0600DB0601
2/2007
Cedar Rapids, IA, USA

Data Bulletin

A Comparison of Circuit Breakers and Fuses for Low-Voltage Applications

Tony Parsons, PhD, P.E.,
Square D / Schneider Electric Power Systems Engineering

I. Introduction

Recent claims by fuse manufacturers regarding the arc-flash and simplified-coordination benefits of fuses do not tell the entire story regarding which type of device is “best” for a given power system. In reality, not only does the wide range of available circuit breaker types allow them to be successfully used on nearly any kind of power system, they can be applied so as to provide selective coordination, arc-flash protection, advanced monitoring and control features, all in a renewable device. This paper gives a feature-by-feature comparison of the merits of circuit breakers vs. fuses, discussing the relative merits of fuses and circuit breakers in each section. While both circuit breakers and fuses are available for application in systems that operate at higher voltage levels, the focus of this guide is on low-voltage systems operating at 600 V or below.

II. Basic Definitions and Requirements

Article 240 of the National Electrical Code® (NEC) [1] provides the basic requirements for overcurrent (i.e., overload, short-circuit, and/or ground fault) protection in a power system. Special requirements for overcurrent protection of certain types of equipment are also contained in other articles—for example, details on protection requirements for motors and motor circuits are given in Article 430, while transformer protection requirements are given in Article 450.

The NEC defines the two basic types of Overcurrent Protective Devices (OCPDs):

> ***fuse***—*An overcurrent protective device with a circuit-opening fusible part that is heated and severed by the passage of overcurrent through it.*
>
> ***circuit breaker***—*A device designed to open and close a circuit by nonautomatic means and to open the circuit automatically on a predetermined overcurrent without damage to itself when properly applied within its rating.*

The NEC also requires that circuits be provided with a disconnecting means, defined as “a device, or group of devices, or other means by which the conductors of a circuit can be disconnected from their source of supply.” Since fuses are designed to open only when subjected to an overcurrent, they generally are applied in conjunction with a separate disconnecting means (NEC 240.40 requires this in many situations), typically some form of a disconnect switch. Since circuit breakers are designed to open and close under manual operation as well as in response to an overcurrent, a separate disconnecting means is not required.

Both fuses and circuit breakers are available in a variety of sizes, ratings, and with differing features and characteristics that allow the designer of an electrical system to choose a device that is appropriate for the system under consideration.

Low-voltage fuses are available in sizes from fractions of an amp to thousands of amps, at voltage ratings up to 600 V, and with short-circuit interrupting ratings of 200 kA or more. Fuses are inherently single-pole devices (i.e., an individual fuse can only operate to open one phase of a multi-phase circuit), but two or three individual fuses can be applied together in a disconnect to protect a multi-phase system. Low-voltage fuses are tested and rated according to the UL 248 series of standards. Several types can be classified as current-limiting, which per the NEC definition means that they *"...reduce the current flowing in the faulted circuit to a magnitude substantially less than that obtainable in the same circuit if the device were replaced with a solid conductor having comparable impedance."* In other words, the current-limiting fuses open very quickly (within 1/2 cycle) in the presence of a high-level fault, allowing them to provide excellent protection for distribution system components or load equipment. Fuses can be applied in equipment such as panelboards, switchboards, motor control centers (MCCs), disconnect switches/safety switches, equipment control panels, etc.

Circuit breakers are also available with a wide range of ratings—10 A to thousands of amps, also with short-circuit interrupting ratings to 200 kA—and are available as 1, 2, 3, or 4-pole devices. The three basic types of LV circuit breakers are the molded-case circuit breaker (MCCB), low-voltage power circuit breaker (LVPCB), and insulated-case circuit breaker (ICCB). MCCBs are rated per UL 489, have all internal parts completely enclosed in a molded case of insulating material that is not designed to be opened (which means that the circuit breaker is not field maintainable), and can be applied in panelboards, switchboards, MCCs, equipment control panels, and as stand-alone disconnects inside a separate enclosure. LVPCBs, which are rated per ANSI standards and are applied in low-voltage drawout switchgear, are larger, more rugged devices that may be designed to be fully field maintainable. ICCBs can be thought of as a "cross" between MCCBs and LVPCBs—they are tested per UL 489 but may share some characteristics with LVPCBs, including two-step stored energy mechanism availability in drawout construction and partial field maintainability [2].

Both types of OCPDs can meet the basic requirements of the NEC, but are circuit breakers or fuses best suited for a particular application? Unfortunately, there is no simple answer to this question—several other factors must be taken into account, such as the level of protection provided by the OCPD, selective coordination requirements, reliability, renewability, and flexibility. The remainder of this guide will provide a discussion of each of these topics.

III. System Protection

As discussed above, both circuit breakers and fuses meet the basic NEC requirements for overcurrent protection of electric power distribution systems and equipment. Any type of OCPD must be sized and installed correctly after taking all derating factors and other considerations into account. Particularly for overloads and phase faults, both circuit breakers and fuses provide excellent protection and either is suitable for most applications. A bit more consideration is warranted for some other aspects of system protection, as discussed in the remainder of this section.

A. Ground-Fault Protection

Conventional wisdom states that the most common type of fault in a power system (by far) is a single-phase-to-ground fault. On solidly-grounded power systems, the available ground-fault current level can be significant. In some situations, ground fault current levels that are even higher than the maximum three-phase fault current level are theoretically possible. However, many ground faults produce only relatively low levels of fault current due to impedance in the fault path (due to arcing or to some other source of impedance from phase to ground). While such faults can cause significant equipment and facility damage if not cleared from the system quickly, phase overcurrent protective devices may not respond quickly to the lower fault levels—if they detect the fault at all. For example, an 800 A ground fault might simply appear as an unbalanced load to a 4000 A fuse or circuit breaker not equipped with ground-fault protection. Because of this, NEC 230.95 requires supplementary ground-fault protection on service disconnects rated 1000 A or more on solidly-grounded, wye systems operating at more than 150 V to ground but not more than 600 V phase-to-phase (e.g., 277/480 V systems). The NEC also defines special ground-fault protection requirements for health care facilities and emergency systems. See the appropriate NEC articles for more details.

Circuit breakers can be equipped with integral ground-fault protection through addition of either electronic trip units that act as protective relaying to detect the ground fault and initiate a trip, or through addition of add-on ground-fault protection modules. Ground-fault trip units typically use the current sensors internal to the circuit breaker to detect the ground fault condition, though an external neutral sensor is normally required to monitor current flowing on the neutral conductor in a 4-wire system. If desired, external relaying and current transformers (CTs) can also be used for ground-fault detection provided that the circuit breaker is equipped with a shunt trip accessory that can be actuated by the external relay.

By themselves, fuses cannot provide ground-fault protection except for relatively high-level ground faults. When ground-fault protection is required in a fusible system, the disconnecting means (usually a switch, sometimes a contactor) must be capable of tripping automatically, and external relaying and a zero-sequence CT or set of residually-connected phase CTs must be installed to detect the ground faults and send the trip signal to the disconnecting means.

While either system can function well if installed properly, extra care must be taken with a fusible system (or circuit breaker-based system with external ground relaying) to ensure that all external sensors are oriented correctly and that all sensor and relay wiring is installed correctly. Performance testing of the ground-fault system, as required in NEC 230.95(C) when the system is installed, should allow for identification of any installation issues.

B. Device Interrupting Ratings

NEC 110.9 states that “equipment intended to interrupt current at fault levels shall have an interrupting rating sufficient for the nominal circuit voltage and the current that is available at the line terminals of the equipment.” Protective devices that are inadequately rated for either the system voltage or available fault current levels present a safety hazard, as there is no guarantee that they will be able to interrupt faults without damage either to themselves or to other equipment in the system. This could result in extended downtime and present a significant fire hazard.

Several types of low-voltage fuses (class R, class J, etc.) carry interrupting ratings of 200 kA or more at up to 600 V. This is typically high enough to interrupt even the most severe fault in the “stiffest” system. In addition, since fuses are single-pole devices, their single-pole interrupting capability equals the full rating of the fuse. Note that the withstand rating of the equipment (e.g., panelboards, switchboards) in which fuses are applied may not always be equal to the ratings of the fuses themselves—equipment manufacturers should be consulted, particularly when system fault currents exceed 100 kA. Note also that some LV fuses have interrupting ratings as low as 10 kA, so care should always be taken to ensure that fuses selected are appropriate for the installation.

Circuit breakers of all types are also available with interrupting ratings up to 200 kA. In the not-too-distant past, fused circuit breakers were required to achieve the 200 kA interrupting ratings, but modern circuit breakers can achieve this rating without fuses. Circuit breakers with lower ratings are also available, typically at a lower cost. Circuit breakers have single-pole interrupting ratings that are adequate for installation on the majority of power systems, though special consideration may be required in some cases. See [3] for additional information.

C. Motor Protection

Overcurrent Protective Devices (OCPDs) in motor circuits have a relatively difficult job to perform. They must not trip on motor inrush current, but should be sensitive enough to provide both overload protection and short-circuit protection to the motor and its associated branch circuit. In many cases, the fuse/circuit breaker (or motor circuit protector—MCP which is essentially a molded-case circuit breaker with no overload element), is oversized to accommodate motor inrush current and a separate overload relay is added that will open the motor contactor during overload conditions. These two devices then combine to provide overload and short-circuit protection for the motor circuit.

Motors can also be damaged by conditions other than short-circuits and overloads. On three-phase systems, one of the most problematic abnormal conditions is system voltage unbalance, which can cause an increase in phase currents and create high negative-sequence currents that flow in the motor windings. Both of these cause increased heating in the motor windings, which can cause insulation degradation or breakdown that can ultimately result in failure of the motor. Unbalance from system sources such as unbalanced load in a facility or voltage unbalance on the utility system is potentially problematic whether circuit breakers or fuses are used as motor OCPDs. However, the use of fuses has the potential to produce a severe unbalance condition commonly referred to as *single-phasing*.

Single-phasing occurs when one phase in a three-phase motor circuit opens but the other two phases remain in service. If the single-phasing occurs upstream of the motor but at the same voltage level, then zero current flows on the phase with the open fuse and elevated current levels flow in one or both of the remaining phases, depending on whether the motor is wye or delta-connected. Single-phasing on the primary side of a transformer feeding the motor can produce elevated currents in all three phases, with two being slightly elevated and the third current roughly double that of the other two.

To help guard against motor damage or failure due to single-phasing:

- Use a circuit breaker-based protection system. If properly maintained, all three phases of a circuit breaker will open in response to a fault or overload, so single-phasing in the facility will be far less likely to occur. However, note that if the utility supply is protected by fuses, this possibility still exists.
- Apply phase-failure or current unbalance relaying, either at the facility main (in smaller installations) or at high-value loads (e.g., larger motors that are more expensive to replace, critical loads where the downtime associated with a motor failure cannot be tolerated, etc.)
- Size motor circuit fuses closer to the full-load current rating of the motor. One fuse manufacturer recommends sizing dual-element, time-delay fuses at 100–125% of the motor's actual load level (not the nameplate rating) to provide better levels of protection against damage resulting from single-phasing [4]. Note that this does not eliminate the possibility of single-phasing occurring, and could increase the possibility of nuisance fuse operation on sustained overloads. In applications where loading on a particular motor varies widely, or in new facilities where actual current draw of a motor may not be known, sizing the fuses properly could be a challenge. Application of external relaying at high-value loads may still be warranted.

D. Component Protection

One of the great advantages of a current-limiting overcurrent protective device is that it can literally limit the peak magnitude of fault current that flows through it by opening within the first half-cycle after fault initiation, before the fault current has a chance to reach its peak value. This helps provide a degree of protection for downstream equipment that could otherwise be damaged by the magnetic or thermal effects produced by the high-level faults. Several types of low-voltage fuses are current-limiting to one degree or another. Highly current-limiting fuses for special applications, such as semiconductor fuses that are designed to protect power electronic equipment, are also available. Same is true of breakers, only that fuses are often more current-limiting.

Current-limiting molded-case circuit breakers are also available in a range of sizes and with interrupting ratings of 200 kA. As with current-limiting fuses, these circuit breakers are tested to determine the peak-let-through current (i_p) and let-through energy (i^2t). While these circuit breakers are not as current-limiting as the faster-acting current-limiting fuses (e.g., class J or class RK-1), they do provide a degree of protection beyond that of a non-current-limiting circuit breaker or fuse, and may be appropriate for many applications.

Proper protection, whether of conductors, motors, or other equipment, depends on OCPDs being applied appropriately. This includes ensuring that devices are sized properly and that they are installed on systems where none of the equipment ratings are violated.

To help prevent misapplication of fuses, NEC 240.60(B) requires that fuseholders are designed to make it difficult to insert fuses intended for application on higher amperage or lower voltage circuits. Additionally, fuseholders intended for current-limiting fuses should reject insertion of a non-current-limiting fuse.

Switchboards and panelboards where circuit breakers are applied do not typically have rejection features that prevent installation of a circuit breaker that is of a compatible frame type but that has a lower interrupting rating.

Realistically, any device can be improperly applied—and improper use of protective devices is an application issue, not an equipment issue. In the “real world”, inadequately-rated circuit breakers can be installed, fuses of a given cartridge size but of a higher ampere rating can be installed into a rejection fuseholder, fuses can be replaced with “slugs” (produced by the manufacturer or of the “homemade” variety), or fuseholders or circuit breakers can be jumpered out altogether by a “creative” electrician with a relatively short length of wire. Proper selection, installation, and maintenance of all OCPDs are all key requirements in providing good system protection.

E. Arc-Flash Protection

With the increased interest in arc-flash hazards in recent years, the ability of OCPDs to provide protection against arcing faults has received much interest. The potential severity of an arc-flash event at a given location in a power system depends primarily on the available fault current, the distance of the worker away from the source of the arc, and the time that it takes the upstream OCPD to clear the arcing fault from the system. In many cases, little can be done about the first two factors—the available fault current levels depend on utility system contribution, transformer impedance values, etc.; while the working distance is limited by the fact that a worker working on a piece of equipment must, in most cases, be physically close to the equipment.

Proper selection and application of OCPDs can have a great deal of impact on the fault clearing time. Clearing the fault more quickly can provide a great deal of protection for workers, as the available incident energy is directly proportional to the duration of the arcing fault—i.e., the incident energy can be cut in half if the fault can be cleared twice as quickly. Equations appearing in IEEE Standard 1584-2002 [5] provide the present “state-of-the-art” methods for determining the arc-flash hazard levels in a system and for evaluating the impact of potential arc-flash mitigation options.

For low-voltage systems, which OCPDs provide the best protection against arc flash?

- Circuit breakers, with adjustable trip units that can be set to strike a balance between providing selective coordination and arc-flash protection?
- Current-limiting fuses, which can clear high-level faults very quickly and minimize damage to both equipment and personnel?

Unfortunately, there is no simple answer to this question, despite claims made by manufacturers of both types of OCPDs. In some cases, both circuit breakers and fuses provide excellent protection. There are situations when circuit breakers can perform better than fuses, and there are situations where fuses can perform better than circuit breakers. And there are situations where *neither circuit breakers nor fuses provide much arc-flash protection at all*, requiring either use of other means of protection (alternative system designs, installing systems that allow for remote operation of equipment, etc.) or a total prohibition of work on or near energized parts.

When evaluating OCPDs in terms of the arc-flash protection that they may provide, three general principles are important to consider:

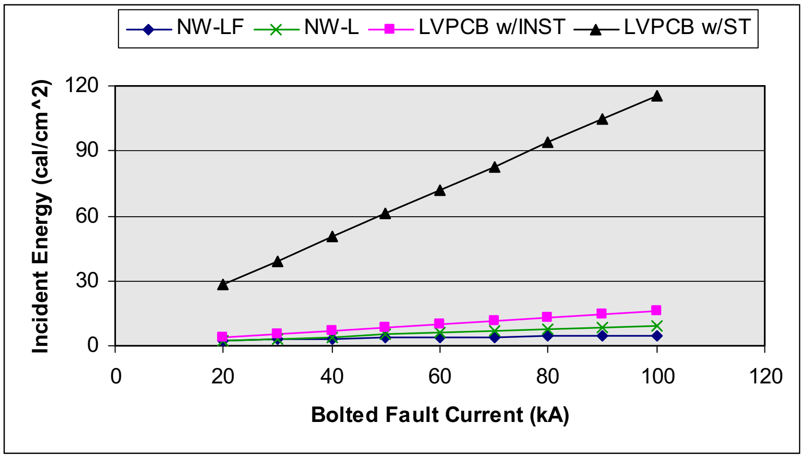
- Evaluate specific devices when possible
- Evaluate devices at the actual system fault current levels
- Evaluate adjustable-trip circuit breakers at their chosen settings

Evaluate Specific Devices

The IEEE 1584 standard contains three basic calculation models that can be used to determine arc-flash hazard levels—an empirically-derived, general model; simplified equations based on testing of current-limiting (class RK-1 and class L) low-voltage fuses; and simplified equations based on calculations performed on “typical” low-voltage circuit breakers. The general equations require information on available fault current levels in the system as well as knowledge of the trip characteristics of OCPDs in the circuit, but can provide accurate results for any type of OCPD and for a wide range of system conditions. The simplified circuit breaker and fuse equations require little to no knowledge of actual device trip characteristics, but differences in the way these equations were developed mean that they should not be used to conduct a direct “apples-to-apples” comparison of specific protective devices.

As discussed above, the simplified fuse equations are based on field testing of specific types of fuses, the simplified circuit breaker equations are based on classes of circuit breakers and on the assumption that the relevant trip settings are maximized, and not on specific devices or actual trip settings. The circuit breaker equations are meant to allow calculation of the “worst-case” arc-flash levels allowed by any example of a circuit breaker within a given class—e.g., 100–400 A MCCBs. If the IEEE 1584 empirical equations are used to calculate arc-flash levels downstream of such a circuit breaker, the values should never be higher than (and in many cases will be well below) those shown by the simplified circuit breaker equations. This is particularly true when using the equations to analyze larger LVPCBs—the simplified IEEE 1584 equations assume that the circuit breaker's instantaneous and/or short-time pickup and delay settings are set to the maximum levels, which can result in the calculation of very conservative arc-flash levels if the circuit breakers are actually set differently. For example, Figure 1 shows the incident energy levels vs. bolted fault current values for 2000 A circuit breakers in a 480 V, solidly-grounded system.

Figure 1: **Incident Energy vs. Bolted Fault Current for 2000 A Circuit Breaker’s Simplified Equations vs. Actual Data**



The “LVPCB w/ST” and “LVPCB w/INST” curves are based on the IEEE 1584 simplified equations for low-voltage power circuit breakers with short-time and instantaneous pickup, respectively. The “NW-L” and “NW-LF” curves show arc-flash values based on actual devices (2000 A Masterpact® NW-L and NW-LF circuit breakers set to trip instantaneously for an arcing fault, respectively).

As shown in the plot, the simplified equations (particularly for the “LVPCB w/ST” curve) are well above the results calculated based on the actual device characteristics. When possible, a comparison of the level of arc-flash protection a given device can provide, should be based on *actual* device characteristics, *not generic* equations.

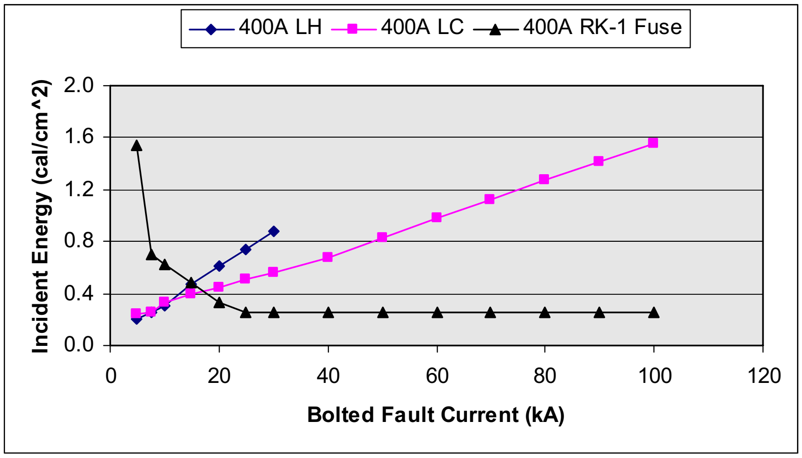
What is the system fault current range?

Current-limiting fuses can provide excellent protection and reduce the available incident energy downstream to minimal levels . . . as long as they are operating within their current-limiting range. For lower fault current levels, the arc-flash levels can elevate.

Thermal-magnetic MCCBs can provide excellent protection as long as they trip instantaneously, but arc-flash levels can escalate for low-level faults that require operation of the thermal element to clear the arc. For higher levels of fault current, RK-1 and L fuses tend to allow a lower level of incident energy than a similarly-sized circuit breaker, but both devices provide an excellent level of protection—allowing for the use of Category 0 PPE in many cases.

For example, see Figure 2, which shows incident energy levels vs. bolted fault current for a 400 A Square D® LH circuit breaker, a 400 A Square D LC circuit breaker, and a 400 A class RK-1 low-voltage fuse. The circuit breakers are assumed to trip instantaneously.

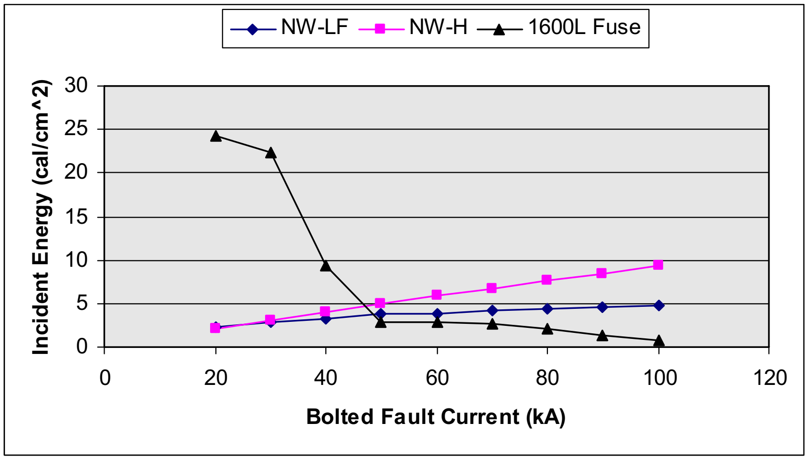
Figure 2: Incident Energy vs. Bolted Fault Current for 400 A Circuit Breakers and 400 A Class RK-1 Fuses.



As shown in Figure 2, the relative performance of the circuit breakers is better for low-level faults, while the incident energy allowed by the fuses is lower for higher fault current levels. However, the incident energy levels for each device over the entire range of fault currents considered is less than 2.0 cal/cm^2 —the maximum level allowed for Category 0 PPE [6], indicating that both circuit breakers and fuses provide excellent protection.

For larger devices, the relative performance of circuit breakers and fuses follows these same guidelines, though the impact can be quite a bit larger. See Figure 3, which shows the incident energy levels allowed by 1600 A Class L current-limiting fuses, as well as two varieties of 1600 A Masterpact® NW circuit breakers. Again, the circuit breakers are assumed to trip instantaneously for an arcing fault so circuit breaker settings must be considered, (see “Consider Circuit Breaker Settings” below), but this does show that 1600 A circuit breakers can perform significantly better than fuses for systems with relatively low available fault current levels.

Figure 3: Incident Energy Comparison for 1600 A Protective Devices



Consider Circuit Breaker Settings

For circuit breakers with adjustable trip settings, proper selection of setting levels is important for both arc-flash protection and for system coordination.

The best protection will be provided when the circuit breakers can be set to trip instantaneously. Little to no protection may be provided by a circuit breaker when the settings are blindly set to maximum, as is sometimes done after a “nuisance trip” of the device. Arc-flash studies can be performed to determine optimum settings for circuit breakers and other devices in a system, but even then, it may not be possible to reduce circuit breaker settings below a certain level to provide additional arc-flash protection if system coordination is to be maintained.

However, an adjustable circuit breaker still gives the flexibility to provide arc-flash protection in such situations, if only on a temporary basis. For example, the instantaneous pickup level of a circuit breaker feeding an MCC can be turned down to the minimum setting when workers are present at the MCC, then turned back up when work is complete. This could allow the circuit breaker to trip instantaneously and provide the best possible level of protection at the MCC when workers are present and exposed to the hazard, while the normal setting allows for proper coordination during normal operation. While this can provide an obvious benefit, it also has its drawbacks, including:

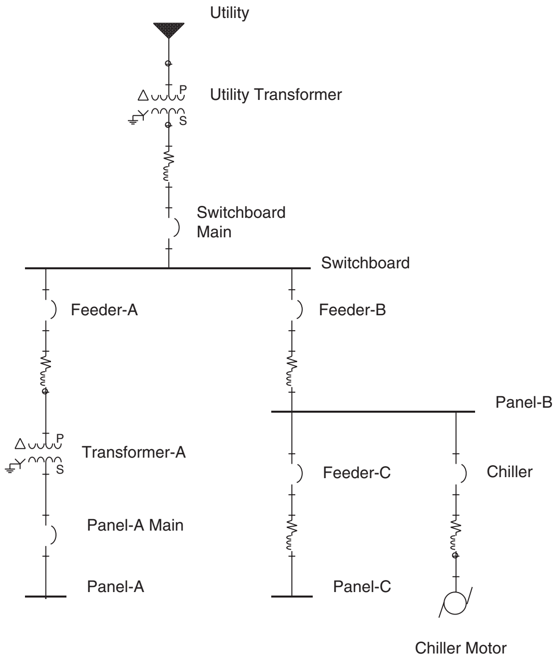
- Requirement for analysis to determine to what level the circuit breaker settings should be reduced to provide additional protection, as well as what level of protection is actually provided.
- Uncertainty over how to provide arc-flash warning labels for such a location—should labels show the available incident energy and required PPE with the “normal” circuit breaker settings, the reduced settings, or both?
- Temporary loss of selectivity can become semi-permanent if the circuit breaker settings are not restored to normal when work is complete.

While a full discussion of issues surrounding arc-flash hazards and their mitigation is beyond the scope of this paper, many other references are available which discuss the subject in more depth, including [7] and [8].

IV. Selective Coordination

Selective coordination of overcurrent protective devices is required to ensure that two somewhat mutually-exclusive goals are met—faults should be cleared from the system as quickly as possible in order to minimize damage to equipment, while the act of clearing the faults from the system should interrupt power to as small a portion of the system as possible. Selective coordination is defined in the NEC as "localization of an overcurrent condition to restrict outages to the circuit or equipment affected, accomplished by the choice of overcurrent protective devices and their ratings or settings." See the simple power system shown in Figure 4, which will be used to illustrate a few example cases.

Figure 4: Sample One-Line Diagram



Suppose that a foreign object produces a bus fault on the main switchboard. The Switchboard Main circuit breaker will detect the fault, then open to clear it from the system—and interrupt power to the entire facility in the process. However, since there are no protective devices (not including those on the utility system) upstream of the main circuit breaker, this device operates as intended and coordination is not an issue. If the fault occurs at Panel-C instead, then the Feeder-C circuit breaker—and only the Feeder-C circuit breaker—should open to clear the fault. If so, then Feeder-C is said to be selectively coordinated with both of the upstream OCPDs that would also carry the fault current. If the switchboard main circuit breaker opens either before or at the same time as Feeder-C, then power is unnecessarily interrupted to other parts of the system—namely, Panel-A, Panel-B, and the Chiller Motor—and the system is not selectively coordinated.

In some situations, even though individual devices are not coordinated, the *system* may still be considered to be well-coordinated. Referring again to Figure 4, consider a fault at Panel-A. The Feeder-A circuit breaker on the primary side of the step-down transformer and the Panel-A Main circuit breaker on the transformer secondary will typically not coordinate well with each other—that is, for a fault at the Panel-A main bus, either or both of the panel main circuit breaker and the transformer feeder circuit breaker may open to clear the fault. However, since the two devices are in series, operation of either/both devices interrupts power to the exact same portion of the power system—namely, Panel-A. In this case, the system is coordinated as long as the Feeder-A circuit breaker coordinates with the switchboard main and the Panel-A Main circuit breaker coordinates with branch devices in Panel-A, even though the two devices, strictly speaking, do not coordinate with one another.

Selective coordination, while always desirable, is not required by the NEC except in certain situations:

- In health-care facilities, per NEC 517.17(C): “Ground-fault protection for operation of the service and feeder disconnecting means shall be fully selective such that the feeder device, but not the service device, shall open on ground faults on the load side of the feeder device.”
- In elevator circuits when more than one elevator motor is fed by a single feeder. See NEC 620.62.
- In emergency and legally-required standby power systems (including those in hospitals and other health-care facilities where so required), per NEC 700.27 and NEC 701.18.

The requirements for selective coordination in emergency and legally-required standby systems, new in the 2005 edition of the NEC, call for each overcurrent device to be “selectively coordinated with all supply side overcurrent protective devices”.

This requirement can be problematic for system designers because it recognizes only device coordination and not system coordination, and because it means that special consideration must be given to circuit breaker-based systems.

Normally, coordination between devices on a time-current plot is demonstrated by “white space” on the plot between the devices—ideally, the upstream device's trip curve will appear above and to the right of the downstream device with no overlap between the curves. This indicates that the downstream device would trip first when both “saw” the same fault. Any overlap between devices indicates an area (i.e., a range of fault currents) where it cannot be conclusively determined, at least from examination of the plot, which device would trip first. For circuit breakers and relays, this graphical comparison of trip characteristics is the primary way that system coordination is assessed.

For fuses, coordination down to 0.01 second can be assessed by a comparison of trip curves, while fuse let-through characteristics must be compared to verify coordination beyond this point. Alternatively, tables produced by fuse manufacturers show minimum ampere ratios between pairs of load-side/line-side fuses that will insure coordination—for fuses with a 2:1 ratio, for example, the amp rating of the line-side fuse must be at least 2X the size of the load-side fuse for them to be properly coordinated.

Fuse manufacturers assert that fuses are often the only type of OCPD that can truly be coordinated over all ranges of fault current, and that the fuse ratio tables make selective coordination of fuses a simple prospect. While this is true in some cases, things are not always this simple. Let us return to the example system of Figure 4. Figure 5 that shows the time-current trip characteristics for the Feeder-A and Panel-A Main circuit breakers.

A 125 A circuit breaker feeds the 480 V primary of the 75 kVA transformer, while a 250 A main on the 208 V panel is selected.

Figure 5: Time-Current Characteristics for Feeder-A and Panel-A Main Circuit Breakers.

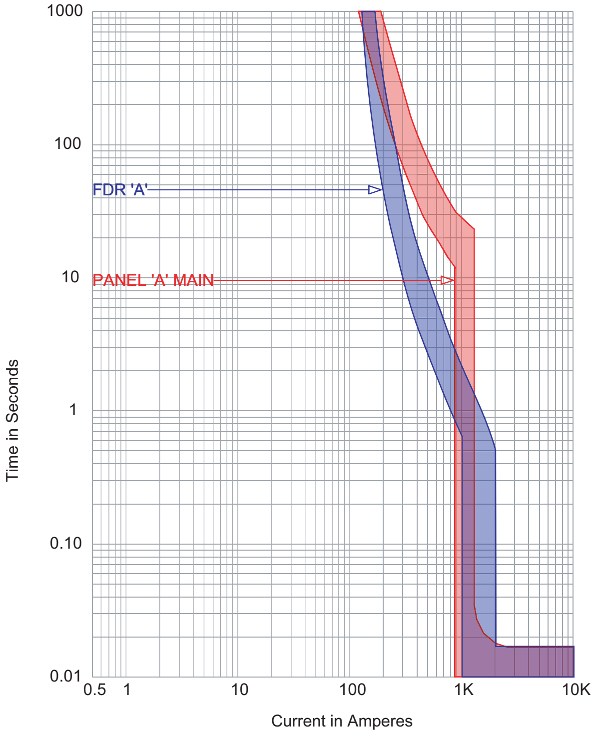
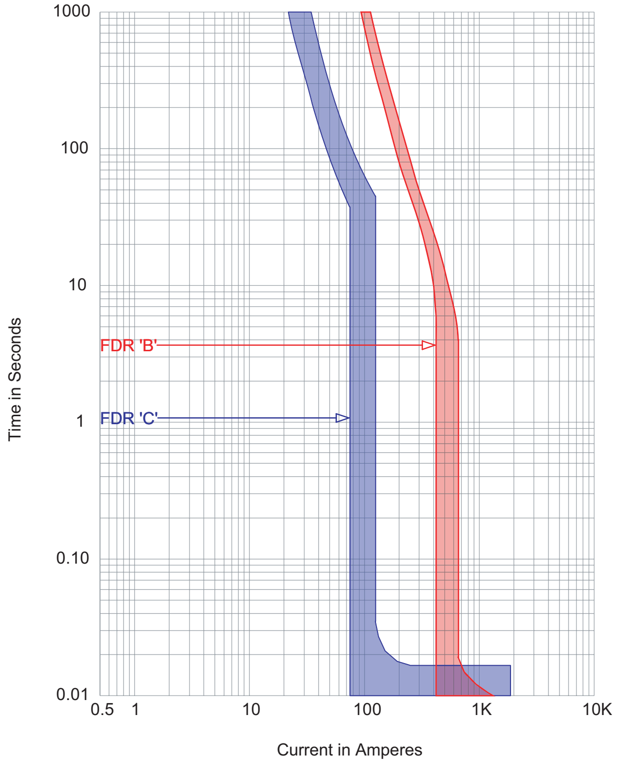


Figure 5 shows that the trip curves of the two circuit breakers overlap, indicating a lack of coordination between them. If the fault current falls into the range where the device curves overlap, it is unclear which will trip first. However, as discussed above, since these devices are in series, system coordination is preserved even though device coordination is not. Unfortunately, a strict interpretation of NEC 700.27 and 701.18 does not recognize system coordination, and so this series installation would be a code violation if installed in an emergency or legally-required standby system.

What if fuses were used instead? The fuse ratio tables do not address coordination between devices operating at different voltage levels, as in this case, so a graphical evaluation of coordination would be required. Selecting a typical 125 A, class RK-1, 600 V fuse for the primary feeder, and a 250 A, RK-1, 250 V fuse for the secondary main will result in overlap between the two devices. The size of the primary fuse must be increased to 175 A for the fuses to coordinate, at least for durations above 0.01 seconds. This still meets the NEC requirements for transformer protection in NEC 450, but could make coordination with upstream devices more difficult depending on the system design.

Figure 6 shows the time-current characteristics of the Feeder-B and Feeder-C circuit breakers in Figure 4.

Figure 6: Time-Current Characteristics for the Feeder-B and Feeder-C Circuit Breakers.

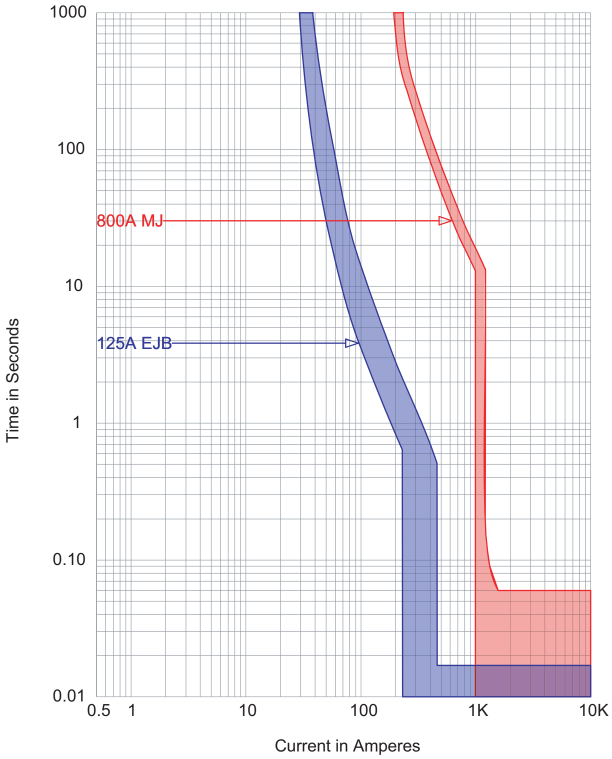


As shown in the plot, the two devices—a 600 A Square D® LC circuit breaker (Feeder-B) and a 200 A Square D LH circuit breaker (Feeder-C) coordinate well, except for currents above approximately 4200 A where the two device curves overlap. If a fault downstream of the Feeder-C circuit breaker drew more than 4200 A fault current, both Feeder-B and Feeder-C would try and respond instantaneously, and it is not clear from the time-current curve (TCC) plot which device would open first to clear the fault. In many cases, this level of coordination between the circuit breakers (i.e., no overlap except for relatively high-level faults) is considered to be acceptable. However, it does not meet the requirements of NEC 700.27 or 701.18.

Does this mean that system designers have to use only fuses in emergency systems? Not necessarily! In light of the new NEC requirements, Schneider Electric has begun to re-evaluate the performance of its low-voltage circuit breaker product line for the selectivity of specific combinations of circuit breakers at high fault current levels. The test results have shown that in many cases the published circuit breaker trip curves, due to dynamic impedance and current limiting effects, are actually somewhat conservative in the instantaneous region when considering selectivity between circuit breakers, and that many line/load combinations of circuit breakers actually do coordinate even if their trip curves indicate otherwise.

For example, see Figure 7, which shows the time-current characteristics for two Square D® thermal-magnetic circuit breakers—an 800 A MJ and a 125 A EJB, both at 208 V.

Figure 7: Trip Curves for 800 A MJ and 125A EJB.



While the curve shows mis-coordination between the circuit breakers in the instantaneous trip region, the test results presented in Data Bulletin 0100DB0501, “Short-Circuit Selective Coordination for Low Voltage Circuit Breakers,” [9] indicates that this particular combination does actually coordinate all the way up to 100 kA, the full interrupting rating of both devices. Not all circuit breaker combinations tested coordinated this well and some testing remains to be completed, but the fact is that fused systems are not the only ones that can meet the strictest NEC requirements for selective coordination.

Selective coordination may also be enhanced through simply designing the power system (whether fuses or circuit breakers are used) with selective coordination in mind. As examples of the latter, situations where OCPDs are applied in series should be avoided as should application of devices upstream/downstream of one another that are close in size (e.g., 800 A panelboard with 600 A circuit breaker feeding a sub-panel), neither of which lends itself to easy selective coordination between those devices. See Data Bulletin 0100DB0403, “Enhancing Short Circuit Selective Coordination with Low Voltage Circuit Breakers” [10] and [11] for additional discussion of selective coordination in circuit breaker systems.

V. Reliability

Circuit breakers, being mechanical devices, require periodic maintenance to ensure that they can operate within expected tolerances when called upon to clear a fault or overload from a system. If a circuit breaker is not properly maintained, it may still be able to operate as intended, it may operate more slowly than intended, or it may not be able to operate at all. Following proper maintenance and testing practices and using modern, durable circuit breakers such as the Square D® Masterpact® NW, which is rated for up to 12,500 mechanical or 2,800 electrical operations before maintenance is required, can help to ensure that circuit breakers will correctly operate when called upon to do so and that potentially defective devices are found and repaired or replaced before they create larger problems.

While fuses themselves require no maintenance, this does not mean that a fusible system requires no preventative maintenance or testing. Fuse holders, cable connections, and disconnect switches (whether manually or automatically operated) must be periodically tested and maintained, just as in circuit breaker systems. Neglecting periodic operation of such devices, periodic maintenance requirements, and infrared scanning can lead to switch contacts that have welded shut, “hot spots” at conductor connections, etc.

If reliability and maintenance requirements of only the overcurrent protective devices are considered, it is true that fuses have a clear advantage over circuit breakers. In reality, however, both fusible and circuit breaker-based systems require at least some degree of periodic maintenance, giving neither type system a clear advantage in this area. For details on recommended maintenance procedures and intervals, contact the equipment manufacturer or see NFPA 70B, *Recommended Practice for Electrical Equipment Maintenance* [12].

VI. Rerating

Both fuses and thermal-magnetic circuit breakers MCCBs operate based on heating produced by overload or fault currents flowing through them. As a result, the ambient temperature can have an effect on the trip characteristics of both types of devices. Square D LV MCCBs will require rerating for ambient temperatures above 40°C. They are actually capable of carrying higher-than-rated currents for ambient levels below 24°C, which may require special consideration to ensure proper conductor protection. See Data Bulletin 0100DB0101, “Determining Current-Carrying Capacity in Special Applications” [13]. Fuses may also require rerating above approximately 25°C, as the elevated ambient decreases both their effective continuous current rating and opening time. Like MCCBs, fuses may carry more than rated current in low-ambient environments, again possibly meriting special consideration to ensure that conductor protection is provided. The response time of thermal-based devices can also be affected by pre-loading (i.e., heating produced by flow of current through an OCPD before an overcurrent condition is present) and harmonic distortion (high-frequency distortion can be problematic for semiconductor fuses in particular; the effect of harmonics on general-purpose fuses and MCCBs is generally not a reason for concern). Use of electronic-trip circuit breakers may be warranted when facing such difficult conditions, as trip units with true RMS metering are relatively insensitive to harmonic current levels (at least for lower-order harmonics), and ambient temperature levels do not have an effect on Square D electronic-trip circuit breakers [13].

VII. Renewability

Fuses clear faults from the system by virtue of the melting of the fusible element. Once that element has melted and current can no longer pass through the fuse, the fault is removed from the system. This melting is a "one-way" process—the fusible link can no longer carry current and must be replaced. For non-renewable fuses—on low-voltage systems, this encompasses all but certain types of Class H fuses—this means that the old fuse cartridge must be removed from the fuseholder and a new one installed before the circuit can be re-energized. Even for renewable fuses, the fuse link itself must be replaced. Stocking spare fuses can help keep potential system downtime to a minimum, but can mean that a substantial inventory of spare fuses must be maintained.

A circuit breaker, on the other hand, clears faults from the system through opening of a set of contacts. As long as the circuit breaker does not sustain damage in the process of clearing the overcurrent, the contacts can be re-closed and the circuit re-energized by manually closing the circuit breaker. A circuit breaker should always be inspected after a high fault, and testing may also be wise—particularly if any damage or stress is seen when the circuit breaker is inspected—to ensure that the device will function properly. In many cases, and particularly if the circuit breaker is properly applied within its ratings, the circuit can be re-energized after only minimal downtime.

Fuse manufacturers have argued that the non-renewability of fuses is actually an advantage over circuit breakers in some situations. OSHA regulations state that:

> *After a circuit is de-energized by a circuit protective device, the circuit may not be manually re-energized until it has been determined that the equipment and circuit can be safely energized. The repetitive manual reclosing of circuit breakers or reenergizing circuits through replaced fuses is prohibited.*
>
> ***NOTE:*** *When it can be determined from the design of the circuit and the overcurrent devices involved that the automatic operation of a device was caused by an overload rather than a fault condition, no examination of the circuit or connected equipment is needed before the circuit is re-energized. (OSHA 1910.334(b)(2))*

The argument is that since fuses must be replaced, the temptation for a worker to simply reset a circuit breaker and re-energize the circuit (thereby possibly violating OSHA regulations) is removed. Realistically, though, a worker who is willing to bypass OSHA regulations and proper work practices in order to quickly get a circuit back in service is just as likely to do this with fused circuits as with circuits protected by circuit breakers. In the "real world", for better or for worse, installations have been found where a single disconnect contains more than one type and/or size of fuse; fuses have been jumpered out or replaced with solid copper or steel bars, etc. Likewise, circuit breakers have been misapplied, bypassed, etc. The type of worker who operates and maintains an electric power system can have just as much, if not more, impact on its performance as the type of overcurrent protective device that is used.

Replacing fuses involves working “on or near” exposed, energized equipment, which per NFPA 70E-2004 is only allowed if de-energizing creates “additional or increased hazards or is infeasible due to equipment design or operational limits.” [6] Therefore, in most situations, replacing fuses in a panelboard or switchboard would require that the entire panel/switchboard be de-energized. If energized work can be justified per 130.1 of NFPA 70E-2004, appropriate flash protection PPE is still required.

While use of appropriate PPE is also recommended when switching circuit breakers, as most power distribution equipment is not rated to contain arcing faults (the exception being “Arc Resistant” gear), the NFPA 70E rules governing energized work would not apply as long as the enclosure door remains closed, as workers would not be exposed to energized parts. While switching circuit breakers with equipment covers and doors in place is not inherently safe, the fact that the worker is not exposed to energized parts should help reduce the likelihood of occurrence of arc-flash events.

VIII. Flexibility

A wide variety of circuit breakers are available—from relatively basic molded-case circuit breakers to the “top of the line” low-voltage power circuit breakers—with optional features that make them appropriate for nearly any application. A summary of some of the more advanced features available on circuit breakers is provided in this section. Many of these features are not available on fusible systems without addition of external metering equipment, relays, or other accessories.

- 1, 2, 3, or 4-pole Construction: a circuit breaker is available that will fit nearly any circuit, even those where providing neutral protection or having a switched neutral may be of benefit. The switched neutral can help to simplify ground-fault protection system design in multi-source systems, for example.
- Integral Ground-fault Protection available: no external relaying and only minimal associated wiring required.
- Adjustable Trip Characteristics: for all but the smallest MCCBs, adjustable trip settings are available that can help provide optimal levels of selective coordination and arc-flash protection in a system. Electronic trip units provide the highest degree of setting flexibility.
- Advanced Protection and Monitoring Features: when applied on a Masterpact® circuit breaker, the state-of-the-art Micrologic® “H” trip units can provide a wide range of protection and control/monitoring features, including:
  - — Neutral conductor protection
  - — Demand current alarm/trip
  - — Undervoltage alarm/trip
  - — Overvoltage alarm/trip
  - — Voltage unbalance alarm/trip
  - — Current unbalance alarm/trip
  - — Reverse power alarm/trip
  - — Overfrequency alarm/trip
  - — Underfrequency alarm/trip
  - — Phase rotation alarm
  - — Available control signal for load-shed schemes
  - — Metering capabilities:
    - voltage
    - current
    - power
    - power factor
    - energy
    - harmonic distortion
    - waveform captures
  - — Trip/alarm history: records type of fault, observed levels of trip quantity (e.g., peak fault current level recorded)
  - — Condition monitoring of circuit breaker: contact wear indicator
  - — Support for communication protocols that allow trip unit to be tied into facility-wide power monitoring or SCADA system
  - — Subsets of these features also available with other circuit breaker/trip unit types
- Interrupting ratings available to 200 kA without fuses.

IX. References

[1] NFPA 70-2005, *National Electrical Code*, National Fire Protection Association, Quincy, MA.

[2] IEEE Std. 1015-1997, *IEEE Recommended Practice for Applying Low-Voltage Circuit Breakers Used in Industrial and Commercial Power System*s.

[3] Gregory, G. D., "Single-pole Short-Circuit Interruption of Molded Case Circuit Breakers," *IEEE Transactions on Industry Applications*, vol. 35, no. 6, Nov.–Dec. 1999, p. 1265-70.

[4] *SPD—Selecting Protective Devices* (Based on the 2005 NEC), Cooper Bussmann, Available: http://www.bussmann.com

[5] IEEE Std. 1584-2002, *IEEE Guide for Performing Arc-Flash Hazard Calculations.*

[6] NFPA 70E-2004, *Standard for Electrical Safety in the Workplace*, National Fire Protection Association, Quincy, MA.

[7] Square D Data Bulletin 0100DB0402, *Arc-Flash Application Guide: Arc-flash Calculations for Circuit Breakers and Fuses*. Available: http://www.us.squared.com

[8] Brown, W.A., Shapiro, R., "A Comparison of Arc-Flash Incident Energy Reduction Techniques using Low-Voltage Power Circuit Breakers," presented at the 2006 IEEE Industrial and Commercial Power Systems Technical Conference, Dearborn, MI.

[9] Square D Data Bulletin 0100DB0501, *Short-Circuit Selective Coordination for Low Voltage Circuit Breakers*. Available: http://www.us.squared.com

[10] Square D Data Bulletin 0100DB0403, *Enhancing Short Circuit Selective Coordination with Low Voltage Circuit Breakers*. Available: http://www.us.squared.com

[11] Square D Data Bulletin 0100DB0403 *Guide to Power System Selective Coordination 600 V and Below*. Available: http://www.us.squared.com

[12] NFPA 70B-2006, *Recommended Practice for Electrical Equipment Maintenance*, National Fire Protection Association, Quincy, MA.

[13] Square D Data Bulletin 0100DB0101, *Determining Current-Carrying Capacity in Special Applications*. Available: http://www.us.squared.com

Schneider Electric USA
3700 Sixth St SW
Cedar Rapids, IA 52404 USA
1-888-SquareD (1-888-778-2733)
www.us.SquareD.com

a brand of Schneider Electric

SQUARE D