Guide to Power System Selective Coordination
600V and Below

1. Introduction

With the inclusion of new language in the 2005 National Electrical Code® (NEC®), the requirements for selective coordination of electrical power systems are, at present, more stringent than ever before. This paper describes the nature of selective coordination, the NEC requirements pertaining to selective coordination, and approaches for obtaining selective coordination in commonly-encountered scenarios for systems 600V and below.

2. Background

2.1. What is Selective Coordination?

The term “selective coordination” refers to the selection and setting of protective devices in an electric power system in such a manner as to cause the smallest possible portion of the system to be de-energized due to an abnormal condition. The most commonly encountered abnormal condition is an overcurrent condition, defined by the NEC as “any current in excess of the rated current of equipment, or the ampacity of a conductor” [1]. The NEC uses a more restricted definition of selective coordination as follows: “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” [1]. This is the definition used herein.

The concept of selective coordination is best illustrated by example. In the example system of Fig. 1, all of the devices shown are overcurrent protective devices, in this case circuit breakers. Five system locations, labeled A-E, have been identified. If selective coordination exists, an overcurrent condition at location E will only cause the lighting panel circuit breaker CB B1 to trip. Similarly, an overcurrent fault at location D should only cause lighting panel circuit breaker CB PM1 to trip. Table I shows the protective device that should operate for a fault in each labeled location in Fig. 1, assuming selective coordination exists.
Overcurrent conditions may be divided into two types. An overload is defined by the NEC as “operation of equipment in excess of normal, full-load rating, or of a conductor in excess of rated ampacity that, when it persists for a sufficient length of time, would cause damage or dangerous overheating” [1]. Similarly, a fault is defined as an unintentional connection of a power system conductor, resulting in an abnormally high flow of current. Faults typically produce higher overcurrents than do overloads, depending upon the fault impedance. A fault with no impedance in the unintentional connection is referred to as a short circuit or bolted fault.

Faults may also be classified as to their geometry. A three-phase fault involves all three phases. A line-to-line fault involves only two phases. A short circuit involving a ground path is referred to as a ground fault, and may be a three-phase-to-ground fault, two-line-to-ground fault, or single-line-to-ground fault (note: the typical usage of the term ground-fault usually means a single-line to-ground fault).
Statistically, ~95% of all system faults are single-line-to-ground faults. A very low percentage of faults are bolted faults. Thus, the frequency of occurrence of high-magnitude bolted faults is much lower than that of lower-magnitude faults, such as arcing ground faults. These statistics should be kept in mind when considering the requirements for selective coordination, for reasons that are outlined herein.

2.3. The Protective Zone Concept

To further visualize the system coordination, the system of Fig. 1 can be divided into protective zones. A fault in a given protective zone causes a given protective device to operate. The ideal primary protective zones for the system of Fig. 1 are shown in Fig. 2. CB B1 should be the only device to operate for a fault in its primary protective zone, CB PM1 should be the only device to operate for an overcurrent condition in its protective zone, etc. Note that the ideal primary protective zone for a given protective device includes the next level of downstream protective devices, since a protective device cannot be assumed to trip for an internal fault in the device itself. In other words, the ideal protective zone boundaries cannot be arbitrarily established, but must take into account which overcurrent conditions each protective device is able to sense and interrupt.

Note that the closer a protective zone is to the source of power, in this case a utility service, the more of the system is de-energized for an overcurrent condition that zone. In fact, in a radial system with only one source of power an overcurrent condition within a protective zone will cause all protective zones downstream from that zone to be affected due to the trip of the overcurrent protective device for that zone.

**Fig. 2: Ideal Primary Protective Zones for the Example System of Fig. 1**
Note also that, for an overcurrent condition in CB B1’s primary protective zone, if CB B1 fails to operate CB PM1 should operate as a backup. Thus, CB B1’s protective zone may be said to be in the backup protective zone for CB PM1. This same relationship follows to upstream devices as well. Each backup protective zone is limited by the lowest level overcurrent condition the protective device can sense. This limit is referred to as the reach of the device and is dependent upon the size and characteristics of the device, its settings (if applicable), and the available fault currents at various points downstream from the device. In practice, however, the backup protective zones should at least overlap the primary protective zone for the next downstream device, to allow each portion of the system to have backup protection should its primary protective device fail to operate.

Typical backup protective zones for the system of Fig. 1 are shown in Fig. 3. (based upon the time-current characteristics and available fault currents for this system). Note that although the backup protective zones overlap in a way determined by the reach of the protective devices, the next upstream device should operate upon failure of the primary protective device. For example, for a fault on the branch circuit supplied by CB B1, CB PM1 should operate if CB B1 fails to operate. For a fault on this circuit close to CB B1, the backup protective zones for CB M1, and CB F1 overlap, as dictated by the reach of these circuit breakers. However, if CB PM1, CB F1, and CB M1 are selectively coordinated, even in the region where the backup protective zones overlap CB PM1 will trip should CB B1 fail to operate. If CB PM1 fails to operate, CB F1 will operate so long as the fault is within its backup protective zone. Should CB F1 fail to operate, then CB M1 will operate, again so long as the fault is within its backup protective zone. In this case a fault on the CB B1 branch circuit, even close to CB B1, is beyond the reach of the utility protective device, so CB M1 is the “last line of defense” to clear a fault on this circuit close to CB B1. Only CB PM1, however, provides backup protection for the entire circuit, since its backup protective zone is the only one which extends around the entire circuit.
A more specific definition of selective coordination between two devices in series may now be stated: “Selective coordination exists between two overcurrent protective devices in series \textit{if and only if} each device is the only device which operates for faults within its ideal primary protective zone, where the ideal primary protective zone begins at the load terminals of that device and ends at the load terminals of the next level of downstream devices.” Operation of a protective device in its backup zone of protection may indicate a lack of coordination or may indicate that a protective device has failed.

Using this definition, the term \textit{system selective coordination} may be applied to an entire electric power system as follows: “\textit{System selective coordination} for an electric power system exists \textit{if and only if} any outage due to an overcurrent condition is restricted to the smallest possible number of loads, as defined by the overcurrent device placement and the ideal protective zone for each device.” While not an official industry term, \textit{system selective coordination} is an important concept as it is the ideal condition for protective device coordination in the context of the over-all system.
2.4. How is selective coordination achieved?

In most cases selective coordination is achieved via the timing characteristics of the devices to be coordinated. For example, each of the circuit breakers for the system of Fig. 1 has its own time-current characteristic; by coordinating these, selective coordination may be achieved. This is usually accomplished by comparing the device time-current characteristics graphically. An example is shown in Fig. 4, which illustrates the time-current coordination between circuit breakers CB M1 and CB F1 from Fig. 1. Note that a log-log scale is used to display the device time-current characteristics. The curves for both devices end at the available fault current for their respective busses, in this case 30kA. Because there is no overlap in the time-current characteristics up to 30kA, selective coordination exists between these two devices. For example, for the 30kA available fault, CB F1 will operate in 0.01 – 0.02s and CB-M1 will operate in 0.22 – 0.31s. CB F1 will therefore operate more quickly than CB M1 for a fault (up to the 30kA available fault current) sensed by both devices.

Using this graphical method, it may be stated that to achieve selective coordination between two devices, they must have no time-current curve overlap up to the available fault current where their ideal primary protective zones meet. This concept is illustrated in Fig. 5. The fact that CB M1 and CB F1 will both sense an overcurrent condition at the primary protective zone boundary, along with the time-current coordination between the two, establishes the actual primary protective zone boundary at the location shown, which in this case coincides with the ideal boundary location.

Fig. 4: Typical Time-Current Coordination Plot
The fact that time is used to coordinate the operation of protective devices in series has an important, and unfortunate, drawback: The closer to the source of power, the slower the protective device must be to coordinate with downstream devices. This means that for faults close to the source of power, fault clearing will be slower than it could be if coordination were not a consideration. This has important implications for equipment damage and arc-flash hazards, both of which must be taken into consideration in an overall system design. It also has important implications for the backup protection described above, since fault clearing will be slower if the closest upstream device fails to operate or clear the fault. Techniques to mitigate these problems, such as Zone Selective Interlocking (ZSI), are available.

Fig. 5: Primary Protective Zones for the System of Fig. 1, Showing the Available Fault Current Referenced in Fig. 4

To illustrate how miscoordination of devices affects the protective zones, consider the coordination between CB F1 and CB PM1 per Fig. 6. CB F1 and CB PM1 have been deliberately selected so as to miscoordinate for purposes of illustration. Note that coordination between CB F1 and CB PM1 exists up to 21.6kA. There is, however, 25kA available fault current at the line terminals of CB PM1 (because protective devices generally do not present significant impedance in the circuit, the available fault current at either the line or load terminals of a protective device is the same. The line side of the circuit breaker is referenced by convention, although the ideal protective zone boundaries meet at the load terminals). This has the effect of causing the primary protective zones for CB F1 and CB PM1 to overlap to the point in the system where the available fault current is 21.6kA. This is illustrated in Fig. 7. Similarly, the primary protective zones for CB PM1 and CB B1 overlap to the point in the system.
where the available fault current is 2kA. It can be readily seen that the primary protective zones in Fig. 7 are not the ideal primary protective zones per Fig. 2.

Fig. 6: Time-Current Plot showing lack of selective coordination between CB F1 and CB PM1

![Time-Current Plot showing lack of selective coordination between CB F1 and CB PM1](image)

Fig. 7: Protective Zones for Time-Current Plot of Fig. 6

![Protective Zones for Time-Current Plot of Fig. 6](image)
From the discussion above that it is apparent that it becomes more difficult to coordinate two overcurrent protective devices as the fault current increases. This is an important concept in light of the statistics presented earlier: *The frequency of occurrence of high-magnitude bolted faults is much less than that of lower-magnitude faults, such as arcing ground faults.*

2.5. What about Equipment Protection?

Equipment protection is an important part of the coordination process. Time-current curves such as those shown above may be used to show protection for cables, transformers and other equipment. Essentially, the damage curve for the equipment in question is superimposed upon the time-current characteristic curve(s) for the device(s) that protect it. Equipment damage curves which fall to the right and above the protective device curves with sufficient margin are considered to be protected by the device(s). Equipment damage curves which fall on top of or to the left and below the protective device curves are considered not to be protected by the device(s).

Because this paper focuses on protective device coordination, device protection is only addressed where it helps illustrate why a particular protective device is set at a given level. However, it should be understood that device protection is important. Reference [2] is an excellent reference both for equipment protection and protective device coordination.

2.6. NEC Requirements for Selective Coordination

The 2005 NEC requirements for selective coordination are, at present, more stringent that ever before (like all code requirements, however, they are subject to interpretation). These requirements are as follows. Code text is in italics [1]:

**240.12 Electrical System Coordination.** Where an orderly shutdown is required to minimize the hazard(s) to personnel and equipment, a system of coordination based upon the following two conditions shall be permitted:

1. **Coordinated short-circuit protection.**
   - Where an orderly shutdown is required, short-circuit protection must be present, but overload protection can be indicating only. This is in lieu of full coordinated overload protection and is intended to minimize the risk of unintentionally shutting down part of a system automatically due to an overload condition where a lack of coordination can cause hazards to personnel and equipment. An overload condition can generally be tolerated for a longer period of time than a fault; the overload indication must be acted upon by operating personnel, but the time can be taken for an orderly, rather than an abrupt, shut-down of the affected equipment.
2.6.2. Elevators, Dumbwaiters, Escalators, Moving Walks, Wheelchair Lifts, and Stairway Chair Lifts (NEC 620.62)

620.62 Selective Coordination. Where more than one driving machine disconnecting means is supplied by a single feeder, the overcurrent protective devices in each disconnecting means shall be selectively coordinated with any other supply side overcurrent protective devices.

This requirement has been in the NEC for some time and is intended to prevent an overcurrent condition in one elevator, escalator, etc., motor from de-energizing the entire feeder which supplies other elevator(s), escalator(s), etc., which is important for fire fighter access during a fire.

2.6.3. Emergency Systems (NEC 700.27)

700.27 Coordination. Emergency system(s) overcurrent devices shall be selectively coordinated with all supply side overcurrent protective devices.

The definition of an “emergency system” is a system “legally required and classed as emergency by municipal, state, federal, or other codes, or by any governmental agency having jurisdiction. These systems are intended to automatically supply illumination, power, or both, to designated areas and equipment in the event of failure of the normal supply or in the event of accident to elements of a system intended to supply, distribute, and control power and illumination essential for safety to human life.” The requirement for emergency system protective device selective coordination is new to the 2005 NEC.

Health Care facilities in Florida have long been subject to the active oversight of the Florida Agency for Health Care Administration (Florida AHCA). Depending upon the jurisdiction, Florida AHCA in the past has required coordination only down to the 0.1s level (i.e., ignoring short-circuit coordination). The advent of the new language above and in NEC 701.18 below will undoubtedly have an effect on this, however as of the time of writing the disposition of this issue with Florida AHCA is unknown.

Note that selective coordination is referenced in terms of devices rather than as system selective coordination as discussed herein. This can have important consequences for engineers trying to meet the requirements of this Code section, as discussed in further detail below.

2.6.4. Legally Required Standby Systems (NEC 701.18)

701.18 Coordination. Legally required standby system(s) overcurrent devices shall be selectively coordinated with all supply side overcurrent protective devices.

The definition of a “legally required standby system” is a system “consisting of circuits and equipment intended to supply, distribute, and control electricity to required facilities for illumination or power, or both, when the normal electrical supply or system is interrupted.” The requirement for legally required standby system selective coordination is new to the 2005 NEC (see comments above).
2.6.5. Service Ground-Fault Protection for Equipment (NEC 230.95)

230.95 Ground-Fault Protection of Equipment. Ground-fault protection of equipment shall be provided for solidly grounded wye electrical services of more than 150 volts to ground but not exceeding 600 volts phase-to-phase for each service disconnect rated 1000 amperes or more. The grounded conductor shall be connected directly to ground without inserting any resistor or impedance device. The rating of the service disconnect shall be considered to be the rating of the largest fuse that can be installed or the highest continuous current trip setting for which the actual overcurrent device installed in a circuit breaker is rated or can be adjusted.

Exception No. 1: The ground-fault protection provisions of this section shall not apply to a service disconnect for a continuous industrial process where a nonorderly shutdown will introduce additional or increased hazards.

Exception No. 2: The ground-fault protection provisions of this section shall not apply to fire pumps.

(A) Setting. The ground-fault protection system shall operate to cause the service disconnecting means to open all ungrounded conductors of the faulted circuit. The maximum setting of the ground-fault protection shall be 1200 amperes, and the maximum time delay shall be one second for ground-fault currents equal to or greater than 3000 amperes.

(B) Fuses. 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 that the ground-fault protective system will not cause the switch to open.

(C) Performance Testing. The ground-fault protection system shall be performance tested when first installed on site. The test shall be conducted in accordance with instructions that shall be provided with the equipment. A written record of this test shall be made and shall be available to the authority having jurisdiction.

Electrical services of 1000A or greater, with over 150V to ground and 600V or less phase-to-phase (such as 480Y/277V systems), require ground-fault protection at the service. This protection must be set to pick up at no more than 1200A and with a maximum time delay of 1 second at 3000A or greater. Exceptions apply to continuous industrial processes and fire pumps. This has a direct bearing on coordination with downstream devices, as explained below.

2.6.6. Feeder Ground-Fault Protection for Equipment (NEC 215.10)

215.10 Ground-Fault Protection of Equipment. Each feeder disconnect rated 1000 amperes or more and installed on solidly grounded wye electrical systems of more than 150 volts to ground, but not exceeding 600V phase-to-phase, shall be provided with ground-fault protection of equipment in accordance with the provisions of 230.95
Exception No. 1: The provisions of this section shall not apply to a disconnecting means for a continuous industrial process or where a nonorderly shutdown will introduce additional or increased hazards.

Exception No. 2: The provisions of this section shall not apply to fire pumps.

Exception No. 3: The provisions of this section shall not apply if ground-fault protection of equipment is provided on the supply side of the feeder.

Feeders disconnects rated 1000A or more on systems with more than 150V to ground and 600V or less phase-to-phase require ground-fault protection with the same requirements for services as stated in NEC 230.95. Exceptions apply to continuous industrial processes and fire pumps, just as for NEC 230.95. In addition, if ground-fault protection is provided on the supply side of the feeder (such as a feeder supplied from a service with ground-fault protection) the ground-fault protection is not required.

517.17 (B) Feeders. Where ground-fault protection is provided for operation of the service disconnecting means or feeder disconnecting means as specified by 230.95 or 215.10, an additional step of ground-fault protection shall be provided in all next level feeder disconnecting means downstream toward the load. Such protection shall consist of overcurrent devices and current transformers or other equivalent protective equipment that shall cause the feeder disconnecting means to open.

The additional levels of ground-fault protection shall not be installed as follows:

(1) On the load side of an essential electrical system transfer switch
(2) Between the on-site generating unit(s) described in 517.35(B) and the essential electrical system transfer switch(es)
(3) On electrical systems that are not solidly-grounded wye systems with greater than 150 volts to ground but not exceeding 600 volts phase-to-phase

517.17 (C) Selectivity. 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. A six-cycle minimum separation between the service and feeder ground-fault tripping bands shall be provided. Operating time of the disconnecting devices shall be considered in selecting the time spread between these two bands to achieve 100 percent selectivity.

2.6.7. Ground-Fault Protection in Health Care Facilities (NEC 517.17)
Note that NEC 517.17 applies to hospitals and other buildings with critical care areas or utilizing electrical life support equipment, and buildings that provide the required essential utilities or services for the operation of critical care areas or electrical life support equipment.

NEC 517.17 (B) requires an additional level of ground-fault protection for health care facilities where a service or feeder disconnecting means is equipped with ground-fault protection. This additional level of ground-fault protection must be at the next level of protective devices downstream from the service or feeder. In NEC 517.17 (C), not only is it stated that selectivity must be achieved, but the amount of selectivity (6 cycles) is specified.

Note that NEC 517.17(B) effectively prohibits the use of ground-fault protection on the essential electrical system. The result is a conflict between NEC 517.17(B) and NEC 700.27 and NEC 701.18. This will be discussed in further detail below.

2.7. The Coordination Study

The only true method for achieving selective coordination and equipment protection, and documenting with certainty the fact that these have been achieved, is via a coordination study. The coordination study, also known as a time-current coordination study, compares the timing characteristics of the protective devices used with each other and with the damage characteristics of equipment to be protected. For electronic-trip circuit breakers, the appropriate settings for the breaker trip units are developed in the coordination study.

Because the short-circuit currents available at different points in the system is a concern, a coordination study is usually performed in conjunction with a short circuit study. The short-circuit study evaluates the short-circuit currents available in the system.

Note that the new, stringent 2005 NEC requirements mentioned above for emergency and standby power systems do not in any way exempt the power system engineer from performing a coordination study. In fact, in order to fit in with the competitive bidding process for equipment the timing of the study may need to be performed sooner in the project timeline than previously, in order to avoid costly mistakes in protective device selection. This is discussed in more detail below.
3. Protective Device Characteristics

Overcurrent coordination is influenced heavily by the characteristics of the overcurrent protective devices themselves. For systems 600V and under, the two primary types overcurrent protective devices are circuit breakers and fuses. The characteristics of each, as they apply to overcurrent coordination, are discussed below.

3.1. Fuses

Fuses are the simplest of all overcurrent protective devices. As such, they offer the least amount of adjustability of any overcurrent protective device. A fuse consists of a melting element which melts with a pre-determined time-current characteristic for overcurrents. Low-voltage fuses are divided into classes based upon their characteristics. Some fuses are classified current-limiting. By strict definition, a current-limiting fuse will interrupt currents in its current-limiting range within ½ cycle or less, limiting the current to a value less than that which would be available if the fuse were replaced by a conductor of the same impedance.

Fuse timing response to a given level of overcurrent may be separated into melting time, which is the time required to melt the current-responsive element, and arcing time, which is the time elapsed from the melting of the current-responsive element to the final interruption of the circuit. The arcing time is dependent upon the circuit characteristics, such as the voltage and impedance of the circuit. The total clearing time is the sum of the melting time and the arcing time, as shown in Fig. 8.

**Fig. 8: Fuse Timing Illustration**

![Fuse Timing Diagram]

For all low-voltage fuse classes, the basic timing characteristics can be classified in the same manner. Fuses are typically assigned a minimum melting characteristic and a total clearing characteristic by their manufacturer. These define the boundaries of the fuse time-current characteristic band. For currents with time durations below and to the left of the time current characteristic band, the fuse will not blow or be damaged. For currents with time durations within the time-current characteristic band, the fuse may or may not blow or be damaged. For currents with time durations above and to the right of the time-current characteristic band, the fuse will blow with a minimum melting time given by the minimum melting time characteristic and a total clearing time given by the total-clearing time characteristic. Alternatively, the fuse may be assigned an average melting time.
characteristic; in this case the total clearing characteristic is considered to be the average melting time characteristic shifted in time by +15%, and the minimum melting characteristic is considered to be the average melting time characteristic shifted in time by -15%. A typical fuse time-current characteristic band is shown in Fig. 9.

Fig. 9: Typical Low-Voltage Fuse Time-Current Characteristic Band

Note that in Fig. 9 the time-current characteristic is only shown down to 0.01 seconds. Below this level the arcing time may be equal to or greater than the maximum melting time [2]. The $I^2t$ energy let-through characteristics are used in this case to determine coordination; the minimum melting energy of the upstream fuse must be less than the total clearing energy of the downstream fuse for two fuses to coordinate. Fuse manufacturers publish selectivity ratio tables to document the performance of fuses under these circumstances.

Consider, then, two fuses in series, as shown in the one-line diagram/time current plot of Fig. 10. It is possible to establish, by means of the time-current plot alone, that fuses FU1 and FU2 coordinate up to 8200A. Above 8200A FU1 operates in 0.01s or less and FU2 may operate in 0.01s or less, and coordination must be established via the fuse selectivity ratio tables.
3.2. Circuit Breakers

Circuit breakers offer many advantages over fuses for the protection of low-voltage power systems. These advantages will not be elaborated upon here, however it should be noted that for this reason circuit breakers are the prevalent form of overcurrent protection for low-voltage power systems. Successful selective coordination with circuit breakers is therefore a vital topic for successful power system design.

Circuit breakers may be subdivided into two basic categories: Molded-case and low-voltage power circuit breakers. Molded-case circuit breakers may be generally divided into thermal-magnetic and electronic tripping types. Molded-case electronic-trip circuit breakers may be generally be further divided into two categories: those with two-step stored energy mechanisms, often referred to as insulated case circuit breakers (not a UL term, but does appear in the IEEE Blue Book [5]) and those without.

From a coordination standpoint, of particular importance is the rated short-time withstand current. This is defined as follows [5]:

“Rated Short-Time Withstand Current: (A) The maximum RMS total current that a circuit breaker can carry momentarily without electrical, thermal, or mechanical damage or permanent deformation. The current shall be the RMS value, including the DC component, at
the major peak of the maximum cycle as determined from the envelope of the current wave during a given test time interval. (IEEE C37.100-1992) (B) That value of current assigned by the manufacturer that the device can carry without damage to itself, under prescribed conditions. (NEMA AB1 – 1993) Syn: withstand rating; short-time rating”

All circuit breakers which have inherent time-delay characteristics (which is essentially every circuit breaker that is not an instantaneous-only circuit breaker) have a short-time withstand capability. This capability may or may not be published as a short-time withstand rating, however it will manifest itself in the time-current characteristics for the circuit breaker since a circuit breaker must be designed so that it will not be damaged for fault currents up to its interrupting rating. Table II gives a summary of the various low-voltage circuit breaker types with respect to typical levels of short-time withstand capability. Because the information given in Table II is general in nature, specific manufacturer’s data must be consulted for a given circuit breaker.

Table II: Low-Voltage Circuit Breaker Types

<table>
<thead>
<tr>
<th>Circuit Breaker Type</th>
<th>Standard</th>
<th>Tripping Type</th>
<th>Short-time Withstand Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molded-Case</td>
<td>UL 489</td>
<td>Thermal-magnetic</td>
<td>Typically much lower than interrupting rating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electronic</td>
<td>Typically lower than interrupting rating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electronic (insulated case)</td>
<td>Often comparable to interrupting rating</td>
</tr>
<tr>
<td>Low-Voltage Power</td>
<td>ANSI C37.13 UL 1066</td>
<td>Electronic</td>
<td>Typically comparable to interrupting rating</td>
</tr>
</tbody>
</table>

1 Other circuit breaker types, such as molded-case circuit breakers with instantaneous-only trip units, are available for specific applications, such as short-circuit protection of motor circuits.

2 Short-time current is defined by ANSI C37.13 as the designated limit of available (prospective) current at which the circuit breaker is required to perform a duty cycle consisting of two ½-second periods of current flow separated by a 15s interval of zero current. For UL 489-rated circuit breakers short-time withstand is not defined and the duty cycle may vary.

3 Insulated-case circuit breakers exceed the UL 489 standard. The term “insulated case” is not a UL term.

3.2.1. Thermal-Magnetic Molded-Case Circuit Breakers

The typical time-current characteristic band of a thermal-magnetic molded-case circuit breaker is shown in Fig. 11. The time band is, by necessity, quite large; for example, the UL 489 standard allows the instantaneous trip characteristic for a circuit breaker with an adjustable instantaneous characteristic to vary from -20% to +30% of the marked instantaneous trip current setting. The long-time portion of the trip characteristic is established by a thermal element and is used for overload and low-level fault protection. The instantaneous characteristic is often adjustable, as shown in Fig. 12, and is used for short circuit protection.
Fig. 11: Typical Thermal-Magnetic Molded-Case Circuit Breaker Time-Current Characteristic Band

Fig. 12: Thermal-Magnetic Circuit Breaker Time-Current Characteristic showing adjustable instantaneous characteristic
3.2.2. Electronic-Trip Circuit Breakers

Electronic-trip circuit breakers typically are equipped with trip units which give the circuit breakers the general characteristics per Fig. 13. The adjustable long-time pickup sets the trip rating of the circuit breaker. The adjustable long-time delay, short-time pickup, short-time delay, and instantaneous pickup allow the circuit breaker’s tripping characteristics to be customized to the application. The trip unit represented by Fig. 13 is referred to as an “LSI” trip unit, since it is equipped with long-time, short-time, and instantaneous trip characteristics. Trip units without a short-time setting are referred to as “LI” trip units, and units without an instantaneous characteristic are referred to as “LS” trip units. In most cases, the instantaneous characteristic on an LSI trip unit can be turned off if necessary. A trip unit which includes ground fault protection is denoted with a “G”, i.e., “LSIG”.

Of particular importance to the tripping characteristic is the instantaneous selective override level. For currents above this override level, even if the instantaneous characteristic is turned off the circuit breaker will trip instantaneously. The override level is factory-set to protect the circuit breaker according to its short-time withstand capability. Therefore, the higher the withstand level, the higher the override is set. This is an extremely important concept and often determines whether two circuit breakers in series selectively coordinate. Note also that the tripping times for the instantaneous characteristic and for currents above the override level are non-adjustable. Further, as is the case for the circuit breaker represented in Fig. 13, there can be a difference in tripping time when the circuit breaker is operating in the instantaneous region below the override level vs. above the override level.
Like fuses, circuit breakers can be designed to limit the flow of prospective short-circuit current. Similar to a current-limiting fuse, a current-limiting circuit breaker limits the let-through $I^2t$ to a value that is less than its prospective value. Circuit breakers which are current-limiting are typically shown with instantaneous characteristics in which the tripping time decreases with current, as shown in Fig. 14.

It is worthy of note that, in some cases, even though the circuit breaker is not officially classified as “current-limiting”, a degree of current-limitation may exist [3]. This results in the circuit breaker exhibiting time-current characteristics similar to those shown in Fig. 14, although the instantaneous characteristic is shown as a horizontal band.
3.4. Circuit Breakers in Series: The Dynamic Impedance Concept

A relatively new, but important, concept in the coordination of low-voltage circuit breakers is the concept of dynamic impedance. Simply stated, a circuit breaker, when it begins to open, serves to limit the prospective flow of current, even if it is not UL listed as a current-limiting circuit breaker [3]. The impedance presented to the circuit by the circuit breaker during opening changes with time as the circuit breaker opens, hence the term dynamic. This impedance can increase the level coordination between two circuit breakers in series by limiting the current that the upstream circuit breaker "sees" for a fault downstream of both circuit breakers when the downstream breaker is opening.

3.4.1. Short-Circuit Coordination Tables

Taking the dynamic impedance characteristics of circuit breakers into account for selective coordination leads to an important new tool for the coordination of circuit breakers: Short-Circuit Coordination Tables. Similar to fuse ratio tables, these show the level of coordination between two circuit breakers in series, as determined by test. Because of the dynamic impedance effects of ordinary circuit breakers, often the level of coordination between two circuit breakers in series is greater than their time-current characteristic bands would indicate. As an example, in Fig. 6 the coordination level
between CB F1 and CB PM1 was established graphically via the
time-current bands as 21.6kA. However, testing shows that these two
circuit breakers in series, as manufactured by one specific
manufacturer, coordinate up to 35kA! So, even though the time-
current bands do not reflect this, CB F1 and CB PM1 do coordinate
up to the available fault current of 25kA, as illustrated in Fig. 15. This
level of "extra" time-current coordination can often make a large
difference, as in this case.

Fig. 15: Time-Current Curve of Fig. 6, Showing Effects of
Dynamic Impedance and Current-Limiting on Level of
Selective Coordination Between CB F1 and CB PM1

As with fuse ratio tables, these tables must be developed by the
manufacturer. It is extremely important that the levels of short-circuit
coordination in the short-circuit coordination tables, if different from
the levels determined from the time-current bands, be determined by
test. The present state of the art does not lend confidence to
calculated values.

3.5. Ground-Fault Protection
of Equipment

Ground-fault protection of equipment is designed to provide sensitive
protection for ground-faults, typically set below the level of phase
overcurrent protection. Typically, ground-fault protection is built into
the trip unit of an electronic-trip circuit breaker or, in the case of a
thermal-magnetic circuit breaker or fuses, can be supplied via a separate ground relay. Note that if fuses are used a separate disconnecting means with shunt-trip capability is required. A typical time-current characteristic is given in Fig. 16.

The current-sensing arrangement for ground-fault protection may consist of a simple residual connection of current sensors/CT’s, a single zero-sequence sensor/CT, or may be a complex affair with differential connections of the sensors/CT’s, known as a modified-differential ground-fault arrangement. The application of the sensors/CT’s is beyond the scope of this paper but the engineer responsible for coordination should be cognizant of the requirements and potential application issues.

Fig. 16: Typical Ground-Fault Protection Characteristic

4. Tying it All Together – Design Philosophies and Guidelines

From a system performance standpoint, it is easy to take the position that selective coordination between overcurrent protective devices is always beneficial, regardless of the circumstances. However, on a practical basis full selective coordination may not always be achievable or desirable. Various industry standards recognize this fact. Compromises may be required between selectivity and equipment protection to achieve the desired results. Further, economic trade-offs are often frequently encountered, as well as code issues. Some examples of wording from various industry standards regarding selective coordination are given in Table III.
### Table III: Selective coordination requirements/comments per various industry standards

<table>
<thead>
<tr>
<th>Standard</th>
<th>Requirement/Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NFPA 110 Standard for Emergency and Standby Power Systems [6]</strong></td>
<td>6.5 Protection</td>
</tr>
<tr>
<td></td>
<td>6.5.1* General. The overcurrent protective devices in the EPSS shall be coordinated to optimize selective tripping of the circuit overcurrent protective devices when a short circuit occurs.</td>
</tr>
<tr>
<td></td>
<td>Annex A</td>
</tr>
<tr>
<td></td>
<td>A.6.5.1 It is important that the various overcurrent devices be coordinated, as far as practicable, to isolate faulted circuits and to protect against cascading operation on short circuit faults. In many systems, however, full coordination is not practicable without using equipment that could be prohibitively costly or undesirable for other reasons. Primary consideration also should be given to prevent overloading of equipment by limiting the possibilities of large current inrushes due to instantaneous reestablishment of connections to heavy loads.</td>
</tr>
<tr>
<td><strong>IEEE Std. 141 IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (Red Book) [4]</strong></td>
<td>Chapter 5 Application and Coordination of Protective Devices</td>
</tr>
<tr>
<td></td>
<td>5.1.3 Importance of Responsible Planning</td>
</tr>
<tr>
<td></td>
<td>Protection in an electric system is a form of insurance. It pays nothing so long as there is no fault or other emergency, but when a fault occurs it can be credited with reducing the extent and duration of the interruption, the hazards of property damage, and personnel injury. Economically, the premium paid for this insurance should be balanced against the cost of repairs and lost production. Protection, well integrated with the class of service desired, may reduce capital investment by eliminating the need for equipment reserves in the industrial plant or utility supply system.</td>
</tr>
<tr>
<td></td>
<td>5.2 Analysis of System Behavior and Protection Needs</td>
</tr>
<tr>
<td></td>
<td>5.2.1 Nature of the Problem</td>
</tr>
<tr>
<td></td>
<td>Operating records show that the majority of electric circuit faults begin as phase-to-ground failures...</td>
</tr>
<tr>
<td><strong>IEEE Std. 241 IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (Gray Book) [9]</strong></td>
<td>Chapter 9 System Protection and Coordination</td>
</tr>
<tr>
<td></td>
<td>9.7 Selective Coordination</td>
</tr>
<tr>
<td></td>
<td>9.7.1 Coordination of Protective Devices</td>
</tr>
<tr>
<td></td>
<td>…On all power systems, the protective device should be selected and set to open before the thermal and mechanical limitations of the protected components are exceeded.</td>
</tr>
<tr>
<td></td>
<td>9.7.3 Mechanics of Achieving Coordination</td>
</tr>
<tr>
<td></td>
<td>…Quite often, the coordination study will not demonstrate complete selective coordination because a compromise has to be made between the competing objectives of maximum protection and maximum service continuity.</td>
</tr>
<tr>
<td><strong>IEEE Std. 242 IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (Buff Book) [2]</strong></td>
<td>Chapter 1 First Principles</td>
</tr>
<tr>
<td></td>
<td>1.1.2 Equipment damage versus service continuity</td>
</tr>
<tr>
<td></td>
<td>Whether minimizing the risk of equipment damage or preserving service continuity is the more important objective depends upon the operating philosophy of the particular industrial plant or commercial business. Some operations can avoid to limited service interruptions to minimize the possibility of equipment repair or replacement costs, while others would regard such an expense as small compared with even a brief interruption of service.</td>
</tr>
<tr>
<td></td>
<td>In most cases, electrical protection should be designed for the best compromise between equipment damage and service continuity...</td>
</tr>
<tr>
<td></td>
<td>Chapter 15 Overcurrent coordination</td>
</tr>
<tr>
<td></td>
<td>15.1 General discussion</td>
</tr>
<tr>
<td></td>
<td>In applying protective devices, it is occasionally necessary to compromise between protection and selectivity. While experience may suggest one alternative over the other, the preferred approach is to favor protection over selectivity. Which choice is made, however, is depended upon the equipment damage and the affect on the process.</td>
</tr>
<tr>
<td><strong>IEEE Std. 446 – 1995 IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (Orange Book) [7]</strong></td>
<td>Chapter 6 Protection</td>
</tr>
<tr>
<td></td>
<td>6.2 Short Circuit Considerations</td>
</tr>
<tr>
<td></td>
<td>…Careful planning is necessary to design a system that assures optimum selectivity and coordination with both power sources...</td>
</tr>
</tbody>
</table>
4.1. Consider Selective Coordination Early in the Design Process

The earlier in the design process selective coordination is considered, the less “painful” achieving selective coordination will be. The need for a coordination study, even a preliminary study, early in the design process is increasingly becoming recognized as a need if selective coordination is to be achieved without costly re-designs.

Working with overcurrent protective device manufacturers early in the design process generally makes the effort to achieve selective coordination go much more smoothly. In some cases this will require changes to the way projects are contracted and managed, since working with a particular manufacturer generally means staying with that manufacturer for the protective devices considered.

Good data is essential to the selective coordination effort. The utility available fault current, impedance data for the generator units to be used, motor fault current contribution, and good estimates of cable run lengths are all crucial. The earlier this information is obtained, the easier the coordination effort will generally be. When obtaining the utility available fault current, avoid “infinite bus” calculations, even on the primary side of a service transformer. “Real world” fault current values will be lower than those which rely on infinite-bus assumptions. While infinite bus assumptions have long been recognized as being conservative for short-circuit and coordination studies, coordination per the 2005 NEC requirements and arc-flash concerns both necessitate obtaining actual fault current values from the utility. Typically, obtaining both a “maximum” available fault current value for use with the short-circuit and coordination studies and a “minimum” available fault current value for use with arc-flash studies is preferred (and is an acknowledgement of the electric utility industry’s assertion that available fault current values can change over time due to system changes), although this is typically a challenge due to the industry’s reliance on infinite bus calculations.

4.2. Recognize the Conflicts and Issues with the 2005 NEC

4.2.1. Selective Coordination – What is it?

The wording of 2005 NEC 700.27 and NEC 701.18 leaves an open issue. Although “selective coordination” is defined in NEC 100 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”, NEC 700.27 and NEC 701.18 contain the wording “shall be selectively coordinated with all supply side overcurrent protective devices”. What about scenarios where two devices that are effectively in series protect a given piece of equipment?

Such a scenario is given in Fig. 17. The transformer shown is protected for short-circuits by the primary circuit breaker, and for overloads by the secondary circuit breaker. For a fault where the protective zones overlap, does it matter whether the primary or secondary circuit breaker trips? The answer is, of course, “no”. However, because of the wording of NEC 700.27 and NEC 701.18 the two circuit breakers would need to be selectively coordinated with
each other, even though it has no bearing on the performance of the system. So long as there are no connections to other devices between the two circuit breakers, the system may be selectively coordinated even though these two circuit breakers themselves do not coordinate. This is a crucial difference between selective coordination of devices and system selective coordination as described in section 2.3 above.

Fig. 17: Typical Low-Voltage Transformer Protection Scenario

Note that for transformers, such as the transformer shown in Fig. 17, removal of the secondary overcurrent protective device may not be possible due to restrictions in NEC 450. Removal of this device may also hinder transformer protection. For these and other scenarios in which two overcurrent protective devices in series must be utilized, the local Authority Having Jurisdiction should be consulted to provide a waiver.

Other possible scenarios for this issue are given in Fig. 18. In both cases, selective coordination of CB 1 and CB 2 is not required for overall system coordination, since there are no additional devices between the two. Both devices could be the same size device with the same settings.
What can be done about this issue? For the short-term, the solution is to minimize occurrences of overcurrent protective devices in series, as discussed below. Long-term actions may include the submission of change proposals for consideration in a future code cycle. The more proposals that are made on this issue, the more likely the issue is to be recognized and corrected.

4.2.2. Ground-Fault Protection in Health-Care Facilities

From the information in the preceding sections, a conflict in the 2005 NEC with respect to health care facilities can be recognized. To do this, consider the typical hospital electrical system per Fig. 19. Per NEC 700.27, all emergency system devices must be selectively coordinated with all supply-side devices. Taken literally, this forces coordination of emergency system protective devices up to the alternate power source and to the utility service. For services meeting the criteria of NEC 230.95 (such as a 480Y/277V utility service 1000A or greater), ground-fault protection is required at the service. This ground-fault protection must be set at no greater than 1200A pickup and a time delay of no more than 1s at 3000A or greater. NEC 517.17(B) requires an additional level of ground-fault protection in health-care facilities, and NEC 517.17(C) requires the two levels of ground-fault protection to coordinate with no less than a six-cycle (0.1s) margin between the two.

NEC 517.26 requires the essential electrical system to meet the requirements of NEC 700, which includes NEC 700.27. NEC 700.27 does not specifically require coordination of ground-fault protection.
To achieve selective coordination for ground-fault protection, the lowest level of ground-fault protection would have to coordinate with the phase time-current characteristics of the next lower downstream device. Most often, this will require additional levels of ground-fault protection to supplement the two required levels per NEC 517.17(B).

However, there is a problem: NEC 517.17(B) also effectively prohibits the use of additional levels of ground-fault protection in the essential electrical system! Therefore, selective coordination of ground-fault protection when the essential electrical system is supplied by the normal (utility) source cannot be achieved, in most instances, without violating NEC 517.17(B). As stated above, ~95% of all system faults are ground faults, therefore this is an issue with important consequences: A ground fault on a given branch of the essential electrical system, when it is supplied from the normal source, can cause that branch to be taken off-line, forcing a transfer to the alternate (generator) source. The response of the generator(s) would be a function of the ground fault current magnitude. All of this can transpire even if the system complies with the wording of NEC 700.27!

Fig. 19: Typical Health-Care Facility Electrical System (Source: NEC 2005 FPN Figure 517.30)

What can be done about this issue? For the short-term, bringing the issue up to the local Authority Having Jurisdiction for resolution is the only recourse. Long-term actions may include the submission of change proposals for consideration in a future code cycle. The more proposals that are made on this issue, the more likely the issue is to be recognized and corrected.
4.2.3. Is Coordination up to the Available Fault current Justified on a Practical Basis?

As mentioned in 2.2 above, the frequency of occurrence of high-magnitude bolted faults is much lower than that of lower-magnitude faults, such as arcing ground faults. Also, the higher the current level to which two overcurrent protective devices are coordinated, the more difficult the coordination effort becomes. The impact of this fact upon system protection and selective coordination are twofold, namely:

1.) It diminishes the practical need for selective coordination up to the available fault current in favor of “practicable” coordination to a lower level of fault current.

2.) It reinforces the need for coordinated ground-fault protection.

The wording of the 2005 NEC ignores the statistical evidence of the frequency of occurrence of high-level bolted faults. In reality, these faults are most common during the commissioning phase of the electrical system in a facility, when damage to cable insulation and other application and installation issues are corrected. During the normal lifetime of the system, these types of short-circuits are rare indeed, especially at lower levels in the system. One practical way to address selectivity in emergency and standby systems might be to set an established limit of 50% of the bolted fault current as the level of coordination for overcurrent devices below a given level (for example, 400A or below); this is an approximate worst-case for the calculated value of the arcing fault current for a 480V system when calculated per the empirical equations in IEEE-1584 IEEE Guide for Performing Arc-Flash Hazard Calculations [8]. Selective coordination up to such a limit would be justifiable on a practical basis. However, no code or standard presently sets this limit.

Arc-flash performance of the system is also a factor. In some cases, arc-flash performance, particularly at the lower levels of the system, may be impaired by forcing selectivity up to the available bolted fault current. The reason for this is that the arc-flash incident energy level is directly proportional to the time duration of an arcing fault, which is the clearing time for the overcurrent protective device which clears the fault.

Also, as described above the NEC effectively prohibits coordinated ground-fault protection in health care facility essential electrical systems, even though ~95% of all system faults are ground faults.

4.2.4. Avoid Placing Protective Devices in Series with No Equipment Between Them

From the foregoing discussion in 4.2.1, in many cases it is possible to meet the wording of NEC 700.27 and NEC 701.18 by avoiding the use of overcurrent protective devices in series with no equipment in between. Two examples of this are shown in Fig. 18 above. Fig. 20 shows the examples re-designed to eliminate redundant protective devices.
Care must be taken to insure that another NEC section is not violated when this is done, and that adequate protection of system components is maintained. For example, the panelboard PANEL 2 of Fig. 20 b.) may be a main-lugs only panel because there is no NEC requirement for a panelboard to have a local main disconnect, only overcurrent protection; this applies in all cases, even when the supplying panel is on a different floor. Overcurrent protection for the feeder cables between PANEL 1 and PANEL 2, and for PANEL 2, is provided by CB 1 in PANEL 1. For the generator of Fig. 20 a.), however, the removal of the circuit breaker at the generator should be verified with the local Authority Having Jurisdiction due to possible conflicts in interpretation of NEC 445.18, which requires a generator to be equipped with a disconnect by which the generator can be disconnected from the circuits it supplies. From a protection standpoint, the cables between the generator and CB 1 can typically withstand more short-circuit current than the generator can provide, and, further, the generator voltage regulator’s control system may have inherent features to shut down the generator if the generator supplies a fault for an extended period of time; this must, of course, be double-checked before making the decision to remove the circuit breaker at the generator. Overload protection for the generator and generator load cables is provided by CB 1.

4.3. Recognize the Pitfalls of Generator Protection

Selective coordination of devices is often difficult or impossible while maintaining adequate generator protection. Consider the system of Fig. 21. It can be shown that adequate short-circuit protection of the generators and coordination of CB 1 and CB 2 with CB 3, CB 4 and CB 5 are usually mutually exclusive, especially if only one generator is running and when CB 3, CB 4, and CB 5 short-time settings have to be maximized to achieve coordination lower in the system (it is assumed that CB 1 – CB 5 are electronic-trip circuit breakers with high short-time withstand ratings, such as ANSI power circuit breakers or insulated-case circuit breakers). This would be the case regardless of the requirements of the NEC for selective coordination.
or the selectivity of downstream devices. As an illustration of the effects of this lack of selectivity, consider the system of Fig. 22, which is the same system from Fig. 21 expanded to show the primary protective zones of the overcurrent protective devices. Note that although CB 3 and CB 6 selectively coordinate, the required settings of CB 1 and CB 2 for generator protection cause their primary protective zones to completely overlap the CB 3 protective zone and extend into the CB 6 protective zone. One method to prevent this is to design the system with a larger number of smaller-size generators, as shown in Fig. 23. This is a gross simplification, but it does illustrate the concept. In reality, reliability concerns will, in many cases, force additional generators to be added for redundancy; this is much more economically feasible for the system of Fig. 22 than for the system of Fig. 23. The addition of 51V or 51C voltage restrained/controlled relays can often improve the generator protection, but will not improve coordination.

**Fig. 21: Application with Paralleled Generators**

![Diagram of Fig. 21](image1)

**Fig. 22: System of Fig. 21 Expanded to Show Primary Protective Zones**

![Diagram of Fig. 22](image2)
Another approach is to raise the settings of the generator circuit breakers so that they coordinate with the next level downstream. In Fig. 22, this means that CB 1 and CB 2 would coordinate with CB 3, CB 4, and CB 5. But, CB 1 and CB 2 would no longer protect the generators adequately for short circuits. However, CB 3, CB 4, and CB 5 can typically be set to protect the generators for short circuits. Therefore, only for a fault on the paralleling switchgear bus between CB 1/CB 2 and CB 3/CB 4/CB 5 are the generators unprotected. This can be remedied by adding a bus differential relay for this bus, as shown in Fig. 24:
In Fig. 24, the differential relay 87B would typically be of the high-impedance type, and would trip CB 1, CB 2, CB 3, CB 4, and CB 5. A fault between CB 1/CB 2 and CB 3/CB 4/CB 5 will cause this relay to trip, and, if it is set appropriately, it will operate faster than the trip unit settings of CB 1 or CB 2, providing short-circuit protection for the generators in this protective zone as well as providing short-circuit protection for the paralleling switchgear bus. Generator overload protection would still be provided by CB 1 and CB 2. Note that generator differential protection is not shown; it could be provided to provide additional protection for the generator, but would not be an aid to selectivity. Generator differential relays, if used, should be of the percentage-differential type rather than impedance type. Note also that lockout relays, while recommended, are not shown. The circuit breakers which must be tripped by the differential relays must be suitable for external relay tripping (suitable insulated case circuit breakers or ANSI power circuit breakers are recommended, but are typically used in this application anyway). Economic concerns (cost of differential relays and CTs and the extra wiring required) must, of course, be taken into account when considering this approach.

A more in-depth treatment of generator protection for emergency and standby power systems is given in a separate paper, “Protection of Low-Voltage Generators – Considerations for Emergency and Standby Power Systems”.

4.4. Utilize Circuit Breakers with High Short-Time Withstand Capabilities

Circuit breakers are the de-facto standard for low-voltage overcurrent protection, for various reasons. As discussed above, circuit breakers need not be ANSI power circuit breakers to have a short-time withstand capability. Contrary to popular belief, circuit breakers also need not be electronic trip breakers to have a short-time withstand capability. When specifying circuit breakers, remember, however, that the UL 489 standard to which molded-case circuit breakers are designed and tested does not require a short-time withstand capability.

The net effect of a high short-time withstand capability for a circuit breaker is in its tripping performance in the short-circuit region. This can be seen by evaluating the time-current characteristics for a given circuit breaker, although short-circuit coordination tables must be used to gain the full advantage from such circuit breakers due to the dynamic impedance and current-limiting effects described above. In many cases it will be necessary to increase the frame size of the upstream circuit breaker in order obtain short-time withstand levels high enough to achieve total selective coordination.

For the service switchgear/switchboards, ANSI power circuit breakers or insulated case circuit breakers are essential, especially for medium- to large systems.
A fairly popular misconception is that when using electronic circuit breakers with the instantaneous function turned off, ANSI C37.20.1 low-voltage power switchgear is required. The reason behind this misconception is that UL 891 switchboard through-bus withstand tests are only required to be conducted for 3 cycles, whereas ANSI low-voltage switchgear is required to have a short-time withstand rating of 30 cycles. The exception, of course, would be where a manufacturer tests a switchboard configuration to the full 30-cycle withstand rating. In reality, the need for a short-time withstand rating for the switchboard bussing is only a concern where ANSI low-voltage power circuit breakers or insulated-case circuit breakers with high (or no) instantaneous override level is provided when the instantaneous function is turned off. In most cases the circuit breakers provided with switchboards have instantaneous overrides that cause the circuit breaker to trip instantaneously above a given level even if the instantaneous function is turned off, and these are tested with the switchboard to insure compatibility.

4.5. Avoid Multiple Levels of Protective Devices Where Possible

It must be stressed that the fewer the number of levels of overcurrent protective devices, the easier coordination becomes. Fig. 25 illustrates this point. In Fig. 25 a.), three panels are arranged so that three levels of selective coordination are required (CB 1 → CB 2 → CB 3). In Fig. 25 b.) the same number of panels has been re-arranged so that only two levels of selective coordination are required (CB 1 → CB 2 and CB 1 → CB 3). Often such an arrangement can be realized in a very economically feasible manner.

Fig. 25: Illustration Showing Multiple Levels of Selectivity:
   a.) Three Levels
   b.) Same Number of Panels Re-Arranged with Two Levels
4.6. Utilize Step-Down Transformers to Lower Fault Current

Remember that transformer impedance will lower the available fault current, and the smaller the kVA size of the transformer, the more drastic the reduction. Where coordination at the 480V level, for example, is not possible, coordination from 480V to 208V through a step-down transformer may be. If loads can be converted to utilize the lower voltage, this can be a way to achieve selectivity.

4.7. Increase Transformer Sizes Where Necessary

Although the smaller the transformer, the lower the available fault current at the secondary, there may be cases where transformers must be up-sized in order to achieve selective coordination. This is usually due to the frame size of the primary circuit breaker required to coordinate with devices at the next level below the transformer secondary main. A careful balance between the required frame size of the primary circuit breaker and the available fault current at the transformer secondary is usually required.


A popular misconception is that zone-selective interlocking (ZSI) between electronic-trip circuit breakers can force otherwise miscoordinated systems to coordinate. While it is true that ZSI can reduce the amount of energy let-through during a fault, it cannot be used to force selective coordination. The reason for this is that ZSI typically uses the short-time or ground-fault pickup (or both) on a downstream circuit breaker to identify that the circuit breaker detects a fault; the downstream breaker then sends a signal to “restrain” the next level upstream circuit breaker from tripping instantaneously while at the same time itself tripping instantaneously to clear the fault. However, the upstream circuit breaker will still continue to time out on its time-current band, ultimately tripping if the downstream circuit breaker fails to clear the fault in time. If the two circuit breakers are miscoordinated, the upstream circuit breaker may trip before the downstream circuit breaker, even with ZSI in place.

Used for the right reasons, however, ZSI is a powerful tool for reducing equipment damage and arc-flash incident energy since, on a coordinated system, it forces the device closest to a given fault to open in the minimum amount of time. Typically this time is somewhat longer than the instantaneous characteristic of the circuit breaker, due to the inherent time delay required for the ZSI logic operation.

4.9. Don’t Forget On-Site Adjustment Requirements

Despite the most careful planning, selective coordination efforts can quickly come to nothing if the overcurrent protective devices are not properly set on-site. Most manufacturers factory-set all but the ampere rating switch for electronic-trip circuit breakers in their lowest positions, for example. The coordination study should include tabulated settings for each overcurrent protective device which requires adjustment, such as electronic-trip circuit breakers, thermal-magnetic circuit breakers with adjustable instantaneous characteristics, ground-fault relays, etc.
5. References


