INSTANTANEOUS CIRCUIT BREAKER SETTINGS FOR THE SHORT CIRCUIT PROTECTION OF THREE PHASE 480, 600 AND 1040V 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 three-phase trailing cables are analyzed and minimum expected short-circuit currents for three-phase 480, 600, and 1040V trailing cables are tabulated. New maximum instantaneous short-circuit currents and typical circuit breaker tolerances are proposed with emphasis on safety. Finally, a typical mine power systems are discussed and field tests cited.

INTRODUCTION

Trailing cables on electric face equipment in underground coal mines undergo more severe service than most other cables in industrial applications. The normal operation of a unit of self-propelled mining equipment subjects its trailing cable to extreme tensile forces, severe abrasion, and frequent flexing, twisting and crushing. As a result of this severe usage, electrical faults in trailing cables occur much more frequently then electrical faults in cables and wiring in stationary industrial installations.

Of the various faults which occur in trailing cables, the short circuit has proven to be one of the most hazardous. The energy expended in a short circuit in a trailing cable is capable of igniting loose coal and coal dust on the mine floor, as well as loose coal, coal dust, hydraulic oil and other combustible materials onboard a mining machine. Between 1952 and 1969, the Bureau of Mines investigated 265 mine fires caused by short circuits in trailing cables. These mine fires were responsible for 13 deaths 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. In “Electrical Hazards in Underground Bituminous Coal Mine” [1], Mason reports that during the period 1952-1968, 21 methane ignitions and explosions were caused by electrical faults in trailing cables. These ignitions and explosions resulted in nine fatalities and 18 injuries.

Even if a short circuit in a trailing cable does not cause a fire or a methane ignition, the energy delivered into the fault can cause combustion of the cable at or near the location of the short circuit, there exists the possibility of flash burns to the hands and eyes.

The frequency of short circuits in trailing cables, coupled with the potential hazards associated with their occurrence, makes adequate trailing cable short-circuit protection extremely important. The importance of trailing cable short-circuit protection has been recognized for many years, and requirements for such protection have been included in Federal standards for permissible electric face equipment since Bureau of Mines Schedule 2C [2] was written in 1930. However, it was not until the Federal Coal Mine Health and Safety Act of 1969 was enacted that short-circuit protection for all trailing cables was required by Federal statute.

Section 306(b) of the Act requires that each trailing cable be provided with short-circuit protection by means of an automatic circuit breaker or other no less effective device approved by the Secretary of the Interior, but does not specify the circuit breaker type or maximum setting. These requirements, however, were developed and promulgated in accordance with the authority and responsibility given to the Secretary of the Interior by the Act and are included in the “Mandatory Safety Standards for Underground Coal Mines” (Title 30, Code of Federal Regulations, Part 75).

Section 75.601-1, 30 CFR 75, specifies the maximum allowable instantaneous settings for circuit breakers used to provide short-circuit protection for trailing cables. These settings were determined by applying a 50% safety factor to the line-to-line short-circuit current calculated by assuming an infinite capacity 250V dc power source and 500 ft. of 2-conductor trailing cable. The 50% safety factor was included to account for power system impedance, voltage dips, circuit breaker tolerances, etc. In addition, a maximum circuit breaker setting of 2500 A was established. Section 75.601-1, 30 CFR 75, also contains provisions for allowing higher circuit breaker settings when special applications justify them.

Since the implementation of the Federal Coal Mine Health and Safety Act of 1969, there has been a significant reduction in the number of mine fires and methane ignitions caused by short circuits in trailing cables. Since 1970, there have been only nine mine fires caused by short circuits in trailing cables. These fires did not result in any fatalities or injuries. During the same period there were no methane ignitions caused by short circuits in trailing cables. It is apparent that improvements in trailing cable electrical protection as well as improvements in trailing cable splicing, mine ventilation and fire protection brought about by the Act have significantly reduced the number of severity of trailing cable short circuits. Nevertheless, 1972 and 1973 accident data reported in [1] indicate that electrical faults in trailing cables continue to result in a significant number of serious flash burn and electrical burn injuries to miners’ hands and eyes.

Although the maximum circuit breaker settings specified in Section 75.601-1, 30 CFR 75, are based on the calculated short circuit current in 250V dc trailing cables, the settings are applied to all trailing cables, including three-phase trailing cables energized at 480, 600, and 1040V. The significant reduction in the frequency of mine fires and methane ignitions caused by short circuits in trailing cables indicates that the settings specified in Section 75.601-1, 30 CFR 75, generally provide adequate short-circuit protection for three-phase trailing cables. Nevertheless, short-circuit surveys conducted by MESA electrical engineers have shown that in certain instances these settings do not provide an adequate margin of safety for three-phase trailing cables.

There are other cases in which the settings specified in Section 75.601-1, 30 CFR 75, are lower than necessary to provide adequate short-circuit protection for three-phase 480, 600, and 1040 V trailing cables. In several of these cases it has been necessary to raise circuit breaker settings to eliminate nuisance tripping as a result of peak machine inrush or operating current.

This paper will attempt to meet the need for a new table of maximum instantaneous circuit breaker settings for the short-circuit protection of three-phase 480, 600, and 1040 V trailing cables based on an analysis of the minimum expected short-circuit current in three-phase trailing cables and the characteristics of the circuit breakers commonly used to provide trailing cable short-circuit protection. The paper will also discuss conditions under which the maximum allowable circuit breaker settings should be reduced to afford an adequate margin of safety as well as the conditions under which the maximum settings may be raised without sacrificing safety.

MINIMUM EXPECTED SHORT-CIRCUIT CURRENT

The requirement for instantaneous short-circuit protection of trailing cables places several constraints on the selection of maximum instantaneous circuit breaker settings. Safety considerations demand that the circuit breaker trip whenever the minimum value of short-circuit current flows in the trailing cable. Consequently, the maximum specified circuit breaker setting must take into account the circuit breaker tolerance as well as the many factors which limit short-circuit current, including fault type and location, circuit voltage, power system impedance, section transformer impedance and trailing cable impedance.

Safety considerations cannot be compromised. However, the short operating time of an instantaneous trip circuit breaker requires that the circuit breaker 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.

In view of the above, any tabulation of maximum allowable circuit breaker settings should take into account sufficient parameters to assure that for the majority of situations encountered, the specified settings will provide the necessary protection without being overly restrictive. On the other hand, the tabulation should be presented in a simple and concise manner so that it is as easy as possible to use. Obviously, a tabulation of maximum circuit breaker settings would lose its usefulness if it was necessary to conduct a short-circuit survey of the mine power system to determine each circuit breaker setting.

Calculation of Minimum Expected Short-Circuit Current

Calculations to determine minimum expected short-circuit current differ from the more common calculations to determine circuit breaker interrupting current requirements. In the latter case, the bolted fault condition yielding maximum current flow (usually the three-phase fault) is used as the basis for the calculation. The fault location yielding highest short-circuit current is chosen. In addition, the fault current contribution of the motors connected to the power system is added to the fault current delivered by the power system. However, when calculating minimum expected short-circuit current, the fault location and fault condition yielding minimum current flow must be used as the basis for the calculation. Motor fault current contribution must be assumed to be zero and a factor to account for reduced current flow due to the impedance of an arcing fault must be applied to the calculated bolted fault current.

Phase-to-Phase Faults

Of the variety of faults that can occur in a three-phase trailing cable, the phase-to-ground fault results in the lowest current flow, since this current is limited by a neutral grounding resistor to 25 A or less in accordance with the requirements of Section 75.901, 30 CFR 75. In addition, Section 75.900, 30 CFR 75, requires that all low- and medium-voltage underground three-phase circuits be provided with ground-fault protection. However, since ground-fault protection is provided by separate devices sensitive to the low magnitude of ground-fault current, it is not necessary for the circuit breaker setting to be based on ground-fault current flow. Other than the phase-to-ground fault, the phase-to-phase fault yields the lowest current flow. Consequently, it is the minimum expected phase-to-phase short-circuit current that must be used to determine maximum circuit breaker settings for trailing cable short-circuit protection.

The calculation of phase-to-phase fault current in three-phase circuits is treated extensively elsewhere; therefore, only the general equation is presented here.

$$I_{\phi\phi} = \frac{K_A E_{\phi\phi}}{Z_1 + Z_2}$$

where $I_{\phi\phi}$ = phase-to-phase fault current,

$E_{\phi\phi}$ = phase-to-phase voltage,

K_A = arcing fault factor,

Z_1 = total positive sequence impedance,

and Z_2 = total negative sequence impedance.

It should be pointed out that an arcing fault factor (K_A) has been applied to the traditional equation for bolted phase-to-phase fault current to account for reduced fault current due to the impedance of an arcing fault.

The negative sequence impedance of a static circuit element (transformer or cable) is equal to the element's positive sequence impedance ($Z_2=Z_1$); however, the positive and negative sequence impedances of a dynamic circuit element (motor or generator) do differ. The difference becomes significant only when the fault is located close to the source generator. When the mine power system is supplied from a utility, the difference between the positive and negative sequence impedance and, in fact, the total impedance of the utility generators is insignificant. Consequently, one can accurately assume that the total negative sequence impedance is equal to the total positive sequence impedance. This allows equation (1) to be further simplified.

$$I_{\phi\phi} = \frac{K_A E_{\phi\phi}}{2Z_1}$$

In instances where the mine power system is supplied power from an onsite generator, a special analysis, involving the transient or subtransient impedance and the negative sequence impedance of the generator, must be made to calculate phase-to-phase fault current.

Base Voltages

Representative manufacturers indicate that the standard nominal secondary voltage ratings of section transformers are 480, 600, and 1040 V. Consequently, these voltages were used as the base voltages (V_B) for calculating supply system and transformer impedances. However, no-load phase-to-phase voltages ($E_{\phi\phi}$) of 456, 570, and 988 were used to calculate minimum expected short-circuit current. These voltages, which are 95% of the base voltages, were chosen to account for reductions in section transformer no-load secondary voltages no uncommon in operating mine power systems.

Impedances Which Limit Phase-to-Phase Fault Current

In estimating the impedances which limit phase-to-phase short-circuit current in a trailing cable it is useful to assume a simplified model of a typical mine power system. (See Fig. 1). From this model, it is possible to identify three impedances which limit phase-to-phase short-circuit current in a trailing cable; supply system impedance, section transformer impedance and trailing cable impedance.

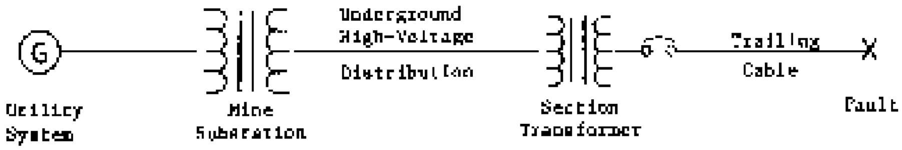

Figure 1. Simplified Model of Typical Mine Power System

Supply System Impedance

The supply system impedance includes the total power system impedance from the generating stations to the primary of the section transformer. For the purposes of calculating minimum expected trailing cable short-circuit current, a supply system positive sequence impedance equivalent to a three-phase short-circuit level of 12.5 MVA at the section transformer primary was assumed. This impedance is equivalent to a 2 MVA substation transformer supplying 4.16 kV power to a section transformer through approximately 14,000 ft of #4/0 AWG, 5 kV SHD-GC cable.

It is recognized that the assumed supply system short-circuit level of 12.5 MVA is a conservative value for large mine power systems utilizing 7.2 kV and 13.2 kV underground distribution. Short-circuit surveys conducted on several such mine power systems have shown three-phase short-circuit levels approaching 40 MVA on the primary of section transformers. However, it is necessary to assume a conservative short-circuit level to insure that the maximum allowable instantaneous circuit breaker settings will provide the necessary protection for the majority of mine power systems.

The assumed supply system short-circuit level is indicative of a long high-voltage distribution system and, therefore, a rather low X/R ratio. Consequently, both the total supply system positive sequence resistance (R_{1s}) and reactance (X_{1s}) were calculated at the section transformer secondary base voltages with the following results:

V_B (Volts)	R_{1s} (ohm)	X_{1s} (ohm)
480	0.0121	0.0139
600	0.0189	0.0217
1040	0.0568	0.0653

Section Transformer Impedance

Representative manufacturers of mining transformers were surveyed to determine typical section transformer characteristics. Summaries of sales records furnished by the manufacturers indicate that three-phase section transformers ranging in capacity from 300 to 1000 kVA and in impedance from 3.0% to 5.5% have been supplied to the mining industry. In recent years, 750 kVA has been the most common section transformer rating at the 480 and 600 V levels, although a considerable number of 500 and 600 kVA units have also been furnished. At the 1040 V level, section transformers are generally rated 750 or 1000 kVA.

Based on these data, section transformer capacities and impedances were assumed to be as follows:

V_B (Volts)	kVA	% R	% X
480	500	1.0	4.9
600	500	1.0	4.9
1040	750	1.0	4.9

Once these assumptions were made, the section transformer positive sequence resistance (R_{1t}) and reactance (X_{1t}) were calculated for the appropriate base voltages with the following results:

V_B	R_{1t}	X_{1t}
480	0.0046	0.0226
600	0.0072	0.0353
1040	0.0144	0.0707

Trailing Cable Impedance

Resistance and reactances for three-phase trailing cables were compiled from values calculated and published by The Anaconda Company [3] and values calculated by several other manufacturers of portable cables and cords. Since the resistance and reactance values were used to determine minimum expected short-circuit current, maximum values were of interest. Consequently, cable resistance values were based on a conductor temperature of 90°C. Likewise, reactance values were based on a flat rather than a round cable construction for the trailing cable sizes which are manufactured in both constructions. Furthermore, the reactances for round trailing cables used in 1040V circuits were based on a type SHD construction.

Trailing cable positive sequence resistances (R_{1c}) and reactances (X_{1c}) used to calculate minimum expected short-circuit current are listed in Table I.

TABLE I

Resistances and reactances of trailing cables and cords.

Conductor Size AWG or MCM	Resistance[1] Ohms/M Ft.	Reactance[2] Ohms/M Ft.	Reactance[3] Ohms/M Ft.
14	3.40	.041	---
12	2.14	.038	---
10	1.35	.035	---
8	.878	.034	---
6	.552	.048[4]	.048[4]
4	.347	.048[4]	.048[4]
3	.275	.047[4]	.047[4]
2	.218	.046[4]	.046[4]
1	.173	.046[4]	.046[4]
1/0	.134	.045[4]	.032
2/0	.107	.045[4]	.031
3/0	.085	.028	.030
4/0	.068	.027	.029
250	.057	.028	.030
300	.048	.027	.029
350	.041	.027	.029
400	.036	.027	.028
500	.029	.026	.028
600	.024	.026	.027
700	.021	.026	.027
800	.019	.025	.026
900	.017	.025	.026
1000	.015	.025	.026

[1] R_{1c}
[2] X_{1c} for 480 and 600 V Circuits
[3] X_{1c} for 1040 V circuits
[4] Flat, 3 conductor, type G cable

Arcing Fault Factor

In equations (1) and (2) a factor (K_A) is applied to account for reduced current flow due to an arcing fault. Considerable theoretical as well as experimental work has been done to determine the factor relating probable minimum arcing fault current to bolted fault current in 480 V power systems. In “Arcing Fault Protection for Low-Voltage Power Distribution Systems,” [4] Kaufmann and Page propose a factor of 0.74 to relate the approximate minimum value of line-to-line arcing fault current to bolted three-phase fault current for a 480 V power system. This value corresponds to 0.8545 of the bolted line-to-line fault current. Consequently, an arcing fault factor of 0.8545 was used to calculate minimum expected trailing cable short circuit current at 480 V. Although there has been little work done to determine an arcing fault factor for 600 V and 1040 V power systems, it has been shown in [4] that the arcing fault factor increases as the system voltage is increased. Consequently, arcing fault factors of 0.9 for 600 V systems and 0.95 for 1040 V systems have been assumed for the purpose of calculating minimum expected short-circuit current in three-phase trailing cables.

Short-Circuit Calculations

Once the arcing fault factor, phase-to-phase voltage, supply system impedance, section transformer impedance, and trailing cable impedance were determined, equation (2) was used to calculate minimum expected trailing cable short-circuit current. Since trailing cable length has a significant effect on the magnitude of short-circuit current, short circuit 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 Schedule 2G [5]. A factor of 1.05 was applied to the calculated trailing cable impedance to allow for possible errors in determining trailing cable length.

An example calculation of minimum expected short-circuit current for a 500 ft., #4/0 AWG, 480 V three-phase trailing cable follows:

$$\begin{aligned} I_{\phi\phi} &= \frac{K_A E_{\phi\phi}}{2Z_1} \\ &= \frac{0.8545(456)}{2(0.0524 + j0.0507)} \\ &= 2673 \ A \end{aligned}$$

where Z_{1s} = 0.0121 + j0.0139 = supply system impedance,

Z_{1t} = 0.0046 + j0.0226 = transformer impedance,

Z_{1c} = 0.0357 + j0.0142 = cable impedance,

and Z_1 = 0.0524 + j0.0507 = total positive sequence impedance.

The minimum expected short circuit currents for each trailing cable size, length, and voltage are presented in Table II.

TABLE II
Minimum Expected Short-Circuit Current--Three-Phase 480, 600, and 1040 V Trailing Cable

CONDUCTOR SIZE (AWG OR MCM)	CABLE LENGTH (FEET)	MINIMUM EXPECTED PHASE-TO-PHASE SHORT-CIRCUIT CURRENT		
		480 V	600 V	1040 V
14	0 - 500	108	141	-
12	0 - 500	171	223	-
10	0 - 500	268	347	-
8	0 - 500	405	521	-
6	0 - 550	570	722	1110
4	0 - 500	936	1146	1563
	501 - 600	797	987	1405
3	0 - 500	1131	1357	1746
	501 - 650	904	1107	1521
2	0 - 500	1348	1580	1914
	501 - 600	1164	1389	1765
	601 - 700	1023	1237	1635
1	0 - 500	1578	1802	2060
	501 - 600	1375	1602	1921
	601 - 750	1150	1370	1741
1/0	0 - 500	1842	2040	2253
	501 - 600	1622	1837	2129
	601 - 750	1379	1595	1962
	751 - 800	1307	1527	1911
2/0	0 - 500	2062	2227	2364
	501 - 600	1834	2026	2253
	601 - 750	1572	1782	2101
	751 - 850	1434	1648	2009
3/0	0 - 500	2439	2547	2459
	501 - 600	2197	2350	2360
	601 - 750	1908	2101	2223
	751 - 900	1685	1896	2100
4/0	0 - 500	2673	2721	2535
	501 - 600	2434	2536	2447
	601 - 750	2142	2297	2324
	751 - 1000	1781	1979	2141
250	0 - 500	2814	2819	2574
	501 - 600	2581	2643	2492
	601 - 750	2293	2414	2378
	751 - 1000	1929	2105	2207
300	0 - 500	2963	2923	2617
	501 - 600	2737	2757	2542
	601 - 750	2453	2538	2437
	751 - 1000	2088	2238	2277
350	0 - 500	3070	2995	2646
	501 - 600	2851	2837	2576
	601 - 750	2573	2627	2476
	751 - 1000	2210	2335	2325
400	0 - 500	3146	3046	2673
	501 - 600	2933	2893	2607
	601 - 750	2660	2690	2513
	751 - 1000	2300	2406	2370
500	0 - 500	3278	3133	2702
	501 - 600	3073	2991	2640
	601 - 750	2810	2799	2552
	751 - 1000	2456	2527	2418
600	0 - 500	3355	3184	2729
	501 - 600	3157	3047	2672
	601 - 750	2400	2863	2590
	751 - 1000	2553	2599	2463
700	0 - 500	3400	3213	2742
	501 - 600	3207	3080	2686
	601 - 750	2954	2900	2607
	751 - 1000	2610	2642	2484
800	0 - 500	3459	3252	2457
	501 - 600	3269	3123	2704
	601 - 750	3021	2948	2628
	751 - 1000	2681	2696	2510
900	0 - 500	3489	3272	2765
	501 - 600	3302	3146	2713
	601 - 750	3057	2973	2639
	751 - 1000	2720	2724	2524
1000	0 - 500	3519	3291	2773
	501 - 600	3335	3167	2723
	601 - 750	3093	2998	2650
	751 - 1000	2758	2752	2537

MAXIMUM ALLOWABLE CIRCUIT BREAKER SETTINGS

Virtually all three-phase 480, 600 and 1040 V 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 without intentional time delay (instantaneously) 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 three-phase trailing cables.

Two nationally recognized standards specify maximum tolerances for adjustable instantaneous magnetic trip units in molded case circuit breakers. The National Electrical Manufacturers Association (NEMA) Standards Publication AB 1-1975 covers molded case circuit breakers with voltage ratings up to and including 600 V ac and 250 V dc. This standard specifies a maximum tolerance of +20% on both the low and high settings of the adjustable instantaneous trip unit for molded case circuit breakers with instantaneous magnetic trip units only. This standard also specifies a maximum tolerance of ± 25% on the low setting and ± 10% on the high setting for circuit breakers with thermal magnetic trip units. Underwriters Laboratories Standard UL 489 covers molded case circuit breakers rated 600 V or less. This standard specifies a maximum tolerance of +10% to -20% on the high adjustable magnetic trip setting. No tolerance is specified for the low setting; however, the standard requires that the trip current at the low setting be less than the trip current at the high setting. Neither the NEMA nor the UL standard specifies maximum instantaneous trip unit tolerances at the intermediate settings. There are no nationally recognized standards that specify magnetic trip unit tolerances for molded case circuit breakers rated at 1040 V ac.

Since circuit breaker manufacturer compliance with the NEMA standard is not mandatory and compliance with the UL standard is mandatory only in installations governed by the National Electrical Code, the instantaneous trip unit tolerances maintained by the major manufacturers of molded case circuit breakers for trailing cables short-circuit protection were examined. Since 1975 one manufacturer has furnished two grades of molded case circuit breakers for trailing cable short-circuit protection. This manufacturer calibrates each pole of standard grade circuit breaker trip units to a tolerance of ±20% on both the high and low settings but does not specify a maximum tolerance for intermediate trip unit settings. This manufacturer calibrates each pole of the premium grade circuit breaker to a tolerance of ±10% on both the high and low settings and specifies a maximum intermediate setting tolerance of ±15%.

Another major manufacturer presently supplies one grade of molded case circuit breakers for trailing cable short-circuit protection. Until early 1977, this manufacturer calibrated each pole of the standard grade circuit breaker trip unit to a tolerance of ±10% on the high setting and ±25% on the low setting. Since early in 1977, this manufacturer has calibrated all standard grade mining duty circuit breaker units, with one exception, to a tolerance of ±10% on both the high and low settings. This manufacturer does not specify a tolerance for the intermediate trip unit settings on standard grade circuit breakers.

TABLE III
Minimum Allowable Circuit Breaker Settings--Three-Phase 480, 600, and 1040 V Trailing Cables

CONDUCTOR SIZE (AWG OR MCM)	CABLE LENGTH (FEET)	MAXIMUM INSTANTANEOUS CIRCUIT BREAKER SETTING (AMPS)		
		480 V	600 V	1040 V
14	0 - 500	75	100	-
12	0 - 500	125	150	-
10	0 - 500	200	250	-
8	0 - 500	300	400	-
6	0 - 550	400	550	850
4	0 - 500	700	850	1200
	501 - 600	600	750	1050
3	0 - 500	850	1050	1350
	501 - 650	700	850	1150
2	0 - 500	1000	1200	1450
	501 - 600	900	1050	1350
	601 - 700	750	950	1250
1	0 - 500	1200	1350	1600
	501 - 600	1050	1200	1450
	601 - 750	850	1050	1350
1/0	0 - 500	1400	1550	1750
	501 - 600	1250	1400	1650
	601 - 750	1050	1200	1500
	751 - 800	1000	1150	1450
2/0	0 - 500	1600	1700	1800
	501 - 600	1400	1550	1750
	601 - 750	1200	1350	1650
	751 - 850	1100	1250	1550
3/0	0 - 500	1900	1950	1900
	501 - 600	1700	1800	1800
	601 - 750	1450	1600	1700
	751 - 900	1300	1450	1600
4/0	0 - 500	2050	2100	1950
	501 - 600	1850	1950	1900
	601 - 750	1650	1750	1800
	751 - 1000	1350	1500	1650
250	0 - 500	2150	2150	1950
	501 - 600	2000	2050	1900
	601 - 750	1750	1850	1800
	751 - 1000	1450	1600	1700
300	0 - 500	2300	2250	2000
	501 - 600	2100	2100	1950
	601 - 750	1900	1950	1850
	751 - 1000	1600	1700	1750
350	0 - 500	2350	2300	2050
	501 - 600	2200	2200	2000
	601 - 750	1950	2000	1900
	751 - 1000	1700	1800	1800
400	0 - 500	2400	2350	2050
	501 - 600	2250	2200	2000
	601 - 750	2050	2050	1950
	751 - 1000	1750	1850	1800
500	0 - 500	2500	2400	2050
	501 - 600	2350	2300	2050
	601 - 750	2150	2150	1950
	751 - 1000	2000	1950	1850
600	0 - 500	2600	2450	2100
	501 - 600	2450	2350	2050
	601 - 750	2250	2200	2000
	751 - 1000	1950	2000	1900
700	0 - 500	2600	2450	2100
	501 - 600	2450	2350	2050
	601 - 750	2250	2250	2000
	751 - 1000	2000	2050	1900
800	0 - 500	2650	2500	2100
	501 - 600	2500	2400	2100
	601 - 750	2300	2250	2000
	751 - 1000	2050	2050	1950
900	0 - 500	2700	2500	2100
	501 - 600	2550	2400	2100
	601 - 750	2350	2300	2050
	751 - 1000	2100	2100	1950
1000	0 - 500	2700	2550	2150
	501 - 600	2550	2450	2100
	601 - 750	2400	2300	2050
	751 - 1000	2100	2100	1950

These same manufacturers have available solid state instantaneous trip molded case circuit breakers. These designs, one introduced in 1972, the other in 1974, have tolerances of ±10% at not only the endpoints, but also at the intermediate settings.

In view of the lack of mandatory standards for maximum circuit breaker instantaneous trip unit tolerances, it is necessary for the maximum allowable instantaneous circuit breaker settings to be based on the worst case tolerances maintained by molded case circuit breaker manufacturers in the past. Consequently, the maximum allowable instantaneous circuit breaker settings for the short-circuit protection of three-phase 480, 600, and 1040 V trailing cables 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 trailing cable short-circuit current tabulated in Table II by the circuit breaker tolerance factor (1/1.3). The resulting maximum allowable circuit breaker setting were rounded off and are presented in Table III.

DISCUSSION

This paper would be incomplete if the range of power system parameters over which the proposed circuit breaker settings are valid were not discussed. However, one must remember that the proposed settings were developed with the safety of the miner and protection of the trailing cable in mind. They should not be increased without serious thought and analysis of the mine power system and mining practices. Furthermore, these settings should be lowered to the minimum necessary to allow operation of mining equipment within its specifications.

The remainder of this paper deals with documented problems experienced by the coal mining industry in an effort to gain compliance with the present settings and the alternative possible in alleviating specialized problems without loss of safety.

Figure 2 illustrates how the proposed circuit breaker settings based on trailing cable length compare to the present settings. For all but the larger size cables, that is #2/0 AWG and above, the new settings are substantially higher for 500 feet of trailing cable, but decrease markedly for longer lengths of cable.

MESA has no documented evidence from the mining industry of compliance difficulty in protecting a trailing cable #6 AWG or smaller. If the new setting is not high enough to keep a unit of equipment in operation, recalibration or replacement of the circuit breaker should be considered before any modification to the mine power system is attempted.

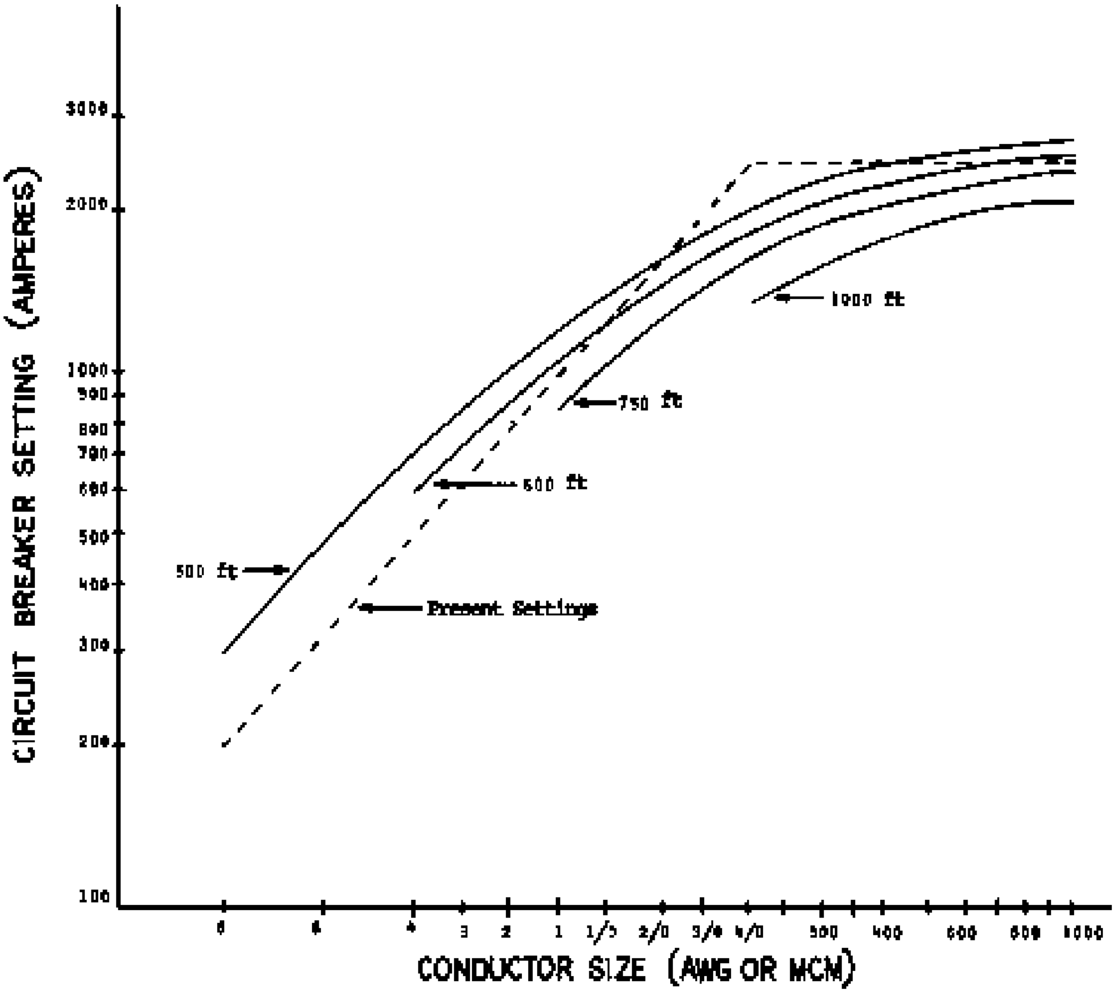

Figure 2. Present and Proposed Circuit Breaker Settings
vs. Trailing Cable Size

Test Procedure

Several coal mine operators were contacted and tests were made at their mines on various pieces of mining machinery. These tests were made in order to document problems and to demonstrate safe solutions to these problems.

Tests at all the mines were conducted using basically the same test equipment. The only item that changed was the current sensor. In one mine, a 60 mV = 600 A shunt was used; in the other mine, a 1000:5 current transformer with a 0.1 ohm burden resistor was used. An oscillograph with a 0 to 5000 Hz response, along with two high-voltage preamplifiers with a 0 to 10,000 Hz frequency response, was used to record the current and voltage.

The preamplifiers were used to isolate the oscillograph from the high voltages present at the load center. Gains on the oscillograph and the preamplifiers were adjusted to provide adequate trace deflection on the oscillograph. There were two mine power systems tested. The machines tested were first started under normal conditions in order to record their normal inrush current. In order to record the highest currents possible, the machine was deliberately stalled. The two systems were then modified to simulate a weaker system in one mine and a stiffer system in the other mine. This was accomplished by adding 250 ft of #4/0 AWG cable to the existing 600 ft of trailing cable, simulating a weaker system. The current and voltage were then measured in the 600 ft of trailing cable. A stiffer system was simulated by eliminating the 500 ft of 500 MCM cable which normally feeds the miner through a distribution box. The 480 ft of #4/0 AWG miner trailing cable was connected directly to the load center and voltage and current measurements were made. Recordings of current and voltage were also made at the distribution box which is the normal operating condition and simulates a weaker system.

Test Results

Consider the following cases which will be referred to during the remainder of this report. Peak currents given are full cycle symmetrical rms values.

Case I. A loading machine with a total of 110 hp had a #2 AWG trailing cable approximately 550 ft long which was connected to a distribution box. There were 500 ft of 500 MCM cable between the distribution box and the power center with 38 MVA available at the primary of the 750 kVA power center transformer. Measurements taken at the distribution box indicated a peak motor inrush of 813 A at a no-load voltage of 478V.

Case II. A continuous mining machine with 550 total hp was supplied power by a #4/0 AWG trailing cable, 480 ft long connected to a distribution box. The distribution box was fed from a 750 kVA power center through 550 ft of 500 MCM cable with 38 MVA available at the transformer primary. The peak inrush current was 1569 A at a no-load voltage of 478 V measured at the distribution box.

Case III. This consisted of the same equipment and setup as Case II. The only change was the elimination of the 550 ft of 500 MCM cable and the connection of the #4/0 AWG trailing cable directly to the power center. The peak inrush current measured was 1626 A at the above no-load voltage.

Case IV. A loading machine with 110 total hp was supplied power by 700 ft of #2 AWG trailing cable. The trailing cable was connected to a 750 kVA power center with 30 MVA available at the transformer primary. With a section voltage of 521 V, the peak inrush current measured was 838 A.

Case V. A continuous mining machine with 535 hp was fed power by 600 ft of #4/0 AWG trailing cable. The trailing cable was connected to a 750 kVA power center with 30 MVA available at the transformer primary. The maximum inrush current measured was 1669 A and the maximum current during stall was 2518 A. No-load voltage was 521V.

Case VI. The same setup was used as in Case V. The only modification was the addition of 250 ft of #4/0 AWG trailing cable to give a total cable length of 850 ft of #4/0 AWG trailing cable. The maximum inrush current measured was 1502 A with a no-load voltage of 521 V. The machine was stalled and the maximum current during stall was 2165 A.

Immediate Relief of New Settings

The possibility of the proposed settings relieving nuisance tripping on motor inrush is apparent. Consider Case I. Under the existing standard, a circuit breaker setting of 800 A is necessary for compliance. However, the proposed standard would allow a setting of 900 A, which is greater than the peak measured inrush current of 813 A. Thus, for this case, the new settings should help alleviate the nuisance tripping problem without any loss of safety.

It should be made clear that the proposed settings are the maximum allowable and not necessarily the recommended. These settings should be lowered to the point where the mining equipment can be operated within its specifications. For example, a shuttle car with 500 ft of #4 AWG trailing cable would be allowed a setting of 700 A. However, if inrush and normal peak operating currents do not exceed 500 A, then a maximum setting of 500 A would suffice. Safety should never be compromised for a higher setting.

No-Load Voltage

The section transformer no-load voltage influences the amount of current necessary to start and operate a particular mining machine. For example, Case II demonstrates a peak inrush current of 1569 A at approximately 480 V and would be allowed a maximum setting of 2050 A. However, if the no-load voltage should drop, the inrush current would also drop at the same rate as would the minimum available fault current. Thus, one would expect to measure an inrush current of 1438 A at a no-load voltage of 440 V. Similarly, the instantaneous setting must be lowered to 1990 A to afford the same level of protection. If the system no-load voltage was higher than the recommended no-load voltage, nuisance tripping of the circuit breaker could occur. This is because the inrush and short-circuit current are directly proportional to no-load voltage. Therefore, it is important that the section transformer no-load voltage be maintained at the recommended voltage level, that is, 480, 600 or 1040 V.

Circuit Breaker Calibration

Due to the wide tolerances of circuit breakers in use today, the circuit breaker trip current could deviate from the trip setting by as much as ±25%. Therefore, a circuit breaker set to trip at 750 A could have an actual trip current as low as 563 A. This could result in nuisance tripping of the circuit breaker. Likewise, the minimum circuit breaker trip current could be as high as 938 A. This does not pose a safety problem, because the maximum circuit breaker settings were derated by a factor to account for a ±25% circuit breaker tolerance. Nevertheless, calibrating the circuit breaker would help to narrow the tolerance band, would safely allow a higher circuit breaker setting, and would reduce the possibility of nuisance tripping. Test sets for calibrating circuit breakers are available today with accuracies of ±5%. This would increase the circuit breaker tolerance factor from 0.7692 to 0.91. For example, 700 ft of #2 AWG trailing cable energized at 480 V has a maximum allowable circuit breaker setting of 750 A. This setting could be safely increased to 900 A by the calibration of the circuit breakers using the appropriate calibration equipment. The increased setting would eliminate the inrush problem which might occur with the proposed settings as applied to the system described in Case IV.

Circuit Breaker Tolerances

The above discussion applies also to circuit breaker manufacturing tolerances. If circuit breakers with a ±15% tolerance were used, the circuit breaker tolerance factor of 0.7692 could be safely raised to 0.8333. This would raise the 750 A setting for the 700 ft #2 AWG trailing cable to 850 A, which would be higher than the maximum current of 838 A drawn in Case IV. Breakers of ±15% tolerance are available today and, if used, would allow a higher setting to be safely used.

Power System Impedance

The power system impedance as seen by the trailing cable is an important factor in determining maximum allowable circuit breaker settings. Figure 3 illustrates the effect this impedance has on the circuit breaker settings for various 480 V trailing cables. The impedance values vary from 0.0157 ohm for a stiff power system with a 53.7 MVA supply and a 1000 kVA section transformer to 0.0589 ohm for a weak power system with a 10 MVA supply and a 300 kVA section transformer. The impedance value indicated by the dashed line (0.0401 ohm) is the typical power system plus section transformer impedance used to calculate the maximum allowable circuit breaker settings; 12.5 MVA available at the primary of a 500 kVA section transformer.

If the power system characteristics differ from those assumed in the calculations, one can determine from the curves the maximum safe setting for a particular power system impedance. A high system impedance will fall on the right side portion of the graph for a particular trailing cable size and result in poor voltage regulation. A power system showing symptoms of poor voltage regulation, such as motor heating or failure, should be examined carefully. Systems unable to supply sufficient current to loads would supply less than expected to faults. Lowered settings should be recognized not only as a necessary safety practice, but also as a necessary mining and engineering practice, allowing a circuit breaker to operate to protect the trailing cable and machinery when faults occur.

In a similar manner, a relatively stiff power system will demand higher minimum short-circuit currents and fall on the left side of the graph. If nuisance tripping occurs, the settings can be altered to the system parameters without sacrificing safety.

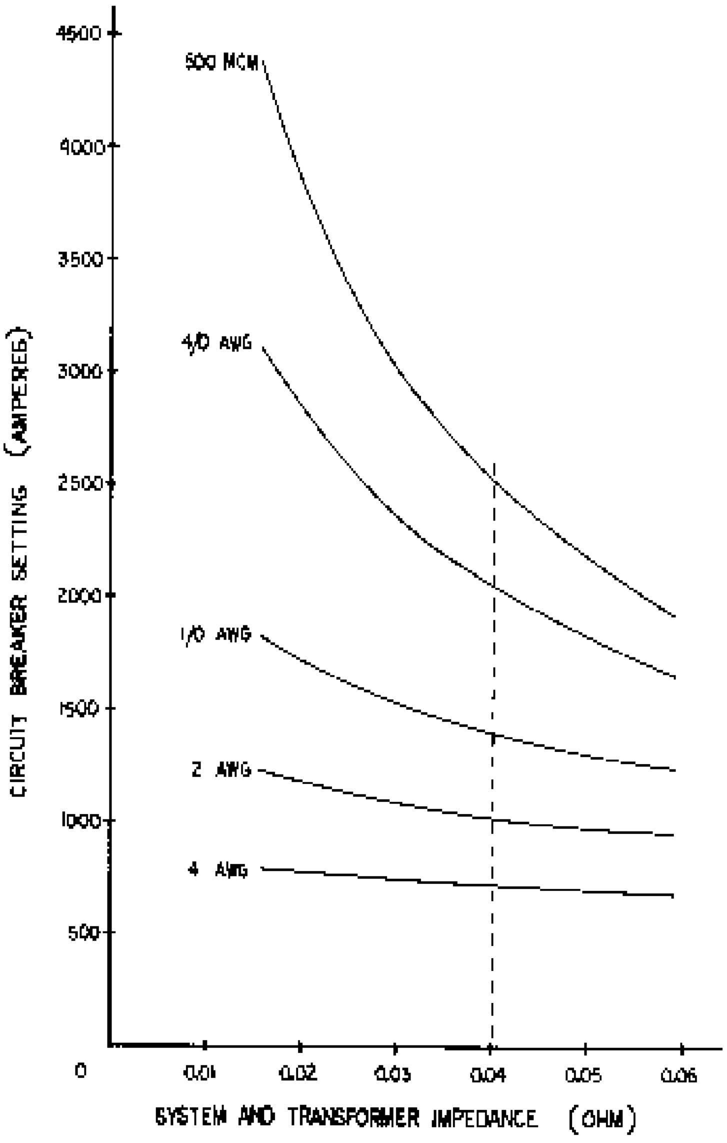

Figure 3. Maximum Circuit Breaker Settings
vs. Total System and Transformer Positive Sequence Impedance

The effects of power system impedance are clearly demonstrated in Cases II, III, V, and VI. In cases II and III, the system impedance went from 0.0213 ohms in Case III to 0.0403 ohms in Case II. The starting current also changed going from 1626 A in Case III (Z = 0.0213) to 1569 A in Case II (Z = 0.0403). The stall currents of Cases V and VI show even a greater spread when system impedance is changed. In Case V the stall current was 2518 A and the system impedance was 0.0229 ohms. In Case VI the stall current was 2165 A with a system impedance of 0.0357 ohms.

The above cases demonstrate the need for circuit breaker settings to be lowered when the system impedance is higher than the 12.5 MVA, 500 kVA typical mine power system used in the calculations. This also indicates that the settings can be safely raised when the system impedance is lower than the 12.5 MVA, 500 kVA typical mine power system.

CONCLUSIONS

Based on a rigorous analysis of available short-circuit current in a three-phase trailing cable, the existing requirements for maximum instantaneous circuit breaker settings provide a varying margin of safety dependent upon cable size. For smaller size cables the margin of safety is adequate, but for the larger cables, #1/0 AWG and above, the degree of safety is unacceptable. The critical point occurs where the system and power center impedance become evident in the circuit.

The proposed circuit breaker settings are based on phase-to-phase 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 without modification. However, if the parameters of a specific mine power system do not compare favorably with those assumed, then the maximum circuit breaker settings must be lowered to afford the necessary margin of safety. If a specific mine power system cannot effectively operate mining equipment under the maximum setting, then the setting may be altered provided the power system is modified to insure no sacrifice of safety.

Further studies should be continued to determine maximum instantaneous circuit breaker settings for both dc and single-phase trailing cables, with safety to the miner and protection of the cable as the prime objectives.

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