

# ARCING FAULT CURRENT AND THE CRITERIA FOR SETTING GROUND FAULT RELAYS IN SOLIDLY-GROUNDED LOW VOLTAGE SYSTEMS

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**Abstract**-In the 1960's numerous damages were documented on 480V, 3-phase, 4-wire power systems due to arcing ground faults. To alleviate this problem, the National Electrical Code (NEC) now requires ground fault protection in low voltage switchgear with continuous current ratings above 1,000A and operating at more than 150V phase-to-ground on solidly-grounded systems. However, burn down damage and personal injury continues to occur. This paper provides a simplified technique to accurately estimate this arcing fault current, and discusses its effects on the settings of relays and interrupting devices utilized in low voltage systems. It suggests that the criteria for setting the ground fault sensing devices should be changed to accommodate the maximum allowable exposure of personnel to arc flashes that may occur in the system. This is a much stricter guideline than that currently required by the NEC.

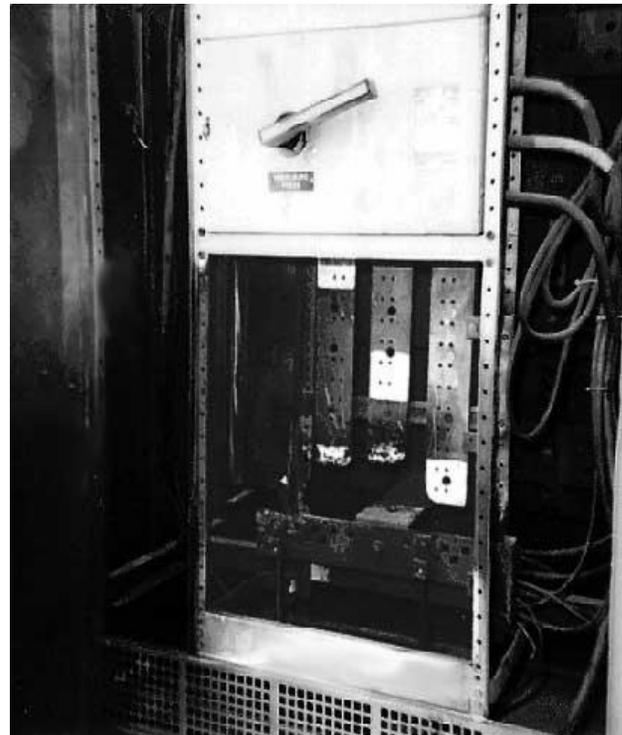
*Index Terms*-Low Voltage Protection, Safety Practices, Arcing Ground Faults.

## INTRODUCTION

The most common type of faults on low voltage 480V power systems are comprised of phase-to-ground with arcing. Figure 1 shows the result of such an arcing ground fault on a 2000A, 480/277V fused switch unit, which was not cleared properly.

This switchboard was installed in compliance with the National Electrical Code (NEC) and was protected by a ground fault relay. However, the overall protection was inadequate to properly protect either the equipment or personnel. Judicial selection of proper protective devices and relay settings can greatly reduce the possibility of damage and injury caused by similar arcing faults.

This paper suggests a simplified method of calculating the fault current in circuits containing an electric arc and shows



**Fig. 1. Arc Damage**

how this information should be used in selecting and setting protective devices. The present NEC requirements are inadequate and need to be changed to further protect against the type of damages still seen in 480V solidly-grounded system.

## OVERVIEW

In low voltage systems, typically the 3-phase bolted fault current (usually the highest possible level) is computed and, based upon this value, the system is designed. The protective devices must be capable of interrupting this current and the equipment must also be able to withstand this value during the time needed to interrupt. However, an arcing fault, in general, results in much lower levels of

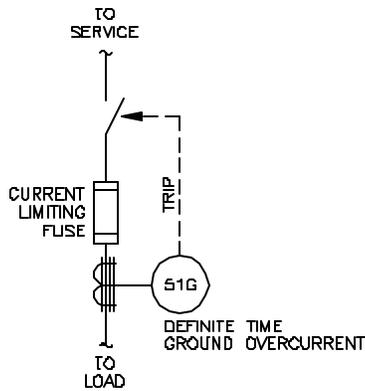
current. Fuses and relays designed to operate at 3-phase bolted levels may not properly respond to these lower values allowing an arcing fault to persist until severe burn down damage occurs.

The most commonly used protective devices in low voltage systems are:

1. Current limiting fuses with manually operated disconnect switches.
2. Molded and insulated case breakers with series trip elements only.
3. Low voltage power circuit breakers with ground fault sensing relay.
4. Current limiting fuses with manually operated disconnect switches which may be opened electrically by a ground fault relay.
5. Molded and insulated case circuit breakers with shunt trip devices operated by a ground fault relay.

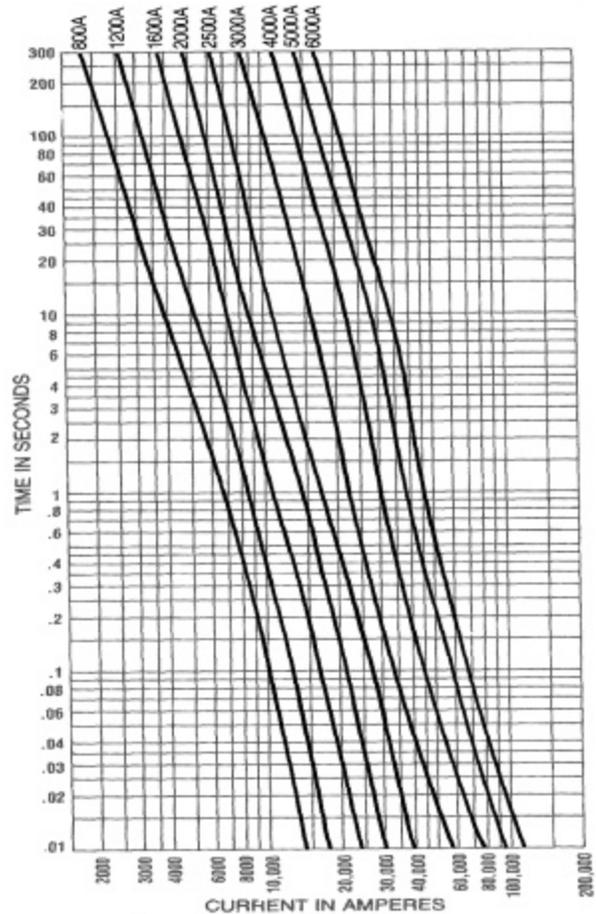
Since 1972, the NEC has allowed only the last three types of devices in service entrance equipment rated 1000A and above.

Figure 2 shows the one-line diagram for a current limiting fused switch with a ground fault relay (item no. 4 above).



**Fig. 2. Fused Switch With Ground Fault Relay**

During a low level fault, such as an arcing ground fault, the relay will sense the ground current, send a trip signal to the electric release on the fused switch, and the switch will open clearing the fault. The operating time of the switch, after receiving a signal to trip, is typically 5 to 7 cycles. The interrupting rating of the switch is quite limited, often much less than the available fault current. Therefore, during a high level fault, such as a 3-phase bolted fault, the switch must not be allowed to clear the fault. For this type of fault the current limiting fuses will operate and clear the fault.

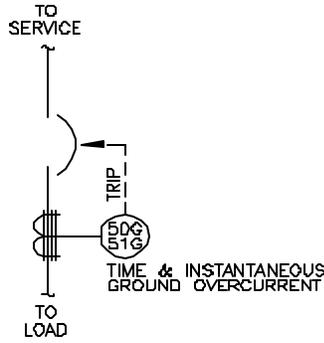


**Fig. 3. Typical Time-Current Curves Current Limiting Fuse**

The opening time of the switch must be intentionally delayed to allow the fuses to clear any fault above the interrupting rating of the switch. This restriction prevents an instantaneous setting for the ground fault relay.

The coordination problem becomes clearer after examining Figure 3, which shows the time-current curves for a common type of current limiting fuse. If the switch has an interrupting rating of 22 kA, and a 2,000A fuse is used, the fuse must clear any fault above 22 kA. According to Figure 3 at 22 kA the fuse will open in 0.1 seconds (6 cycles). If we assume no coordination time between the fuse operating time and the time it takes the switch to begin to open, the switch opening would have to be delayed a minimum of 6 cycles to insure that the switch does not interrupt a fault above 22 kA. At lower fault levels generated by the arcing ground faults, the switch will operate before the fuse, even though it is delayed by 0.1 seconds.

Figure 4 shows the one-line diagram for a typical breaker with a ground fault relay (item no. 5 above). The operation



**Fig. 4. Breaker With Ground Fault Relay**

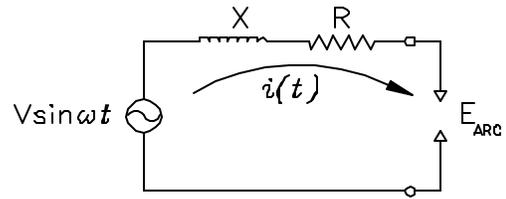
differs from the fused switch because the breaker is rated to interrupt the available 3-phase fault current and the device will clear all faults. No coordination is necessary between the phase tripping elements and the ground fault relay. Also, no delays are required and an instantaneous setting for the ground fault relay may be chosen, and a low voltage circuit breaker can clear a fault within 1/2 to 4 cycles of receiving a trip signal from the relay.

The most commonly used relays in low voltage systems have two settings. The current "pick-up" and the "time-delay" setting that determines the amount of time the pick-up current must persist before the relay will send a trip signal. The minimum "pick-up" value recommended by most manufacturers is between 100-200A primary. An instantaneous (with no intentional time delay) can be specified. However, most commonly the relay is supplied with a typical minimum delay setting of 0.05 to 0.1 seconds. In the case of a relay-operated fused switch, such as the one used on the gear shown in Figure 1, most manufacturers will offer a relay with a minimum time delay of at least 0.1 seconds.

### MATHEMATICAL MODELING AND FAULT CURRENT CALCULATION

It is often suggested that the available arcing ground fault current can be estimated by multiplying the bolted 3-phase fault current by some multiplier. Multipliers between 0.19 and 0.38 are often suggested for a 480V systems [4]. However, the rms value of the current can be calculated accurately by using the following method.

A typical electrical system can be modeled by its Thevinin equivalent circuit as shown in Figure 5.



**Fig. 5. Thevinin Equivalent Circuit With Arc Included**

With the arc included, the current  $i(t)$  through the circuit can be calculated [1] for the first half cycle as:

$$i(t) = \begin{cases} 0 & t \leq 0.0042 \text{ (s)} \\ \frac{V}{Z} [\sin(\omega t - \alpha) - A] - B & t > 0.0042 \text{ (s)} \end{cases} \quad (1)$$

Where:

$$A = e^{-\frac{R\omega}{X}(t-0.0042)} \sin(0.0042\omega - \alpha)$$

$$B = \frac{E_{ARC}}{R} \left( 1 - e^{-\frac{R\omega}{X}(t-0.0042)} \right)$$

$$\alpha = \arctan \frac{X}{R}$$

$$Z = \text{System Impedance} = \sqrt{R^2 + X^2} \text{ (}\Omega\text{)}$$

$$X = \text{System Inductive Reactance (}\Omega\text{)}$$

$$R = \text{System Resistance (}\Omega\text{)}$$

$$\omega = \text{System Frequency (rads/sec)}$$

$$E_{ARC} = \text{Arc Voltage (V)}$$

The value 0.0042(s) corresponds to an assumed arc re-strike time of 1/4 cycle and should give the minimum possible current in a circuit containing the arc [1].

The value of the arc voltage ( $E_{ARC}$ ) may be calculated as a function of the arc length and available 3-phase bolted fault current [2] using equation (2).

$$E_{ARC} = 36 + 2.4d + 3.2 I_p \quad (2)$$

Where:

$$d = \text{Arc Length (mm)}$$

$$I_p = \text{Available 3-Phase Bolted Fault Current at Arc (kA)}$$

Using equations (1) and (2), the minimum rms value of arcing fault current may be calculated for a single-phase-to-ground fault. The ground fault relay pick-up setting must be set to respond to this minimum rms value of the current.

TIME DELAY SETTING IN ARCING  
GROUND FAULT

Equipment of the type shown in Figure 1 is often used in commercial and light industrial facilities. The electricians installing and servicing this type of gear are often independent contractors, who seldom use protective clothing. The time delay should be set at the minimum possible value to prevent injury to any workmen involved in an arcing fault incident. This would also minimize the equipment damage.

Both personal injury and equipment damage have been correlated to the amount of energy produced by the arc. Equation (3) has been suggested [5] to estimate the incident energy delivered in  $t_A$  seconds, at a distance D, and due to an enclosed 3-phase arc with a length of 1.25 inches.

$$E_{MB} = 1038.7D^{-1.4738} t_A \left( 0.0093I_p^2 - 0.3453I_p + 5.9675 \right) \quad (3)$$

Where:

$E_{MB}$  = Maximum Incident Energy (cal/cm<sup>2</sup>)

$I_p$  = 3-Phase Bolted Fault Current (kA)

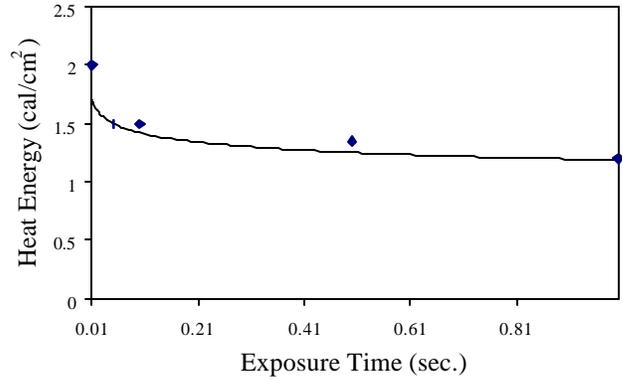
D = Distance from Arc Electrodes (in.)

Since this equation was developed for a 3-phase arc, it will yield a higher value of incident energy than would be delivered by a 1-phase arc. This will, in effect, produce a conservative result.

Figure 6 displays the previously published data [6] and shows the amount of incident energy exposure bare skin can tolerate for periods up to one second. From this data a conservative curve fit (also displayed in Figure 6) can be derived as given by Equation (4).

$$E_{MB} = 1.187 t_A^{-0.078} \quad (4)$$

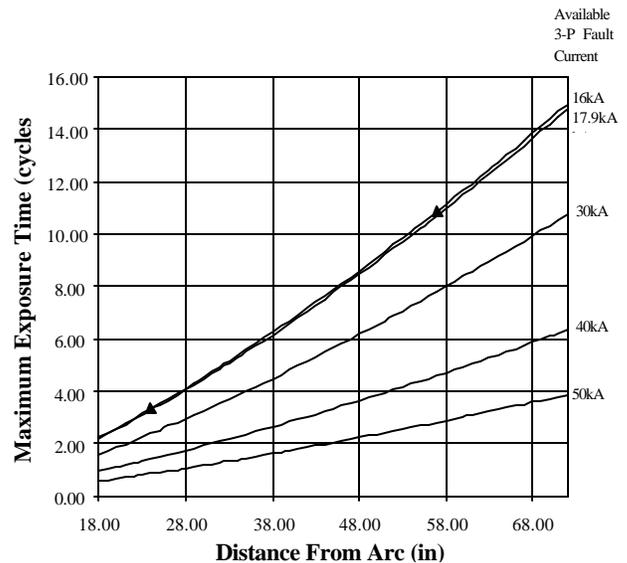
Substituting equation (4) into equation (3) and solving for time yields equation (5).



**Fig. 6. Human Tissue-Tolerance to 2nd Degree Burns**

$$t_A = 0.143D^{1.3671} \left( I_p^2 - 37.13I_p + 641.67 \right)^{-0.927t} \quad (5)$$

Equation (5) gives the maximum time (sec.) bare skin can be subjected to an arc at a distance D (inches) when the available 3-phase bolted fault current (kA) is  $I_p$ . To protect personnel from the effects of an electric arc inside switchgear, the time-delay setting of the relay plus the operating time of the breaker or switch must be faster than the time calculated from equation (5). The results of equation (5) for available 3-phase fault current levels between 16 and 50 kA are shown in Figure 7.



**Fig. 7. Maximum Exposure Time (16kA-50kA)**

Another factor that must be considered when setting the time-delay discussed above is the way the arcing fault can be expected to develop. Most arcing faults begin as single-phase-to-ground faults. Within the first two cycles air is ionized and metal vapors and other contaminants provide many low impedance paths to ground, thus developing additional arcs and the fault quickly becomes a 3-phase to-ground fault with multiple arcs. At this point, equations (1) and (2) are no longer valid. Also, the ground fault relay will not be as sensitive to a three-phase-to-ground fault as it was to a single-phase-to-ground fault. If the ground fault relay is to reliably interrupt the fault, it must sense and trip the breaker or switch within the first few cycles.

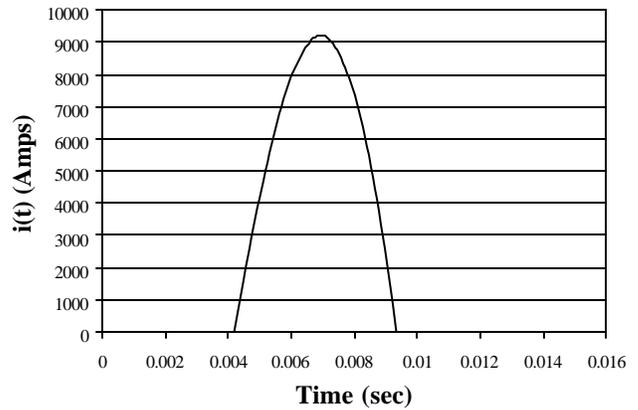
AN EXAMPLE

As an example let's use the system that resulted in the damage shown in Figure 1. The Thevinin impedance of the system up to the point of the arc was  $0.0031 + j0.0152$  ohms and the available fault current was calculated to be 17,856A. The length of the arc is assumed to be 1.25 inches. An analysis of the damage indicated that the fault began as a single-phase-to-ground fault and developed into a three-phase-to-ground fault before the fault was cleared. The switchboard was protected by 2,000A current limiting fuses and a ground fault relay, set at its minimum setting of 0.1 sec. (6 cycles) and a current pick-up value of 200A. No fuse operated during the fault, and the fault was eventually cleared when the relay caused the switch to open. The workman involved was not wearing any type of protective clothing and was severely burned and required skin grafts.

Using equation (2), the arcing voltage  $E_{ARC}$  is found to be 169.3V. The solution to equation (1) produces the current wave shown in Figure 8, for the first 1/2 cycle, and the calculated rms value is approximately 5,200A or 29% of the bolted 3-phase fault.

Since the ground fault relay was set to pick up at 200A, it should have easily sensed the current level encountered in the first half cycle of the single-phase fault. The pick-up setting of this relay could have been much higher. Using this same method, the available arcing fault current for the 480V circuit farthest from the service entrance was calculated to be 1,100A (rms). The suggested setting for this relay would be 80% of this value, or 880A, to detect an arcing ground fault anywhere in the 480V system.

An examination of Figure 7 reveals that for a workman 24 inches from the arc, the fault could persist for only 3.35 cycles before injury would occur. Adding the six cycle time delay built into the relay to an assumed five cycle operating time for the switch (for a total of 11 cycles) the workman



**Fig. 8. Arcing Current First 1/2 Cycle**

had to be approximately 57 inches away from the arc to escape injury.

Assuming that a workman may work within 24 inches of energized bus, it is clear that a ground fault operated fused switch, with an operating time of five cycles, would have been incapable of operating quickly enough to prevent injury even if the ground fault relay operated within the first 1/2 cycle. However, a circuit breaker, with an operating time of 1/4 4 cycles, and a ground fault relay with an instantaneous (1/4 cycle or less) setting may have operated quickly enough to prevent injury.

DISCUSSION

The question may be asked, why a ground fault relay with an instantaneous setting cannot be coupled with a fused switch? This would only be possible if the switch had an interrupting rating equal to the available fault current. These devices usually have an interrupting rating far below the available fault current level. A low-level ground fault (below the interrupting rating of the switch) will be sensed and cleared by the ground fault relay by opening the switch. In the case of fault current higher than the interrupting rating of the switch, the opening of the switch must be delayed until the fuses can clear the fault. This is the reason for the required minimum time delay. This condition prohibits the use of an instantaneous setting on this type of device. The NEC 230-95 (b): "If a switch and fuse combination is used, the fuses employed shall be capable of interrupting any current higher than the interrupting capacity of the switch during a time when the ground-fault protective system will not cause the switch to open," specifically allows this condition.

Also, in this class of protective and disconnecting devices, the fuse provides virtually no arcing ground fault protection. At the calculated arcing fault current value of 5,200A the fuse would take 200 seconds (3.3 minutes) to clear the fault

(Fig. 3). If the fault were allowed to escalate to a 3-phase fault, currents would increase, but would not be expected to approach the bolted fault level. In the example, even a bolted 3-phase fault would not produce enough current to enter the current limiting region of the fuse and the clearing time of the fuse would be 18 cycles. For a fuse to provide any protection against arcing faults the current must be high enough to enter the current limiting region of the time-current curve.

If the available phase-to-ground fault current had been higher than 30kA, the fuse shown in Figure 3 would have opened in less than  $\frac{1}{2}$  cycle. If a single fuse had sensed the fault and opened, the fault may still be fed from the other phases through connected equipment. Opening only one pole will not insure the fault will clear. After the first fuse opens, and if the fault is still being fed, the current can be expected to decrease. If it decreases below the current limiting region of the remaining fuses they cannot be expected to quickly clear the remaining fault. In order to quickly clear a single-phase-to-ground fault with fuses, the fault current must be high enough, in all modes in which the fault can exist, to open all fuses before injury and damage occur.

For a 2,000A current limiting fuse, an available 3-phase fault current of 130kA (sym.) is required for the fuse to open and limit the arc energy below the injury level [7]. This high level of available fault current is unlikely on a commercial 480V power system. For the available fault current in the example, a fuse as small as 800A would still have been too large to limit the arcing fault energy to a non-injurious level [7]. For this and other reasons discussed by Kaufmann and Dunki-Jacobs [8][9] fuses commonly found in service entrance equipment cannot be relied upon for arcing ground fault protection. A reliable, quickly acting, ground fault sensing and interrupting device is necessary to clear the fault, preferably before it can escalate into a three phase fault.

A close examination of Figure 7 shows that, for available fault currents above 50kA, the protective device must interrupt the current in less than  $\frac{1}{2}$  cycle to prevent injury to bare skin within 18 inches of the arc. The importance of protective clothing for anyone working near energized equipment is emphasized by the fact that even the fastest devices are unable to accomplish this at the current values expected during an arcing fault [6].

#### ARCING FAULTS AND THE NEC

It has long been recognized that, to prevent injury and minimize damage, an arcing fault must be cleared as quickly as possible. Whenever possible an instantaneous value

(without any intentional time delay) should be chosen for the ground fault time-delay setting. If the interrupting device is a fused switch, as discussed earlier in the example, that is not rated to interrupt the available fault current, the introduction of a time-delay becomes necessary. Once introduced, this time-delay will exist, not only during a high level fault which must be cleared by the fuses, but also during a low level fault (e.g. arcing ground fault) that could be cleared by the switch. This is undesirable since it allows arcing faults to persist longer and this may cause further damage.

It is recommended that the NEC should revisit this situation and may consider requiring the ground-fault-interrupting device be capable of interrupting all available fault currents, thus deleting section 230-95(b). This change would allow the fastest possible clearing of arcing ground faults preventing needless injury and minimizing damage.

It is also recommended that the relay settings guidelines be changed to accommodate the maximum allowable exposure to personnel of the arc flash available at the service entrance equipment, where potential for such injury is greatest. This is a much stricter guideline than currently appears in the NEC which allows a time-delay setting of up to 1.0 sec.

#### CONCLUSION

Due to the high potential for injury and damage historically associated with arcing ground faults in 480V service entrance equipment, care should be exercised in specifying the best interrupting device and ground fault protection. Proper "time-delay" and "current pick-up" settings must be provided to enable the protection scheme to detect and isolate arcing ground faults while not allowing nuisance tripping.

In order to specify and calculate proper settings for ground fault relays used in low voltage systems, the following steps are also recommended:

1. Estimate the likely minimum arc length. The bus to ground distance in the panel board or switch gear may be used as a good estimate.
2. Calculate the maximum bolted 3-phase fault current level at the arc location.
3. Calculate the arc voltage,  $E_{ARC}$  using equation (2).
4. Calculate the minimum arcing ground fault current (rms) at the service entrance, and at the point farthest from the service entrance needing ground fault protection (these may be the same point), using equation (1).

5. Set the relay “pick-up current” to 80% of the available arcing fault current at the farthest point from the service entrance (step 4).
6. Calculate the maximum time duration technical personnel can be exposed to the level of arcing fault current available at the service entrance, without serious injury, using equation (5) or estimate from Figure 7.
7. Set the “time delay” setting faster (lower) than the time calculated in step 6, remembering that this time is the sum of the intentional delay time plus the interrupting device operating time.

In most cases, a device needing an intentional time delay to prevent exceeding its interrupting rating will be inadequate to meet the necessary criteria. Therefore, the National Electrical Code should consider requiring that all ground-fault devices must be capable of interrupting the maximum available fault current.

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