

The Use of Low-Voltage Current-Limiting Fuses to Reduce Arc-Flash Energy

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Abstract—Current-limiting fuses, in their current-limiting range, reduce the available short-circuit current and clear faults in one-half cycle or less. Available fuse test data, such as let-through I^2t and peak let-through current, is based upon single-phase bolted-fault tests at full voltage. Currently, there is no data available that relates single-phase current-limiting fuse test data with energy released by downstream three-phase arcs. A three-phase 600-V test program was conducted using Class L and RK1 fuses to determine the let-through arc energy and the incident energy produced 18 in away from a three-phase arc in a 20-in cubic box. Incident energy produced by the downstream arc is correlated with the degree of current limitation and fuse bolted-fault test data. The benefit provided by current-limiting fuses in reducing arc-flash energy is quantified.

Index Terms—Arc burn, arc burn prevention, arc flash, arc thermal energy, current-limiting fuses.

I. INTRODUCTION

SINCE energy is the integral of power with respect to time, one would expect, and tests have confirmed, that the thermal incident energy from an electric arc exposure is directly proportional to the time duration of the arc [1], [2]. Any mechanism which detects the presence of the arc and opens the circuit in a relatively short time is effective in limiting the amount of incident energy exposure created by the arc. One common class of protective equipment that provides quick circuit opening in the event of an arc with high currents is the current-limiting fuse. When operating in the current-limiting range, the fuse typically opens the circuit in less than 1/2 cycle or 8.3 ms.

Results of recent tests provide a method of estimating the thermal incident energy produced by three-phase arcs on 600-V electric power distribution systems [3]. The incident energy pre-

diction algorithms in [3], however, cannot be used to determine incident energy from arcs produced by three-phase 600-V circuits with fuses in them. Within their current-limiting range, the fuses introduce additional impedance into the circuit and reduce the amount of energy that is produced by a three-phase arc.

Persons who design, operate, and maintain electrical power distribution systems have a need to know how much arc-flash protection is provided for personnel by installing current-limiting fuses into electrical power distribution circuits. The authors decided to conduct three-phase arc tests on 600-V circuits with current-limiting fuses inserted in the circuit just ahead of the arc. Since a majority of electric arcs occur in electric equipment enclosures, the decision was made to enclose the three-phase arc in a 20-in cubic metal box, similar to the test setup used in [2] and [3].

The current-limiting fuses selected for testing included 400- and 600-A Class RK1 fuses and 800-, 1200-, 1600-, and 2000-A Class L fuses. The Class L fuses chosen are typically used in fused low-voltage power circuit breakers or bolted pressure switches. The 400- and 600-A Class RK1 fuses are typically used in feeders, motor control center mains, bus duct plugs, or large motor starters.

II. CURRENT-LIMITING FUSE DATA

In order to determine the performance of current-limiting fuses, fuse manufacturers typically perform single-phase bolted-fault fuse tests based on the UL (U.S.)/CSA (Canada)/ANCE (Mexico) tri-national 248 series of standards. Table I shows average results of actual fuse tests performed on the fuse types selected for use in the three-phase arc tests. Note that the 248 series of standards calls out the maximum let-through values so that all fuses listed to the standard will have a uniform maximum let-through which can be utilized by equipment manufacturers and designers.

Manufacturers determine the fuse current-limiting and let-through characteristics from the fuse test data. Fuse let-through charts for Class RK1 and Class L fuses used in the three-phase arc tests are shown in Fig. 1. In order to read a fuse let-through chart, enter the x axis at the available rms symmetrical short-circuit current. Move up until the appropriate fuse curve is intersected. Then, make a left turn, proceed horizontally until reaching the y axis, and read the peak let-through current. To read the equivalent rms let-through current, start with the available rms short-circuit current on the x axis. Move up until the fuse curve is intersected, turn to the left and proceed horizontally to the "A-B" line. Then, move down to the x axis and read the equivalent rms let-through current. For example, in

Paper PID 00-21, presented at the 1999 IEEE Petroleum and Chemical Industry Technical Conference, San Diego, CA, September 13-15, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Petroleum and Chemical Industry Committee of the IEEE Industry Applications Society. Manuscript submitted for review September 15, 1999 and released for publication June 6, 2000.

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Publisher Item Identifier S 0093-9994(00)09255-0.

TABLE I
AVERAGE U L FUSE BOLTED FAULT TEST DATA

Fuse Description		Avail.	Test	Circuit	Meas.	Let-Through
Fuse Class	Rated Current	Sym. I kA	Voltage V	Power Factor	Peak I kA	Pt x 10 ³ amp ² -sec.
RK1	400 A	16.8	612	6.0%	17.7	815.5
RK1	400 A	102.9	612	14.0%	32.5	778.7
RK1	400 A	208.0	604	16.0%	40.1	730
RK1	600 A	103.0	611	14.0%	44.6	2427
RK1	600 A	203.0	606	17.0%	55.9	2225
L	800 A	26.2	603	5.5%	35.4	3311
L	800 A	103.9	610	14.6%	50.1	3183
L	800 A	213.3	606	19.0%	67.6	3513
L	800 A	306.0	602	18.0%	73.2	3460
L	1200 A	26.2	603	5.5%	50.9	8704
L	1200 A	102.0	605	11.5%	69.1	9573
L	1200 A	213.2	613	19.0%	86.9	10344
L	1200 A	306	602	18.0%	126	17500
L	1600 A	25.8	606	6.0%	58.6	12789
L	1600 A	50.6	604	11.0%	66.0	12320
L	1600 A	103.4	607	16.0%	83.2	15783
L	1600 A	213.5	600	No Data	104	18050
L	2000 A	25.0	600	No Data	55.8	12500
L	2000 A	51.0	603	18.0%	78.9	18503
L	2000 A	102.6	519	18.0%	85.2	17856
L	2000 A	213.5	600	No Data	119	26250
L	2000 A	306.0	602	18%	129	17700

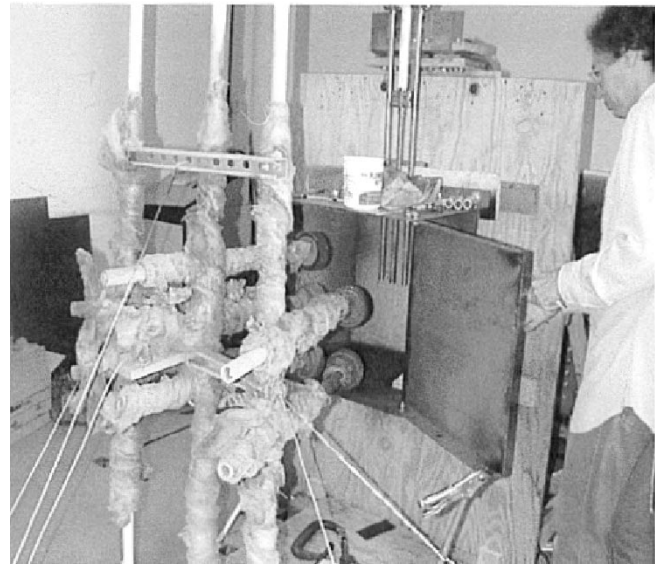


Fig. 2. Test setup.

equivalent rms let-through current, start out as above, but at the “A–B” line intersection, move down to read 22 000 equivalent rms amperes on the x axis.

III. THREE-PHASE FUSE ARC TEST PROGRAM

A. Test Setup

All tests described herein were performed in the medium-current cell of a high-power test laboratory. In this test cell, the test board is connected by 1/2-in \times 8-in copper bus to the low-voltage side of a 300-MVA short-circuit delta-connected transformer bank. Primary transformer power was supplied from a 640-MVA (short circuit) synchronous alternator through a reactive load bank. The load bank consisted of air-core inductors selected to yield the desired current/voltage combinations in the test cell. Rotation for the alternator was provided by a relatively small dc motor that, in turn, was powered from the electric utility through a solid-state dc drive. The 64 000-lb alternator rotor acts as a flywheel and at rated speed has 650 kJ of stored kinetic energy. Thus, the power delivered to the test cell for a short period of time may exceed the motor drive capability by several orders of magnitude. Power was delivered to the test cell through a 4-ft length of 1/2-in \times 6-in copper bus which was braced to withstand the 6-cycle bolted-fault shots.

One test setup was used for all three-phase arc testing. The test setup utilized electrodes mounted inside and 4 in from the back of an unpainted, carbon steel cubic box (20 in wide \times 20 in high \times 20 in deep) as shown in Fig. 2. The 4-in distance was selected to minimize damage to the rear wall of the box as well as to facilitate electrode maintenance during testing. Fuses were inserted into the test circuit electrically ahead of where the conductors entered the cubic metal box. Tests were conducted with the box ungrounded, since earlier testing [2] indicated that the ungrounded box produced the maximum incident energy.

For each test, an array of seven copper calorimeters was located in front of the box, 18 in from the centerline of the electrodes. A set of three calorimeters was located in a horizontal row at the same height as the tip of the electrodes. A second

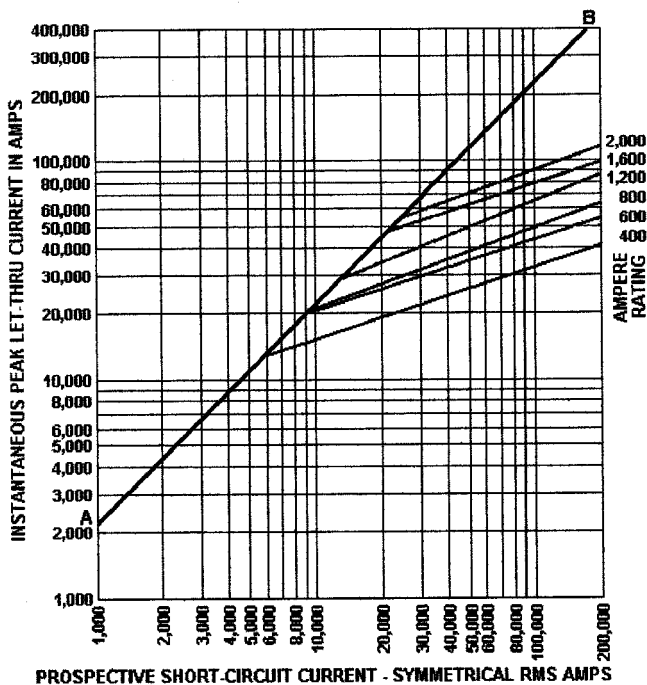


Fig. 1. Peak let-through chart—test fuses.

Fig. 1, assume an available short-circuit current of 100 000-A rms, and an 800-A Class L fuse. Beginning at 100 000 A on the x axis, move up to the 800-A fuse line. Turn to the left and read the peak let-through current as 50 000-A peak. To read the

TABLE II
THREE-PHASE FUSE ARC TEST RESULTS: 600-V SYSTEM—1.25-IN ARC GAP

Avail. Bolted Fault Current kA	X/R Ratio	Current Limiting Fuse Type	Mean Max. Current kA rms	Mean Max. Peak Current kA Peak	Average Arc Energy kW-Sec.	Average Let-through Pt Amp ² -Sec. X 10 ³	Aver. Ckt. Imped. Arc Energy/Pt kW/Amp ²	Average Incid. Energy cal/cm ²	Mean Max. Incid. Energy cal/cm ²
106	7.9	None	45.98	72.3	4205	587777	0.0072	22.42	35.71
106	7.9	CL L-2000A	29.80	48.3	524	40574	0.0130	1.94	2.39
106	7.9	CL L-1600A	28.80	41.4	70	7444	0.0094	0.29	0.36
106	7.9	CL L-1200A	24.05	37.9	33	3499	0.0095	0.14	0.20
106	7.9	CL L-800A	19.35	34.8	45	3867	0.0115	0.18	0.22
106	7.9	CL RK1-600A	17.00	30.0	8	1170	0.0064	0.03	0.04
65.9	9.95	None	36.77	58.1	2918	360565	0.0081	16.21	21.29
65.9	9.95	CL L-2000A	25.50	38.7	915	71154	0.0107	6.48	8.24
65.9	9.95	CL L-1600A	22.97	35.3	179	14693	0.0113	0.99	1.24
65.9	9.95	CL L-1200A	23.15	33.9	39	3943	0.0098	0.18	0.24
65.9	9.95	CL L-800A	18.90	31.2	33	3040	0.0109	0.14	0.17
65.9	9.95	CL RK1-600A	16.95	27.0	12	1416	0.0085	0.05	0.09
44.1	11	None	25.97	44.4	1433	205772	0.0070	12.23	15.68
44.1	11	CL L-2000A	21.78	37.0	1440	111286	0.0132	9.90	13.05
44.1	11	CL L-1600A	22.80	33.9	141	13902	0.0103	0.73	0.92
44.1	11	CL L-1200A	18.60	29.2	50	4719	0.0107	0.24	0.30
44.1	11	CL L-800A	14.18	24.7	21	2086	0.0102	0.09	0.15
44.1	11	CL RK1-600A	12.33	21.2	11	1310	0.0087	0.05	0.07
22.6	4.9	None	15.80	24.3	875	73274	0.0120	5.93	7.79
22.6	4.9	CL L-2000A	15.95	25.2	2637	223106	0.0118	23.12	28.89
22.6	4.9	CL L-1600A	15.53	23.8	2637	223106	0.0118	7.01	9.47
22.6	4.9	CL L-1200A	12.33	22.2	627	28649	0.0213	4.65	6.33
22.6	4.9	CL L-800A	14.83	22.3	139	8431	0.0153	0.63	0.84
22.6	4.9	CL RK1-600A	12.25	20.2	23	2557	0.0091	0.10	0.15
22.6	4.9	CL RK1-400A	8.42	15.7	2	770	0.0048	0.02	0.03
5.04	15	CL RK1-600A	4.69	11.7	2765	51392	0.0536	21.06	26.29
5.04	15	CL RK1-400A	6.88	10.8	86	2126	0.0387	0.29	0.35

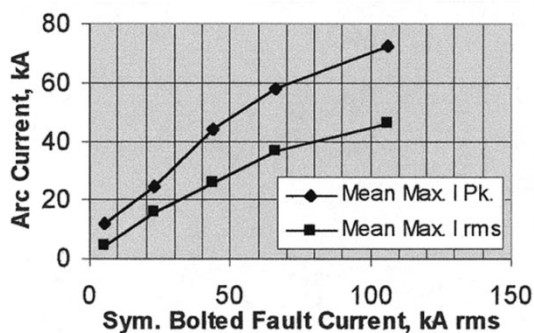


Fig. 3. Three-phase arc current as a function of bolted-fault current. Affect of arc impedance on current.

set of three calorimeters was located in a horizontal row 6 in below the elevation of the electrode tips. The middle calorimeters in each set were aligned with the center electrode. A single calorimeter was located 6 in above the center electrode tip.

Hard-drawn copper conductors, diameter of 3/4 in, were used for the arc electrodes. Electrodes were vertically oriented in a flat configuration with a side-side spacing of 1.25 in, the spacing that was determined to produce maximum incident energy in previous tests [2]. Arcs were initiated by a #10 gauge

wire connected between the ends of the electrodes. For all tests, it was necessary to install insulating support blocks between adjacent electrodes to prevent the electrodes from bending outward due to the extremely high magnetic forces created by the arc currents.

Open-circuit test voltages were selected at or above the nominal system voltage of 600 V. The bolted-fault current available at the test terminals was measured by shorting the electrodes together. The current-to-voltage transducers employed in the bolted-fault calibration shots were 30-m Ω low-inductance current-viewing resistors. The voltage signals from these transducers were coupled to an eight-channel digital oscilloscope through analog fiber-optic links. The duration of all arc tests was selected to be 6 cycles (100 ms).

In order to quantify arc energy, phase currents and voltages were measured. Current transformers (CTs), 20 000/5 A, were employed for current measurement. Voltage signals from the CT burden were coupled through a 3-kHz low-pass RC filter to the digital oscilloscope. Phase voltages were measured with three resistive attenuators connected between the electrodes and the derived neutral configuration. The attenuator signals were coupled to the digital oscilloscope through the analog fiber-optic links and the 3-kHz filters.

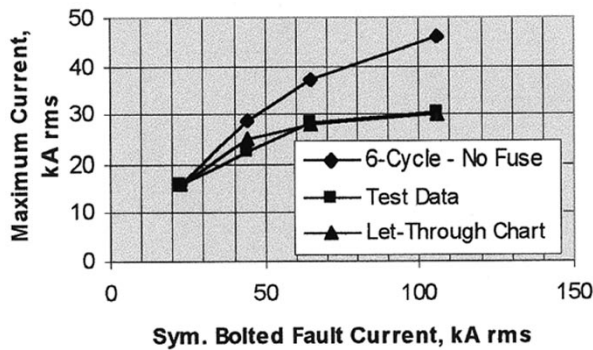


Fig. 4. Maximum current as a function of bolted-fault current—2000-A Class L fuse.

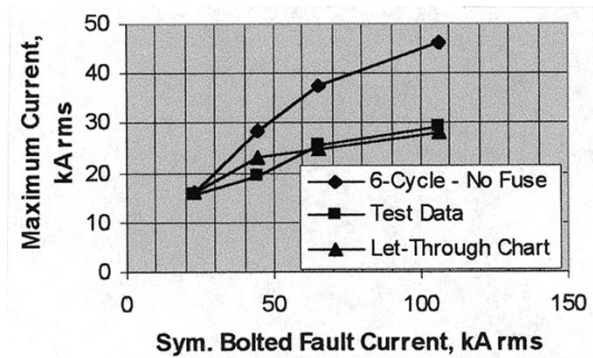


Fig. 5. Maximum current as a function of bolted-fault current—1600-A Class L fuse.

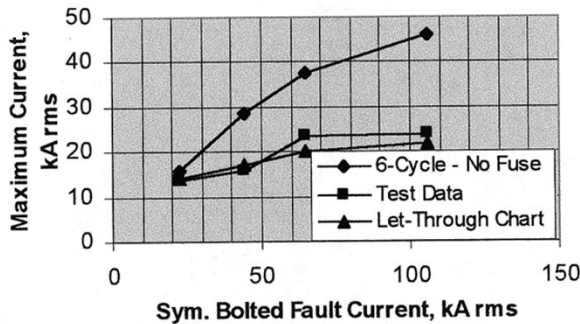


Fig. 6. Maximum current as a function of bolted-fault current—1200-A Class L fuse.

The current and voltage waveforms were captured on the oscilloscope at a 20-kHz sampling rate. Upon capture of the voltage and current traces, the phase power curves versus time were obtained by multiplication of the phase current/voltage pairs. The phase energies were then obtained by integration of the phase power curves over the arcing interval. All of the described curve manipulation was performed using the menu/computation functions resident on the digital oscilloscope.

Incident energy was measured by the copper calorimeters mounted on stands. Copper calorimeter temperature rise data in degrees Celsius was converted into incident energy in cal/cm² (conversion factor 0.135 cal/cm² °C). Sensor absorption measurements have determined that absorbed energy is equal to or greater than 90% of incident energy for copper calorimeters.

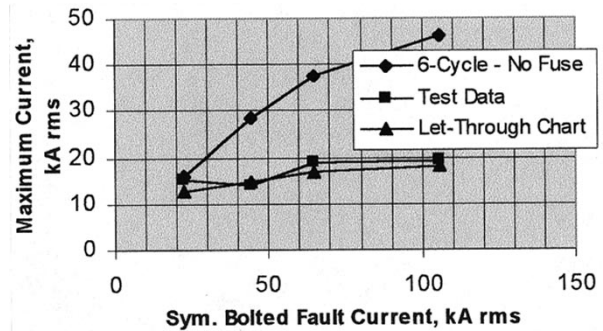


Fig. 7. Maximum current as a function of bolted-fault current—800-A Class L fuse.

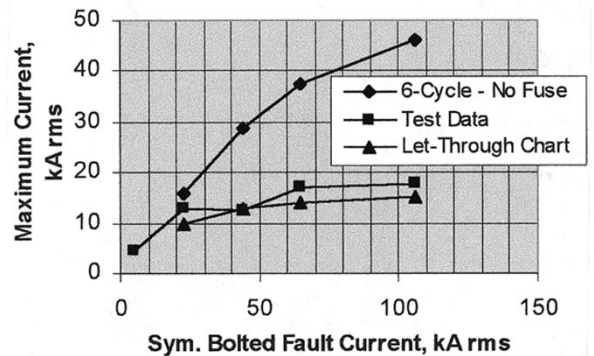


Fig. 8. Maximum current as a function of bolted-fault current—600-A Class RK1 fuse.

Henceforth, incident and absorbed energy will be considered as equivalent, and the term incident energy will be used.

B. Test Sequence and Results

A series of three-phase arc tests was conducted during two one-week periods. The tests measured the incident energy 18 in from the arc electrodes for different available symmetrical bolted-fault currents. In order to reduce the impact of arc variability, multiple tests were run for each setup and the results averaged. Since arc duration varies slightly from test to test, a time-duration correction factor was applied to the temperature rise data from the seven copper calorimeter sensors to insure that each reported incident energy was based on an arc duration of 6 cycles. The mean incident energy for the seven sensors and the mean maximum incident energy recorded by a single sensor were calculated for each test.

At each level of available bolted-fault current, tests were first conducted without any fuses in the test circuit. Then, fuses were inserted into the test circuit and tests repeated for each different size of current-limiting fuse. Test results are shown in Table II.

IV. ANALYSIS OF TEST DATA

Readers should be aware that data provided in this technical paper is based only upon measured incident energy under specified test conditions. *Real arc exposures may be more or less severe than these laboratory-simulated arc exposures.* The potentially hazardous effects of molten copper splatter, projectiles, pressure impulses, and toxic arc byproducts have not been considered in the test results or the analysis.

A. Impact of Arc Impedance on Fault Current

The fault current for a three-phase arcing fault is reduced below the available bolted-fault value due to the addition of the resistive arc impedance into the circuit. Fig. 3 shows the arc current as a function of available symmetrical rms bolted-fault current on the supply side of the arc. Note the significant reduction in current flowing through the circuit due to the arc impedance. For example, with an available symmetrical bolted-fault current of 66-kA rms, the three-phase symmetrical arc current is reduced to 36.8-kA rms, a current reduction of 44%. The introduction of the arc resistance into the circuit also lowers the effective X/R ratio of the circuit.

Given the available bolted-fault current on the supply side of a current-limiting fuse, using Fig. 3 one can estimate the amount of current that will be available to flow through the fuse in the event of a three-phase arcing fault downstream of the fuse. This reduced current value can then be applied to the let-through chart in Fig. 1 to determine the degree of current limitation that is provided by the fuse. For example, if the available bolted-fault current on the supply side of the fuse is 66 kA, then Fig. 3 indicates that the actual current that would flow in the event of a three-phase arc downstream of the fuse is 36.8 kA. Consider the effect of inserting a 1200-A Class L fuse into the circuit ahead of the arc location. Using the let-through chart in Fig. 1, enter the bottom of the chart at the available fault current of 36.8 kA, move up until the 1200-A fuse line is intersected, move left until the $A-B$ line is intersected, and then move down and read the equivalent let-through current value of 20 kA. Thus, the insertion of the 1200-A Class L fuse into the circuit further reduced the arcing fault current from 36.8 to 20 kA, significantly reducing the incident energy available from the three-phase arc.

Figs. 4–8 show maximum rms current as a function of available symmetrical rms bolted-fault current for each test fuse except the 400-A Class Rk1 fuse (due to insufficient test data). The top line shows the maximum measured “no fuse” data, or the rms current that was measured without a fuse in the circuit. The other two plots show the maximum measured let-through rms current and the expected equivalent rms let-through current read from the let-through chart in Fig. 1 using the procedure described in the paragraph above. There is a very good correlation between the measured and expected let-through values.

A fuse performance chart can be constructed using the test data for performance of current limiting fuses when upstream of a three-phase arcing fault. Fig. 9 shows the locus line for each fuse type determined by plotting peak let-through current against available bolted-fault current for each arc test. Fig. 9 can be used to determine the peak let-through current of a fuse when upstream of a three-phase arcing fault. Enter the bottom of the chart at the available symmetrical rms bolted-fault current level and move up until the fuse line is intersected. Then, move left to read the peak let-through current.

B. Measured Incident Energy Levels

An incident energy level of 1.2 cal/cm² was chosen as the minimum energy threshold for a second-degree burn of human skin based upon data shown in Fig. 10 [1]. If the measured inci-

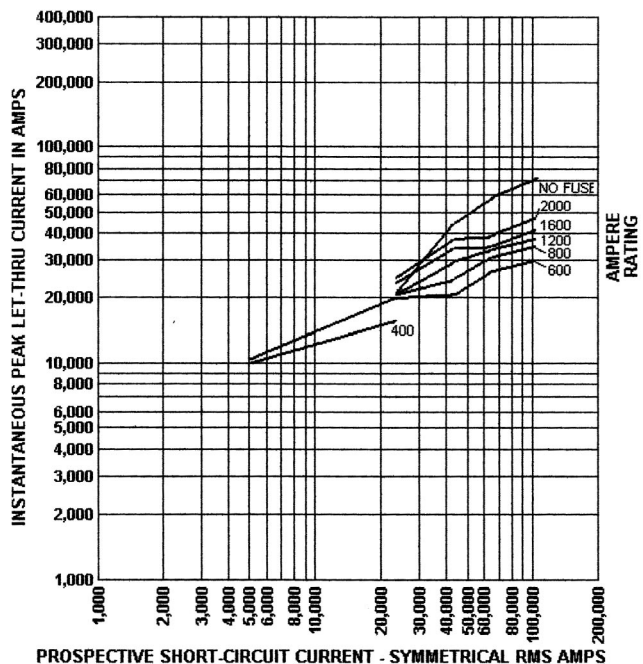


Fig. 9. Fuse performance chart for three-phase arcs.

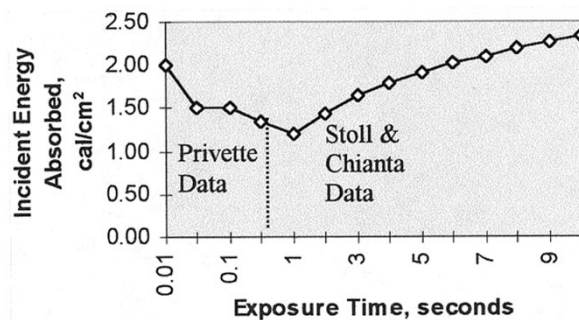


Fig. 10. Human tissue tolerance to second-degree burn. Second-degree burn energy limits.

dent energy in Table II exceeds 1.2 cal/cm², then the possibility exists for a second-degree burn of human skin.

Figs. 11–16 depict measured incident energy 18 in from the three-phase arc as a function of available bolted-fault current for each tested current-limiting fuse. Beginning with a 2000-A Class L fuse and working down to a 400-A Class RK1 fuse, these graphs show that once the current-limiting threshold is reached, the incident energy is dramatically reduced. For example, for 800-A Class L fuses (Fig. 14), the incident energy dropped below 0.5 cal/cm² when the available bolted-fault current reached 44 100 A, and continued below that level at 69 500 and 106 000 A available. At 22 600-A bolted-fault current, the 800-A fuses were not as current limiting, showing a worse case incident energy of 1.54 cal/cm². Further testing could determine the actual point at which the 800-A fuses limit the arc energy to below 1.2 cal/cm², somewhere between 22 600 and 44 100 A. Fig. 15 shows similar information for a 600-A Class RK1 fuse. In this case, since the fuse was smaller than the previous example, it should be current limiting at a lower bolted-fault current. The tests proved this to be true. For all values of available

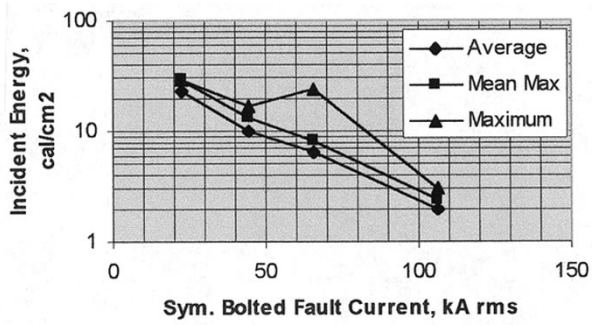


Fig. 11. Incident energy 18 in from three-phase arc downstream of 2000-A Class L fuse.

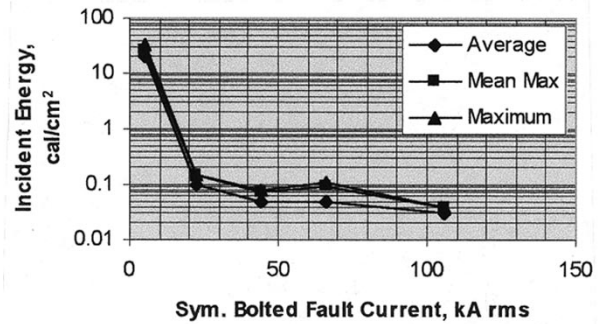


Fig. 15. Incident energy 18 in from three-phase arc downstream of 600-A Class RK1 fuse.

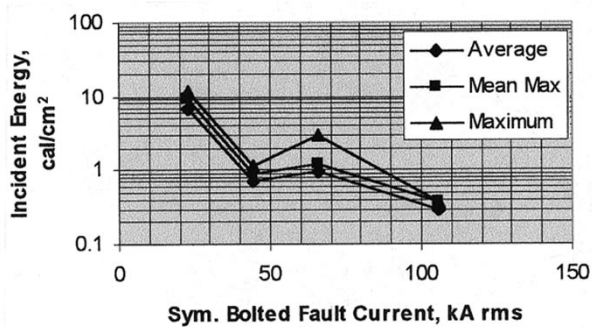


Fig. 12. Incident energy 18 in from three-phase arc downstream of 1600-A Class L fuse.

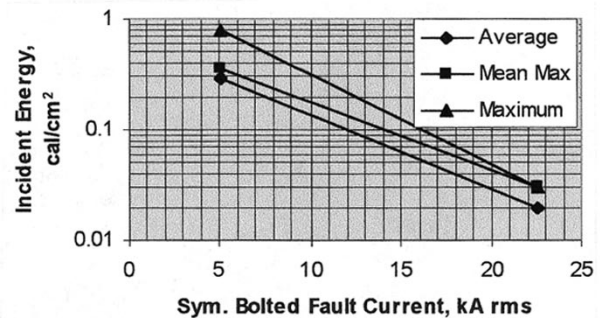


Fig. 16. Incident energy 18 in from three-phase arc downstream of 400-A Class RK1 fuse.

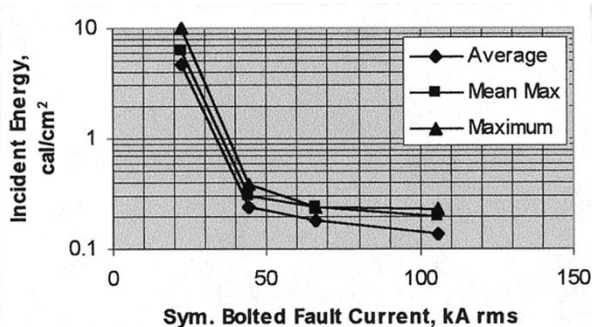


Fig. 13. Incident energy 18 in from three-phase arc downstream of 1200-A Class L fuse.

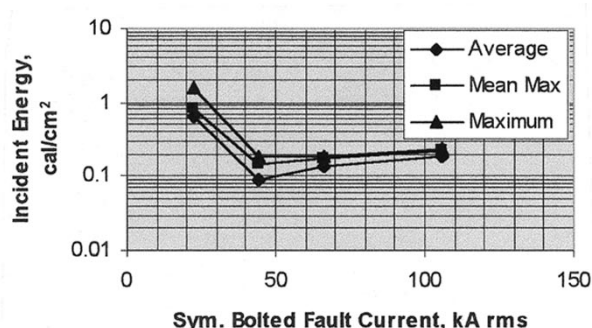


Fig. 14. Incident energy 18 in from three-phase arc downstream of 800-A Class L fuse.

fault amperes, the fuses were not in their current-limiting range, did not interrupt the fault within the allotted time, and the test operator interrupted the fault. Again, further testing could point out the actual point where the 600-A fuses begin to dramatically reduce the arc energy, somewhere between 5040–22 600 A.

V. FUSE ARC INCIDENT ENERGY PROTECTION LIMITS

Test data provide an indication of the boundary limits on fuse operation to minimize the risk of second-degree burn to human skin. Figs. 11–16 clearly indicate that, if a current-limiting fuse is not operating in the current-limiting region, the clearing time is significantly longer than 1/2 cycle, and there is increased incident energy produced from the three-phase arcing fault downstream of the fuse. When current-limiting fuses are applied, it is important for the user to understand the limits of protection from arc-flash energy that apply to the specific fuse in use. Fig. 17 is a copy of the fuse let-through chart shown in Fig. 1 with the addition of vertical dashes on each fuse curve indicating where the second-degree burn limit (1.2 cal/cm²) is reached for all test fuses except the 400-A Class RK1 fuse. To minimize the possibility of second-degree burn to bare skin of humans located no closer than 18 in from a three-phase arcing fault, the available symmetrical bolted-fault current intersection with the fuse line should be on the right side of the intersecting vertical dash.

Readers should be aware that data provided in Fig. 17 are based only upon measured incident energy under specified test conditions. Real arc exposures may be more or less severe than these laboratory-simulated arc exposures. The potentially hazardous effects of molten copper splatter, projectiles, pressure

symmetrical bolted-fault current above 22 600 A rms, the incident energy was 0.15 cal/cm² or less. At 5040 available bolted-

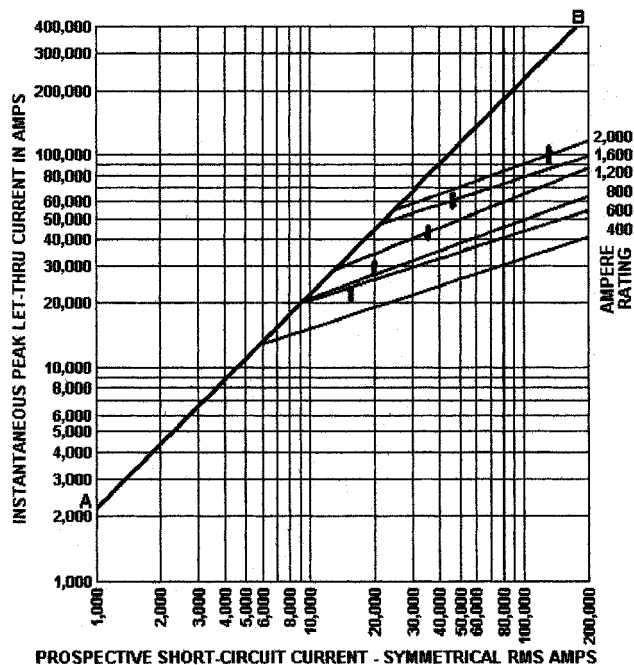


Fig. 17. Current-limiting fuse second-degree burn limit.

impulses, and toxic arc byproducts have not been considered in the test results or the analysis.

When using Fig. 17, be sure to determine the available symmetrical bolted-fault current at the potential location for the three-phase arcing fault. Any impedance between the fuse and the location of the fault must be included in determining the available bolted-fault current. For example, assume a 1200-A Class L fuse is installed in a fused low-voltage switchgear circuit breaker on the secondary side of a unit substation transformer. The available bolted-fault current on the line side of the circuit breaker is 65 000 rms symmetrical amperes. A long cable feeder is installed from the low-voltage switchgear feeder breaker to a remote motor control center. The available bolted-fault current on the motor control center main bus is calculated to be 45 000 rms symmetrical amperes. The design engineer wants to know if the risk of second-degree burn to the bare skin of personnel located 18 in away from the conductors in the main switch compartment of the motor control center has been minimized in the event of a three-phase arcing fault. Using 45 000 symmetrical rms amperes, the available bolted-fault current at the fault location, enter Fig. 17 and move up until the 1200-A Class L fuse line is intersected. The intersection is to the right of the second-degree burn limit mark, so the potential for a second-degree burn from this hypothetical exposure has been minimized.

The test data for Class L fuses in Figs. 11–14 were interpolated to find the minimum available bolted-fault current that is required to minimize the possibility of second-degree burn to a person wearing Class 1 FR clothing, who is located no closer than 18 in from a three-phase arcing fault on a 600-V power system. Table III lists the minimum symmetrical bolted-fault currents to minimize the possibility of second-degree burn to a person with bare skin or to a person who is wearing Class 1 FR Clothing (arc thermal performance value (ATPV)-5 cal/cm²).

TABLE III
CLASS L FUSE—MINIMUM AVAILABLE BOLTED FAULT CURRENT TO MINIMIZE THE POSSIBILITY OF SECOND-DEGREE BURN AT 18 IN

System Description	Minimum Available Prosp. S. C. Current @ Fault Loc. To Minimize The Possibility Of 2nd Degree Burn @ 18"			
	Cl. L Fuse 2000A	Cl. L Fuse 1600A	Cl. L Fuse 1200A	Cl. L Fuse 800A
Bare				
Human Skin 1.2 cal/cm ²	130 kA sym.	45 kA sym.	35 kA sym.	20 kA sym.
Class 1 FR Clothing 5 cal/cm ²	80 kA sym.	30 kA sym.	25 kA sym.	15 kA sym.

This table indicates that, as fuse size increases, higher available short-circuit current is required to minimize the possibility of a second-degree burn (insuring that the fuse operates in the current-limiting region).

VI. USING LOW VOLTAGE SWITCHGEAR FUSED BREAKERS AND FUSED SWITCHES FOR ARC-FLASH PROTECTION

Low-voltage switchgear breakers and fused switches are often applied with listed current-limiting fuses. The current-limiting fuses increase the interrupting rating of the fuse-breaker assembly, and also have the side benefit of reducing the let-through energy in the event of a fault on the downstream side of the switch or breaker. (It is more difficult to predict results if “limiters” are utilized with switchgear breakers because the “limiters” do not typically have the let-through limits specified in the 248 series of fuse standards.) Using Table III, a power system designer can calculate the maximum length of a motor control center feeder (supplied from a fused low-voltage switchgear breaker or disconnect switch) to minimize the possibility for a second-degree burn to bare skin of personnel located 18 in away from an arcing fault on the main bus in the motor control center.

Table IV shows a tabulation of the maximum length of a motor control center (MCC) feeder to minimize the possibility of a second-degree burn to a person's bare skin located 18 in from an arcing fault on the 600-V MCC bus. The MCC feeder consists of two parallel 3/C-500-kcm cables. Maximum distances are shown for various substation transformer sizes. The available symmetrical bolted fault on the primary side of the substation transformer was assumed to be 500 MVA. Table V shows similar information for a person wearing a Class 1 FR clothing system as defined in [3].

VII. SYSTEM GROUNDING CONSIDERATIONS

In practice, the majority of faults experienced in industrial low-voltage systems are phase-to-ground faults. For solidly grounded wye systems, low-level phase-to-ground faults can easily burn down 480/277-V systems unless ground-fault protection is provided. This is the reason for NEC Section 230-95. While equipment ground-fault protection will not limit the magnitude of the arcing fault, it may limit the duration (if

TABLE IV
MAXIMUM 600-V MCC FEEDER LENGTH (2-3/C 500 KCM) TO MINIMIZE
SECOND-DEGREE BURN OF BARE SKIN AT A DISTANCE OF 18 IN FROM ARC

Transf. KVA	Maximum Feeder Length, Ft., To Minimize 2nd-Degree Burn Of Bare Skin @ 18"			
	Cl. L Fuse 2000A	Cl. L Fuse 1600A	Cl. L Fuse 1200A	Cl. L Fuse 800A
	1000	none	none	none
1500	none	none	none	275
2000	none	none	50	395
2500	none	25	130	460
3000	none	80	185	505
3750	none	130	230	550

TABLE V
MAXIMUM 600-V MCC FEEDER LENGTH (2-3/C 500 KCM) TO MINIMIZE
SECOND-DEGREE BURN OF A PERSON WEARING CLASS 1 FR CLOTHING
AT A DISTANCE OF 18 IN FROM ARC

Transf. KVA	Maximum Feeder Length, Ft., To Minimize 2nd-Deg. Burn with Cl. 1 FR Clothing @ 18"			
	Cl. L Fuse 2000A	Cl. L Fuse 1600A	Cl. L Fuse 1200A	Cl. L Fuse 800A
	1000	none	none	none
1500	none	none	110	530
2000	none	130	240	645
2500	none	205	310	710
3000	none	255	355	750
3750	none	300	400	795

the relay operates instantaneously) and may prevent the fault from going phase-to-phase. Ground-fault protection will do nothing for a phase-to-phase, phase-to-neutral, or three-phase arcing fault. However, the use of current-limiting fuses for high-level phase-to-phase, phase-to-neutral, three-phase, and phase-to-ground arcing faults, and ground-fault protection for low level phase-to-ground faults, would seem to be an optimum combination of devices for minimizing arc-flash hazards for solidly grounded systems.

Typically, for high-resistance grounded systems, the first phase-to-ground fault will be of such a low current value that no damage occurs, the phase overcurrent protective device does not open, and the plant continues to run. Ideally, the ground detectors, which are required by the NEC to be installed on the system, alert the maintenance crew to go out and fix the first fault, before a second fault occurs. While there are some issues with single-pole interrupting ratings of multipole molded-case circuit breakers, high-resistance grounded systems are an excellent choice for continuous process industrials where qualified maintenance personnel are available on a 24-hour basis. The high-resistance grounding scheme will do nothing for phase-to-phase or three-phase arcing faults, but the combined use of high-resistance grounding for ground faults and current-limiting fuses for phase-to-phase and three-phase arcing faults is an effective way to minimize arc-flash hazards.

While many new industrial installations are being installed with high-resistance grounded systems, it was common practice many years ago to install ungrounded systems. Because there are so many ungrounded plants still in existence, and because these plants are still undergoing expansion, it is essential that the engineer also understand the effects of ungrounded systems on arc-flash hazards. Typically, for ungrounded systems, the first phase-to-ground fault will also be of such a low current value that no damage occurs, the phase overcurrent protective device does not open, and the plant continues to run. While ground detectors are not required by the NEC, they are really a necessity in order to alert the maintenance crew of the first fault to ground, so that the fault can be found and removed before a second ground fault occurs (The second fault to ground from another phase is actually a phase-to-phase fault and, therefore, can be of a very high magnitude). There are similar issues with the single-pole interrupting rating of multipole molded-case circuit breakers used on these systems and issues with high transient voltages on the other phases during arcing conditions. As with high-resistance grounding schemes, ungrounded systems will not affect phase-to-phase or three-phase arcing faults, but the combination of an ungrounded system for ground faults and current-limiting fuses for phase-to-phase and three-phase arcing faults minimizes arc-flash hazards.

Another grounding scheme that was quite popular, and is still being used, is the corner-grounded delta system. One corner of the delta is intentionally grounded, and has no overcurrent protection in that phase. (A fuse can be used in the grounded phase if it is providing motor running (overload) protection, or a three-pole circuit breaker can be used if all three poles open simultaneously.) The advantage of such a system is that 1/3 of potential ground faults are eliminated because one phase is already intentionally grounded. Faults from either of the other two energized phases are at full line-line voltage and require overcurrent devices capable of handling the phase-phase voltage across only one pole. While the corner-grounded delta system offers help by eliminating 1/3 of the phase-to-ground faults, and no help for energized phase-to-phase or energized phase-to-ground faults, the addition of current-limiting fuses for phase-to-phase and three-phase arcing faults also minimizes arc-flash hazards associated with these systems.

VIII. CONCLUSIONS

A test program has been conducted to examine the let-through characteristics of current limiting fuses when located upstream of a three-phase arcing fault. The effects of arc impedance and fuse current limitation in reducing available bolted-fault current have been quantified. Incident energy 18 in from a three-phase arcing fault in a 20-in cubic box downstream of a current-limiting fuse has been measured. The benefit provided by correctly applied current-limiting fuses in minimizing second-degree burn of human skin has been verified.

When low-voltage switchgear utilizes fused switches or circuit breakers with properly sized Class L fuses, and the motor control center feeder length is limited as indicated in Table IV, then the probability of an electrical worker receiving flash burns on bare skin from arcing faults at a distance of 18 in from the

motor control center is minimized. From a design viewpoint, such an electrical system would be optimized by reducing the potential arc-flash hazard to a practical minimum without requiring the purchase of arc-resistant motor control equipment.

Results of the test program indicate that correctly applied current-limiting fuses are an effective measure to reduce potential exposure to thermal hazards associated with arc flash. If proper application of current-limiting fuses is coupled with the use of high-resistance grounded systems, ungrounded systems, corner-grounded delta systems, or solidly grounded wye systems with ground-fault protection, the potential for arc-flash injuries and equipment downtime from arcing faults on 600-V electric power systems can be minimized.

ACKNOWLEDGMENT

The authors would like to thank M. Bowler, T. Curran, J. Finch, A. Thiesing, T. Bommarito, J. Maricic, E. Fitzwalter, T. Majers, and T. Hudson of the Bussmann Paul P. Gubany Center for invaluable assistance provided.

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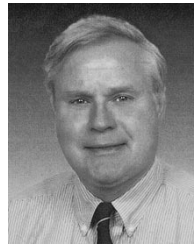
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