Designing for Circuit Breaker Instantaneous Selectivity

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Much has been written over the last several years on the concepts and details of selective coordination of overcurrent protective devices. Changes in the 2005 and 2008 National Electric Code (NEC) have stimulated an increased interest in this topic. While the fundamental concept of selective coordination is straightforward, its implementation in the design of commercial or industrial facilities can become complex. Overcurrent protective devices must coordinate with each other while also providing the intended protection without nuisance trips under a variety of conditions that include motor starting and transformer energization.

For the purposes of this paper, the term selective coordination (or terms selectivity or coordination used singularly) is used in the same context as defined by article 100 of the 2005 through 2011 NEC – "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". Overcurrents encompass any current that results from overload, short circuit or ground fault. This paper will focus on one specific aspect of the selective coordination challenge – coordination of the short circuit protection between low voltage circuit breakers. References 1 through 4 should be consulted for information on the general concept of selective coordination and where it must be applied.

Preliminary Concepts

Before discussing specific means by which circuit breakers may be coordinated, it is important to first understand several principals. It is convenient to think of circuit breaker coordination as having two main components – instantaneous and non-instantaneous. The instantaneous component is that part of the breaker's protective response that initiates breaker opening without any intentional delay. This type of response provides the desired fastest protection in the presence of higher-level fault currents. The non-instantaneous component is the breaker response that occurs with a time delay. This component includes the long-time and short-time portions of the breaker's time current curve. If the breaker has ground fault protection, a separate ground fault curve is also non-instantaneous. The article 100 definition of selective coordination in the 2005 through 2011 NEC does not distinguish between instantaneous and non-instantaneous coordination. The term "overcurrent" in the article 100 definition includes the full range of fault current from overload up to the available short circuit current. This range of fault current requires both instantaneous and non-instantaneous protection. The accepted interpretation of the NEC articles calling for selective coordination would require both the instantaneous and non-instantaneous components to coordinate for compliance. The local Authority Having Jurisdiction (AHJ) has ultimate discretion in the enforcement of NEC selectivity requirements. Some AHJs take exception to coordination of the instantaneous component and only mandate non-instantaneous coordination. Instantaneous coordination has traditionally been the more challenging component and code changes first appearing in 2005 have spurred recent circuit breaker developments to meet this challenge.

Traditionally, circuit breaker coordination is demonstrated by plotting time-current curves and selecting the pick-up and delay settings (if they exist) such that the curves of two circuit breakers in series do not overlap, with the upstream device curve always being to the right and/or above the downstream device curve. Obtaining non-instantaneous coordination generally starts with adequate separation of the ampere rating (or long-time pick-up) between breakers in series. Non-instantaneous coordination is a simpler matter when working with electronic trip units because of the narrower tolerance bands they possess (compared to thermal-magnetic breakers) and because of the ability that some have to independently adjust the various parts of the curve. Achieving coordination in one of the components (either instantaneous or non-instantaneous) does not assure coordination in the other.

An important characteristic of a circuit breaker is its requirement to protect itself when applied within its ratings. It is this characteristic that creates the extended "foot" on the time current curve and increases possibilities for overlap with upstream devices. It is important to clearly differentiate between a breakers ability to safely interrupt current and the current level to which breakers can coordinate. The breaker interrupting capability (or AIC rating) must always be above the available fault current at the location where the breaker is applied. The AIC rating is associated with an individual breaker, except in the case of UL recognized series ratings. The coordination level of a breaker must always be stated with reference to either an upstream or downstream breaker and indicates the maximum current for which the pair of breakers coordinate. In order to achieve instantaneous coordination, the coordination level of a breaker pair must be equal to or greater than the available fault current at the downstream breaker. Design for selective coordination should be based on the available fault current at each bus, not the specified AIC or bus bracing level. Coordination capability of breakers above the available fault current is generally not a concern since it is impossible for short circuits to exceed the correctly calculated maximum short circuit current for a given system topology. However, having some coordination capability that exceeds the available short circuit current may be desirable if future upgrades are anticipated so that changes in the system that cause the maximum short circuit current to increase do not result in non-selective performance at the higher fault values.

The AIC rating of a breaker is normally indicated on a time-current curve by the end of the instantaneous protection plot on manufacturer published curves. When time-current curves are produced by system analysis software, the limit of the instantaneous response is normally shown at the calculated available fault current.

Instantaneous Coordination

This paper will describe four readily available means by which the design engineer can achieve instantaneous coordination between breakers in a low voltage system. They are

1) Impedance
2) Selective Coordination Tables
3) Waveform Recognition
4) Instantaneous Zone Selective Interlocking

Impedance may be considered a physical solution to instantaneous coordination, as its presence is a result of system properties. Selective coordination tables are vendor specific and document a variety of circuit breaker and trip unit combinations in a convenient form that allows the user to easily identify the coordination performance of selected pairs of breakers. The later two means are specific capabilities provided within the breaker electronic trip unit to increase instantaneous coordination capabilities. These later two means have only recently become available. The four methods listed here are not the only means to evaluate and select circuit breaker pairs for instantaneous coordination. Several analytical methods are also available (references 5, 6, and 7), and in fact some of these analytical techniques are used in constructing selective coordination tables.

A method used by some to achieve instantaneous coordination between a main and a feeder on switchgear is to disable instantaneous protection on the main breaker. While this does provide perfect coordination between the main and feeders, it cannot be characterized as an instantaneous coordination solution since instantaneous response does not exist on both breakers. It is also a solution that can increase risk during an arcing event on the main bus because the main breaker must wait until its short time delay is reached before it begins to open. From a worker safety standpoint, using a main breaker without instantaneous protection is no longer a justifiable practice given the need to mitigate arc flash incident energy and the alternatives for doing so while achieving coordination. For information on how the circuit breaker coordination technologies covered in this paper can affect arc flash energy levels, the reader should consult the paper by Fox (reference 8).

Impedance

Impedance is a natural ally to coordination. The opportunity to have selective coordination increases as the impedance increases between any two breakers in series. As impedance between two breakers increases, so does the difference in the available fault currents at each breaker's location. The ideal situation is reached when the available fault current at the downstream breaker is below the instantaneous pick-up (less any tolerance) of the upstream breaker. In this case, instantaneous coordination is assured.

While conductors contribute impedance to an electrical system and cause the available fault currents further down in an electrical distribution system to decline, it is impractical to use conductor length as a design tool to achieve coordination for a variety of reasons. Circuit breakers on the same equipment bus have negligible impedance between them and experience essentially the same available fault current. Transformers, however, provide significant impedance and the available fault current on the transformer secondary is always significantly lower than the available fault current on the transformer primary on a same voltage basis. If the difference in available fault current is large enough such that the primary side breaker instantaneous pick-up is above the available fault current on the secondary side bus, instantaneous coordination between the primary side breaker and every downstream breaker is guaranteed.

This is illustrated in Figure 1, which is a generic example for coordination across a general-purpose transformer used to supply 208V and 120V loads connected via a downstream panel. The horizontal scale is current and the vertical scale is time. These graphs are plotted on logarithmic scales for both current and time, but axis scaling is omitted for simplicity. Breakers "B" and "C" are on the same panelboard bus and exposed to the same fault current. Point 1 is the maximum possible fault current on the transformer secondary. The responses of breakers "B" and "C" are cut-off at this value of amperage. The actual amperage value for Point 1 will be primarily influenced by the transformer capacity and impedance. Point 3 represents the instantaneous pick-up setting of breaker "A". Point 2 is the breaker "A" instantaneous pick-up adjusted for breaker and trip unit tolerance.

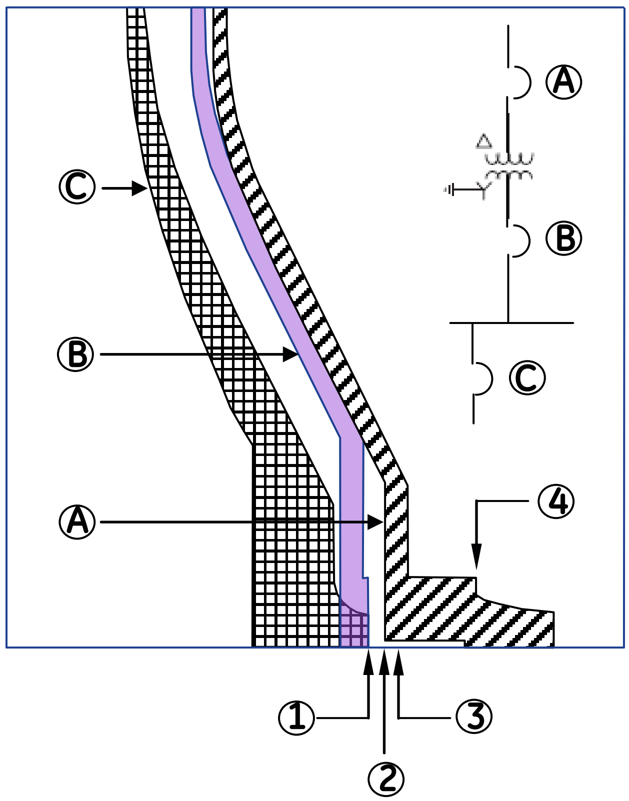

Figure 1. Coordination Across a Transformer (horizontal axis is current, vertical axis is time)

The transformer primary and secondary devices (breakers "A" and "B" in the figure) are instantaneously coordinated. When Point 2 is above Point 1, instantaneous coordination is achieved between the transformer primary breaker and every breaker on the secondary side. Coordination between the transformer secondary and the feeders/branches (breakers "B" and "C" in figure 1) are also of concern, but impedance is not the vehicle for instantaneous coordination in this case. As seen in figure 1, some portions of the time-current curves overlap in the non-instantaneous region. The transformer primary and secondary breakers are not selective in the non-instantaneous range but no unnecessary loss of circuits results from this lack of coordination because no additional loads are interrupted by the primary device operating instead of the secondary device. This is an allowable situation under the exceptions in Articles 700.27 and 701.27 (formerly 701.18 in the 2005 and 2008 NEC) of the 2011 NEC. Vendor specific templates for transformer coordination, such as reference 9, can be used to ensure the proper breaker ratings are selected to achieve coordination across general-purpose transformers.

Selective Coordination Tables

Selective coordination tables describe the instantaneous coordination behavior of two specific breakers in series. These vendor specific documents are becoming increasingly comprehensive, but at their core list an upstream breaker, a downstream breaker, and the value of fault circuit current to which the pair instantaneously coordinates. While leveraging impedance to provide coordination relies on a system property, the coordination tables capture paired breaker interactions that are rooted more in the breakers construction and dynamic characteristics during fault clearing. The instantaneous coordination performance of two breakers in series is not necessarily determined by evaluating the relationship between their time current curves. In many cases, the time current curve analysis under-predicts the actual instantaneous coordination capability. The reason for this disparity lies in the fact that a breaker's time-current curve is established by testing the individual breaker with a current source. When two breakers are in series, however, the dynamic operation of the downstream breaker influences the fault current that the upstream breaker experiences as the downstream breaker begins to open. This interaction tends to be more pronounced when the downstream breaker's instantaneous trip is faster than the upstream breaker's. This interaction is also enhanced by a downstream circuit breaker that is current limiting. The true current limiting nature of breakers that have this property is often not reflected in manufacturers' published time-current curves, again contributing to the discrepancy between instantaneous coordination predicted by time-current curve analysis and actual performance.

Using selective coordination tables is the simplest means to achieve an instantaneously coordinated system, especially for breakers on the same bus where techniques 3 and 4 are not used. Manufacturer coordination tables may include assumptions that should be carefully reviewed. Normally a key assumption is that the upstream breaker has its instantaneous pick-up set to the maximum possible. The coordination performance is heavily influenced by the breaker type, frame size, rating plug or ampere rating, and sensor size (rating plugs and sensors are applicable to electronic trip breakers only). For example, the following pairs are extracted from the "*GE Overcurrent Device Instantaneous Selectivity Tables*" (reference 10).

Upstream Breaker	Downstream Breaker	Maximum Coordination
FG (600A)	FB (100A)	65,000 A
FG (600A)	TEY (100A)	6,000 A
FG (600AF/400AS/250AT)	THQB (100A)	22,000 A
FG (600AF/250AS/250AT)	THQB (100A)	2,500 A

AF = frame amps; AS = sensor amps; AT = trip amps

Table 1. Selectivity Table Examples

The values for "maximum coordination" in table 1 represent the fault current at the downstream device. The first two rows show an order of magnitude difference in coordination performance between the same upstream breaker and two different downstream breakers.

Similarly, an order of magnitude difference in performance occurs between the third and fourth rows when changing the sensor size of the upstream breaker. General examination of selectivity tables will show that coordination performance decreases as the separation in frame size between the upstream and downstream devices decreases. Even when adequate frame separation is present, the above table demonstrates that other variables must be carefully observed to optimize coordination performance.

Returning to Figure 1, time-current curve examination would normally lead one to conclude that breakers “B” and “C” do not instantaneously coordinate due to the overlap in their curves. If breakers “B” and “C” are listed as an upstream-downstream pair in the vendor coordination tables, then the breakers will coordinate instantaneously if the value in the table is at least as high as the fault current available at Point 1 (and all other conditions for use of the tables are met).

Waveform Recognition

The previous methods have relied on system and breaker properties. Waveform recognition, as well as instantaneous zone selective interlocking in the next section, is a specific modern electronic trip unit capability. A modern trip unit and breaker are inherently fast enough to perform their traditional instantaneous protection function with time to spare relative to a three cycle clearing requirement. A trip unit with waveform recognition takes advantage of this “extra” time by sensing current and making a trip decision after instantaneous pick-up current is detected, but before it commits to tripping. If the downstream breaker is current limiting, an upstream breaker with waveform recognition can identify a current signature caused by the downstream breaker responding to the fault. The upstream trip unit will recognize this current limiting signature, understand the downstream breaker is in the process of clearing the fault, and not commit to tripping. Since the trip unit “extra” time is limited, this strategy can only be applied with downstream current limiting breakers. Current limiting breakers are generally available in 600A frame sizes or less. This method also works when the downstream device is a current limiting fuse.

This method requires no explicit communications or wiring between the two breakers involved. The shared power path between the two breakers is the sensing path. No information is entered into the trip unit to identify the downstream device. An upstream breaker with waveform recognition will not commit to tripping when the fault is both below the downstream current limiting device and of sufficient magnitude to be within the current limiting range of the downstream device. Otherwise, the upstream breaker will commit to tripping if the downstream device fails to clear or if the fault is between the upstream and downstream device. A current limiting device is not current limiting throughout its entire range of overcurrent protection. The time current curve for breaker “A” seen in Figure 1 is representative of a current limiting breaker. Point 4 in Figure 1 is the current limiting threshold. The ever-decreasing clearing time beyond this point is characteristic of a current limiting breaker. The instantaneous pick-up (less tolerance) of the upstream breaker trip unit equipped with waveform recognition must be set past the current limiting threshold of the downstream device when using this coordination technology. Manufacturer information should be used to select the minimum instantaneous pick-up setting that will ensure selective coordination above a specific current limiting device.

Instantaneous Zone Selective Interlocking

This technique is a logical extension of waveform recognition for the situation where the downstream breaker is not current limiting. In the case where the downstream breaker is not current limiting, there may not be enough time for the upstream breaker to determine via waveform sensing if the downstream breaker is clearing a fault before the upstream breaker must commit to tripping. The technical solution thus becomes communication between breakers instead of sensing. When the downstream breaker senses the short circuit fault current, it provides a voltage signal to the upstream breaker. The upstream circuit breaker then interprets the signal to mean the downstream breaker sees the fault and will clear it. The upstream breaker then responds by restraining its own instantaneous response, allowing the downstream breaker to clear the fault. Such a solution is often referred to as interlocking, or zone selective interlocking (ZSI). Should the downstream breaker fail to clear the fault for any reason, the upstream breaker provides fast backup protection.

ZSI has been available for many years and has been offered by numerous vendors to provide improved short time and ground fault protection. Only recently has this concept been extended to provide instantaneous coordination. In order to use this method both the upstream and downstream breakers and their electronic trip units must be capable of supporting the scheme. Currently, only low voltage power circuit breakers are able to support instantaneous zone selective interlocking as either the upstream or downstream breaker. Selected molded case circuit breakers are only able to function in the role of the downstream breaker that sends the ZSI signal to the upstream breaker in the scheme.

Instantaneous ZSI offers instantaneous coordination up to the withstand rating or interrupt rating of the breaker. The coordination performance of two breakers interlocked using instantaneous ZSI will exceed the coordination performance for the same breaker pair found in selective coordination tables. This method may also allow instantaneous coordination at lower instantaneous pick-ups at the upstream breaker compared to waveform recognition because the coordination capability is not limited to values above a current limiting threshold of the downstream device. Instantaneous ZSI may, therefore, be considered even when the downstream breaker is a current limiting molded case circuit breaker when a lower instantaneous pick-up on the upstream breaker is desirable. Instantaneous ZSI can be applied to breakers on the same bus (mains, ties, and feeders) and between a feeder and a breaker on a downstream piece of gear. Unlike waveform recognition, wiring is required between two breakers that use instantaneous ZSI.

Implications for the Design Engineer and Specifier

Engineers now have great flexibility to meet the challenges of coordinating complex systems. Coordination tables provide a readily available tool for engineers designing systems requiring instantaneous coordination of circuit breakers. There are now a number of circuit breaker and trip unit technologies that enhance instantaneous coordination between circuit breakers, and in some cases between circuit breakers and fuses. When instantaneous coordination is required beyond what is documented in selective coordination tables, the designer should consider using waveform recognition or instantaneous ZSI technologies in their design. Some or all of the methods discussed here may be utilized in the same system to achieve coordination goals. Specifications must, however, be carefully worded in order to achieve the desired coordination. Specifying breakers to coordinate to the AIC rating of the breaker may increase the cost of the equipment provided compared to specifying breakers to coordinate to the available fault current.

Often, coordination studies are specified as part of a project. It must be recognized that the coordination study is most useful in selecting the proper breaker protection settings such that the protective devices allow for transient events such as motor starting without nuisance tripping, and coordinate with each other in the non-instantaneous region using the minimum delays and pick-ups. The coordination study should not be expected to determine settings that achieve instantaneous coordination if it is performed after the equipment and protective devices have been selected and released for manufacturing. Instantaneous coordination is achieved by careful design of the system and proper specification of breakers and trip unit capabilities. The engineer performing a coordination study will not be able to make circuit breakers coordinate in the instantaneous range via the selection of instantaneous pick-up settings if the system layout is improper and or the appropriate capability has not been specified. The system designer should, therefore, perform a preliminary coordination study during the design process to be assured that instantaneous selective coordination is possible with the proposed system topology.

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