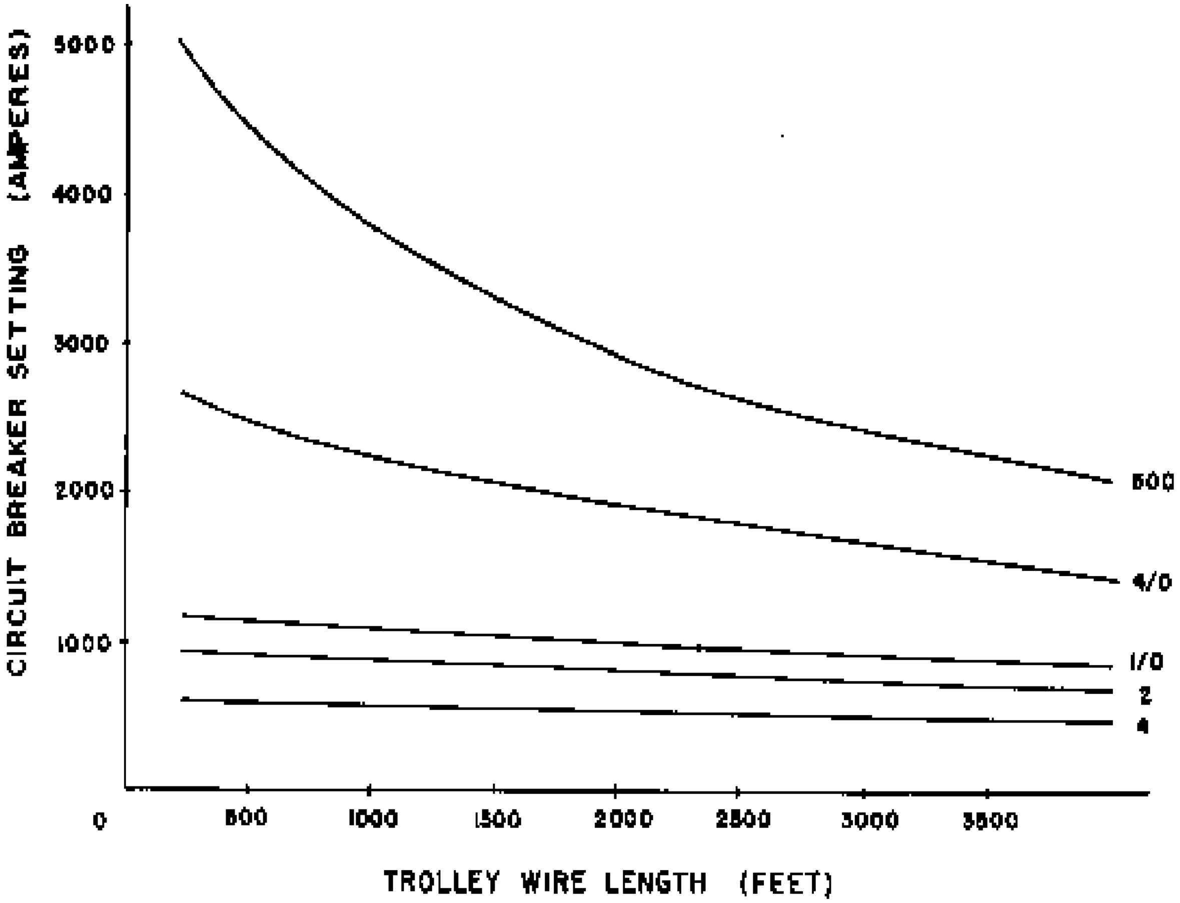

Figure 3. Maximum Circuit Breaker Settings vs.
Total System and Transformer Impedance

Comparing the proposed settings with those of Figure 3, shows that power system impedance has little effect on smaller size cables. However, for No. 4/0 size cable and above, the distance between the rectifier and nipping station is crucial. As the trolley wire length approaches the right side of the curve, the proposed settings no longer give adequate protection. Although available fault current decreases, starting and operating currents will increase due to the lower system voltage at the section. A reduced setting necessary for adequate protection would probably result in nuisance tripping and considerable down time. It is recommended that fuses, because of their characteristics, would better protect trailing cables that are nipped off of the trolley wire a substantial distance from the rectifier and avoid loss of equipment operating time.

## CONCLUSIONS

Based on a rigorous analysis of available short-circuit current in dc trailing cable, the existing requirements for maximum instantaneous circuit breaker settings appear marginal for most cable lengths and sizes. The proposed circuit breaker settings are based on line-to-line and line-to-ground fault current produced by an average mine power system with the consideration of pertinent safety factors. These settings will be directly applicable to the vast majority of mine power systems. If a specific mine power system cannot effectively operate mining equipment under the maximum setting, the operator should analyze the power system before seriously considering altering the circuit breaker setting.

Further studies should be continued to determine maximum instantaneous circuit breaker settings for ac single-phase cables, and maximum fuse sizes for dc trailing cables that nip off the trolley.

## ACKNOWLEDGMENT

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