Selectively coordinated overcurrent protection for power systems

When designing a safe and reliable power distribution system, it is imperative to consider life safety and equipment protection.

Marius Popescu, PE; Ali Ashur, PE; and Michael Stevens
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Learning Objectives

- Know the industry best practices for electrical circuits overcurrent protection and selective coordination of protective devices.
- Understand how these best practices can be applied on projects to minimize power disruption.
- Understand overcurrent-based protection of electrical systems and how to achieve selective coordination.

PEER REVIEWED

Even the most robustly designed and well-maintained electrical systems can experience faults. Faults can be the result of natural events including lightning; environmental factors, such as aging and deterioration of electrical equipment; or human error, like the shorting of bus bars with a metallic tool. If left unchecked, faults in the electrical system can lead to equipment damage, arc blasts, and building fires. This is due to the mechanical forces and thermal energy that result from the huge fault currents that flow in the system. Protection, therefore, is vital for the electrical power system and its components.

The most basic function of a protection system is to recognize abnormal or faulty circuit operation and to then remove the faulted circuit from the electrical system to minimize damage to equipment and safeguard personnel and property. Protection can be defined based on the electrical system component being protected-generator protection, transformer protection, transmission-line protection, bus protection, feeder protection, and motor protection (which is the most common type).

An alternative way to define protection is based on the principle used in the protection scheme. This includes overcurrent protection, differential protection, distance protection, over/under voltage protection, and over/under frequency protection.

The following discussion will be limited to coordinated and selectively coordinated overcurrent protection-the most common form of circuit protection. Coordinated protective devices provide an optimal balance between fault localization and circuit protection based on the responsible engineer's judgment. Selectively coordinated protection is required for a few select power systems, such as emergency systems, critical operations power systems, and fire pumps. The objective of selective coordination is to ensure coordination in the full range; there is no engineering judgment as to what level of coordination is acceptable.

Key electrical codes, standards, and definitions

There are multiple electrical codes and standards that apply when designing and constructing projects, and they all require diligent consideration to ensure life safety, reliable power, and equipment protection. NFPA 70: National Electrical Code (NEC), is the industrywide standard in the United States regarding safely installing electrical wiring and equipment. It is typically adopted by state and local agencies to standardize the enforcement of safe electrical practices in their jurisdictions. An overview of key terms from 2017 Edition of NEC Article 100 includes the following:

- **Overcurrent:** Any current in excess of the rated current of equipment or the ampacity of the conductor. This may result from overload, short circuit, or ground fault.
- **Overload:** The operation of equipment in excess of the normal, full-load rating or in excess of rated ampacity (conductors) when it persists for a sufficient length of time to cause overheating. A fault, such as a short circuit or ground fault, is not considered overload.
- **Short-circuit current:** An overcurrent resulting from a fault of negligible impedance between live conductors having a difference of potential under normal operating conditions.
- **Ground fault:** An unintentional electrically conducting connection between an ungrounded conductor of an electrical circuit and the normally non-current-carrying conductors, metallic enclosures, metallic raceways, metallic equipment, or earth.
- **Selective coordination:** Refers to the localization of an overcurrent condition to restrict outages to the circuit or equipment affected. This is accomplished by the selection and installation of overcurrent protective devices (OCPDs) with their ratings or settings for the full range of available overcurrents, from overload to the maximum available fault current, and for the full range of OCPD opening times associated with those overcurrents.

NEC's selective coordination requirements specifically define selective coordination in Article 100 and mandate the proper selection and coordination in Article 110.10. Selective coordination shall be selected by a licensed professional engineer or another qualified person primarily in the design, installation, or maintenance of electrical systems. Selective coordination is not typically required between overcurrent devices connected in series if no loads are connected in parallel with downstream devices. Additional key selective coordination requirements defined in NEC include:

- **Article 240.12** (Electrical System Coordination) defines electrical system coordination based on two conditions: coordinated short-circuit protection and overload indication based on monitoring systems.
- **Article 517.17** (Ground-Fault Protection) requires that the ground-fault protection of the feeder and disconnecting means to be fully selective for hospitals and other buildings with life-support equipment, and for buildings that provide essential services for the operation of critical care equipment. Also, article 517.17 (G) states that essential electrical systems are required to be coordinated for the period that a fault's duration extends beyond 0.1 second.
- **Article 620.62** (Selective Coordination) requires selective coordination for elevators in the cases where more than one driving machine's disconnecting means is supplied by a single feeder.
- **Article 645.27** (Selective Coordination) requires that the overcurrent devices associated with the critical operation data systems to be selectively coordinated with all supply-side OCPDs.
- **Article 695.3** (C)(3) (Multibuilding Campus-Style Complexes [Fire Pumps]) requires selectivity between each disconnecting means and all supply-side OCPDs.
- **Article 700.32** (Emergency Systems Selective Coordination) requires that the emergency system overcurrent devices be selectively coordinated with all supply-side OCPDs.
- **Article 701.27** (Selective Coordination) requires that the standby system overcurrent devices be selectively coordinated with all supply-side OCPDs for Legally Required Standby Systems.
- **Article 708.54** (Selective Coordination) has similar requirements as shown above in Article 701.27 but for Critical Operations Power Systems [COPS].

Overcurrent protective devices

An OCPD is installed to protect against instances when the current exceeds the rating of the conductors or the

equipment. These instances can result from either a short circuit, a ground fault, or general overload. There are several devices that are designed to protect against overcurrent, the most common include:

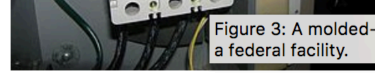


Figure 3: A molded-case circuit breaker (MCCB) ins
a federal facility.

- **Overcurrent relays**, which are auxiliary devices that, in connection with a circuit breaker or switch, operate when the current in the circuit exceeds a predetermined threshold or pickup setting by sending a trip (or open) command to the breaker's trip unit or the switch. Overcurrent relays are commonly used in medium- and high-voltage systems, but they have recently found uses for some low-voltage applications. The main disadvantages of electromechanical-type relays are they can generate signalnoise due to the mechanical system, they require higher input power to operate, they lose their settings due to moving-parts failures, they have a slower response time, and they cannot operate in areas with large electromagnetic forces. An electromechanical overcurrent relay is shown in Figure 1.
- **Power fuses** are devices that protect a circuit by opening its current-responsive element (the fusible art that is heated and severed) when an overcurrent passes through them. The main functional characteristics are combined sensing and interrupting elements in a self-contained device. A power fuse is a direct-acting device that responds to a combination of magnitude and duration of current flowing through it. It is inherently a single-phase device and does not include provisions for manually making or breaking the circuit; it needs replacement before restoration of service (exception: current-limiting fuses) and it typically has a larger footprint than circuit breaker equipment. Installed power fuses are shown in Figure 2.

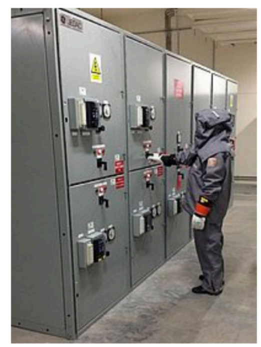
- **Low-voltage circuit breakers** are defined by NEC as devices designed to open and close a circuit by nonautomatic means, and to open the circuit automatically on a predetermined overcurrent level without damage to themselves when properly applied within its rating. Unlike fuses, circuit breakers are inherently 3-phase (where all three phases actuate simultaneously) and are resettable in most cases (no element replacement). IEEE C37.100 classifies low-voltage circuit breakers in molded-case circuit breakers (MCCBs) and low-voltage power circuit breakers (LVPCBs). MCCBs and LVPCBs are shown in Figures 3 and 4.

The insulated-case circuit breaker (ICCB) is derived from a MCCB and is used to designate a circuit breaker with a supportive and enclosing housing of insulating material and a stored-energy mechanism. ICCB uses characteristics of design from both the power and molded-case classes. Examples of trip units used in LVPCBs include:

Electromechanical trip devices. In the past, LVPCBs were equipped with an electromechanical trip device of the moving armature type, using a heavy copper coil carrying the full-load current to provide the magnetizing force. In this trip unit, overload protection is provided by a dashpot restraining the movement of the armature. Short-circuit protection is provided when the magnetic force suddenly overcomes a separate restraint spring.

Solid-state trip devices. Solid-state trip devices operate from a low-current signal generated by current sensors or current transformers in each phase. Signals from the sensors are fed into the solid-state trip unit, which evaluates the magnitude of the incoming signal with respect to its calibration setpoints and acts to trip the circuit breaker if preset values are exceeded.

The total clearing time of a circuit breaker is the sum of the breaker's sensing time, unlatching time, mechanical operating time, and arcing time. A fuse's total clearing time is the total opening time from the occurrence of an overcurrent until the fuse stops current flow. This is the sum of link-melting and arcing time. The time current curve (TCC) for an adjustable circuit breaker includes the following zones:



- **Long time pickup (LTP)** is the level of current the circuit breaker will carry without tripping; LTP typically can be adjusted from 20% to 100% of the breaker's nominal rating.
- **Long time delay (LTD)** is used to intentionally delay the breaker's tripping to allow temporary inrush currents (e.g. starting a motor) to pass through.
- **Short time pickup (STP)** is used for selective tripping, allowing the downstream protective device to clear short-circuit currents without tripping the upstream device. The STP is typically adjustable between 1.5 to 10 times the trip-unit ampere setting.
- **Short time delay (STD)** is used in conjunction with STP and delays the short time pickup by a predetermined time period, allowing better coordination between thermal-magnetic circuit breakers and fuses; there are two modes: fixed-time and I2t ramp.
- **Instantaneous pickup** is used to trip the circuit breaker without an intentional delay.
- **Ground-fault pickup** is used to control the amount of ground-fault current that will cause the breaker to interrupt the circuit. This is typically set from 20% to 70% of the maximum breaker rating, but the trip point should be a maximum of 1,200 A (refer to NEC 230.95(A)).
- **Ground-fault delay** is used to provide an intentional delay of the ground-fault trip.

Selective coordination and protection study

System protection is achieved if the overcurrent devices settings are above the load operating levels and below electrical equipment damage curves. The selectivity is met when an OCPD on a circuit is interrupted and only the closest upstream device opens, such that only the section of the electrical system with a problem is removed from service. The circuit protection and selective coordination among protective devices associated with the power distribution system is not an easy process and requires knowledge and experience with local and national codes and standards.

The circuits protection and coordination should meet the following characteristics:

- Rapidly isolate the affected portion of a distribution system to maintain the normal service as much as possible and to minimize the damages.
- Minimize the magnitude of the fault current.
- Minimize the duration of the equipment outages.

To ensure proper circuit protection and coordination, the electrical engineer needs to perform the following studies: load analysis, short-circuit calculations, protective device selection, and coordination. There are several power-analysis programs on the market that can be used to model the power distribution system and evaluate its behavior on faults at different locations.

The four main steps summarized in Table 1 are used in evaluating the circuit's protection:

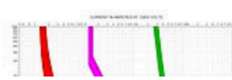
Table 1: Evaluating circuit protection

Step	Task	Description
1	Data collection	Obtain the available fault current (3-phase, 1-phase to ground, reactance-to-resistance (X/R) ratio) and permissible voltage range from the utility. Obtain single-line drawings of the facility, verify and update single-line drawings based on the existing conditions. Collect all the available info about existing equipment (nameplates info, electrical equipment data sheets, breakers or relays settings, etc.)
2	Distribution system modeling	Prepare the electrical distribution system model using power-analysis software.
3	Short-circuit analysis/simulation	A short-circuit study is performed to evaluate if the electrical equipment is adequately rated to withstand the calculated short-circuit duty. The analysis program is used for calculating the short-circuit currents for 3-phase and line-to-ground faults. The single-line-to-ground fault to determine the settings of the ground-fault relays and the 3-phase symmetrical fault that typically produces the highest overall fault current. The available short-circuit current at each bus should be equal to or less than 1) the momentary withstand capability of the bus and breakers and 2) the interrupting capability (measured in kiloamperes; kAIC) of breakers.
4	Protective device coordination study	This study is performed to determine if the settings of the protective devices ensure/maintain adequate coordination. The coordination study proceeds in a bottom-to-top order to select the settings for the faster downstream feeder breaker before selecting the settings for the upstream, slower source breaker, ensuring in this way the selective coordination and protection.

TCCs are provided by the protective device manufacturer to show the amount of time required for a protective device to trip at a given overcurrent level. These curves are essential for the proper coordination of protective devices (breakers, fuses). Generic TCC curves for different protective devices are shown below in Figure 5. Fuses operate in a time-current band between maximum clearing times and minimum melt (or damage) times. The difference is the arcing time within the fuse. The minimum melt time is important when the fuse backs up other devices.

There are several protective device coordination methods that can be used, including current-type selectivity, time-type selectivity, zone selectivity, energy selectivity, and backup protection. Description of these protective device coordination methods are as follows:

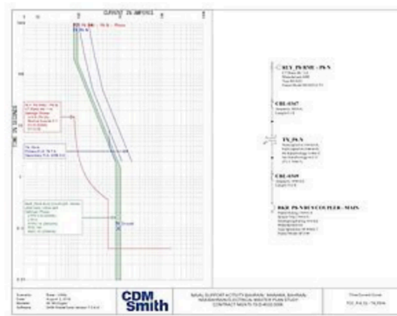
- **Current-type selectivity:** This method considers that the highest fault (short-circuit) current is given by the proximity to the power source (i.e., the closer the fault is to the power source, the higher the short-circuit current will be). This coordination is recommended for end user power distribution systems since it involves low short-circuit currents due to the high impedance between the source and load. The overcurrent setting allows the protective device to trip and isolate the fault at the load side, and it does not cause nuisance trips at the power-source side. This solution is easy to implement and is cost-effective.
- **Time-type selectivity:** This method uses the fault-current magnitude and the duration of the fault to define the tripping threshold of the protective device. In other words, a protective device will trip after an established time delay to allow those devices closer to the fault to trip. This method is easy to implement and helps reduce the number of loads affected by a fault (providing increased reliability).



- **Zone selectivity:** This method uses communication between current-measuring devices and protective devices to allow detection of the specific zone affected by a fault. This solution is typically used in the primary distribution switchgear (load side of transformers or generators). This can be implemented by using a supervision system that monitors the current flows in the circuit (information received from measuring devices), compares with a threshold level, and then decides which protective device to trip. Another way to implement this coordination is by using protective devices capable of sending a blocking signal to the upstream devices when a certain current-value threshold is exceeded. Zone selectivity reduces the protective trip times, reduces damages produced by a fault, and increases safety.

- **Energy selectivity:** This method counts on the current-limiting characteristics of a protective device (current-limiting fuse, current-limiting circuit breaker). This type of coordination/selectivity is typical for secondary distribution.
- **Backup protection:** This method requires two protective devices connected in series (one at the power-source side and one at the load side), which are open simultaneously (or just at the power-source side) when a fault occurs.

Methods to improve selective coordination include, but are not limited to, increasing the withstand capabilities of the upstream line-side OCPDs, changing the type of circuit breaker (for example, from molded-case type to ICCB or LVPCB), selecting a current-limiting-type protective device, using fuses that do not overlap in the instantaneous range, or using manufacturer-tested, series-rated protective devices.

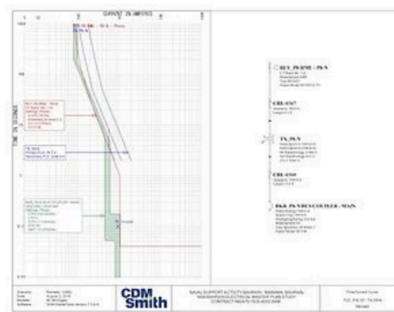


Even the most robust, well-designed and maintained electrical systems can experience faults. If left unchecked, faults in the electrical system can lead to equipment damage, arc blasts, and building fires. Protection, therefore, is vital for the electrical power system and its components. Selectively coordinated protection is required for a few select power systems, such as emergency systems, critical operations power systems, and fire pumps. Coordinated protective devices minimize disruption to plant operations by restricting an outage to only the faulted circuits and therefore provide an optimal balance between fault localization and circuit protection based on the responsible engineer's judgment.

Case study: Improving the electrical utility system at NSA Bahrain

Naval Support Activity (NSA) Bahrain is a U.S. naval base located in the Kingdom of Bahrain and serves as a central point of U.S. military operations in the region.

NSA Bahrain is also the home of the U.S. Naval Forces Central Command and U.S. Fifth Fleet. In recent years, NSA Bahrain has undergone significant changes, expansions, and upgrades with the addition of new operations and facilities to support military operations. An electrical equipment photograph from the project is shown in *Figure 6*.



Using Power Tools for Windows (PTW) software, also known as SKM, CDM Smith performed an electrical system analysis that included a protective device coordination study from the 66-kV utility supply to the 415-V level. The existing protective devices' settings showed a lack of selective coordination between the medium-voltage (MV) relay and the low-voltage (LV) bus-feeder circuit breakers. The MV relay curve, time dial, and instantaneous pickup settings were adjusted to better coordinate the overcurrent protective devices. [WEB ONLY]Before and after time-current curve samples from the MV/LV side of the power distribution system are shown in Figures 7a and 7b.

To perform the study, CDM Smith conducted onsite data-collection activities using mobile computing devices. The final report included:

- Power system models that were developed using SKM Power Tools software.
- A variety of power system analyses that were conducted on the model, including short-circuit analysis and a protective device coordination study.

The final report documented the findings and made more than a dozen recommendations to the U.S. Navy to improve the electrical utility system coordination at NSA Bahrain.

Marius Popescu is a senior electrical engineer at CDM Smith. Popescu has more than 20 years of experience in the power industry (generation and distribution). **Ali Ashur** is a senior electrical engineer at CDM Smith. Ashur has 10 years of electrical engineering experience, specializing in both design and studies of electrical power distribution systems and involving complex projects for municipal, federal, and industrial clients. **Michael Stevens** is a technical writer at CDM Smith. Stevens has been supporting technical submittals and deliverables across multiple engineering disciplines for more than 20 years.
