



Introduction to Protective Device Coordination Analysis

An Online Continuing Education Course for Engineers

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Introduction to Protective Device Coordination Analysis

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General

Electrical power systems must be designed to serve a variety of loads safely and reliably. Effective control of short-circuit current, or fault current as it is commonly called, is a major consideration when designing coordinated power system protection. In order to fully understand the nature of fault current as it is applied to electrical power system design, it is necessary to make distinctions among the various types of current available, normal as well as abnormal. It is also important to differentiate between the paths which the various types of current will take. Both types of current and current path, as well as current magnitude, will affect the selection and application of overcurrent protective devices.

Normal Current

Normal, or load, current may be defined as the current specifically designed to be drawn by a load under normal, operating conditions. Depending upon the nature of the load, the value of normal current may vary from a low level to a full-load level. Motors offer a good example. Normal motor current varies from low values (under light loading) to medium values (under medium loading) to maximum values (under maximum loading). Maximum load current is called full load current and is included on the motor nameplate as FLA (Full-Load Amperes). Normal current, therefore, may vary from low values to FLA values. Additionally, normal current flows only in the normal circuit path. The normal circuit path includes the phase and neutral conductors. It does not include equipment grounding conductors.

Overload Current

Overload current is greater in magnitude than full-load current and flows only in the normal circuit path. It is commonly caused by overloaded equipment, single-phasing, or low line voltage, and thus is considered to be an abnormal current. Some overload currents, such as motor starting currents, are only temporary, however, and are treated as normal currents. Motor starting current is a function of the motor design and may be as much as twenty times full-load current in extreme cases. Motor starting current is called locked-rotor current and is included on the motor nameplate as LRA (Locked-Rotor Amperes). Overload current, then, is greater in magnitude than full-load amperes but less than locked-rotor amperes and flows only in the normal circuit path.

Short-circuit Current

Short-circuit current is greater than locked-rotor current and may range upwards of thousands of amperes. The maximum value is limited by the maximum short-circuit current available on the system at the fault point. Short-circuit current may be further classified as bolted or arcing.

- *Bolted short-circuit current.* Bolted short-circuit current results from phase conductors becoming solidly connected together. This may occur from improper connections or

metal objects becoming lodged between phases. Obviously, large amounts of short-circuit current will flow into a bolted fault.

- *Arcing short-circuit current.* Arcing short-circuit current results from phase conductors making less than solid contact. This condition may result from loose connections or insulation failure. When this happens, an arc is necessary to sustain current flow through the loose connection. Since the arc presents impedance to the flow of current, smaller amounts of current will flow into an arcing fault than will flow into a bolted fault.
- *Failure classifications.* Short-circuit currents, whether bolted or arcing, will involve two or more phase conductors. Line-to-line faults involve two-phase conductors (A-B, B-C, C-A) while three-phase faults involve all three phases (A-B-C). Although three-phase bolted short-circuits rarely occur in practice, short-circuit studies have traditionally been based upon the calculation of three-phase, bolted short-circuit current. Modern personal computers and associated software have made the calculation of all types of fault currents easier to accomplish.

Ground-fault Current

Ground-fault current consists of any current which flows outside the normal circuit path. A ground-fault condition then, results in current flow in the equipment grounding conductor for low-voltage systems. In medium- and high-voltage systems, ground-fault current may return to the source through the earth. Ground-fault protection of medium-voltage and high-voltage systems has been applied successfully for years using ground current relays. Ground-fault protection of low-voltage systems is a considerable problem because of the presence and nature of low-level arcing ground faults. Ground-fault current on low-voltage systems may be classified as leakage, bolted, or arcing.

- *Leakage ground-fault current.* Leakage ground-fault current is the low magnitude current (milliampere range) associated with portable tools and appliances. It is caused by insulation failure, and is a serious shock hazard. Personnel protection is accomplished by using ground-fault circuit interrupters (GFCI) in the form of GFCI-receptacles or GFCI-circuit-breakers.
- *Bolted ground-fault current.* Bolted ground-fault current results when phase conductors become solidly connected to ground (i.e., the equipment grounding conductor or to a grounded metallic object). Bolted ground-fault current may equal or even exceed three-phase, bolted short-circuit current if the system is solidly grounded. Equipment protection is accomplished by using standard phase and ground overcurrent devices depending upon system voltage levels.
- *Arcing ground-fault current.* Arcing ground-fault current results from a less than solid connection between phase conductors and ground. Because an arc is necessary to sustain current flow through the connection, the magnitude of arcing ground-fault current will be less than that of bolted ground-fault current. Depending upon the arc impedance, arcing ground-fault current may be as low as several amperes (low-level) or as high as 20-38 percent of three-phase, bolted short-circuit current (high level) on a 480V system.

Considerable research has been conducted in the area of arcing ground-fault current magnitudes on low voltage systems. Some designers use the 38 percent value while others use the 20 percent figure. NEMA PB2.2 applies ground-fault damage curves instead of performing a calculation. Equipment protection is accomplished by using ground-fault protective (GFP) devices. Due to ionization of the air, arcing ground faults may escalate into phase-to-phase or three-phase faults.

Sources of Short-circuit Current

All sources of short-circuit current and the impedances of these sources must be considered when designing coordinated power system protection.

- *Synchronous generators.* When a short-circuit occurs downstream of a synchronous generator, the generator may continue to produce output voltage and current if the field excitation is maintained and the prime mover continues turning the generator at synchronous speed. The flow of short-circuit current from the generator into the fault is limited only by the generator impedance and downstream circuit impedances. The magnitude of generator fault current depends on the armature and field characteristics, the time duration of the fault, and the load on the generator. The ability of a generator to supply current during a fault is a function of the excitation system.
- Some generator excitation systems do not have the ability to sustain short-circuit current. The magnitude of fault current is determined by the generator reactance, and, for such systems, can be essentially zero in 1.0 to 1.5 seconds.
- Static exciters derive excitation voltage from the generator terminals. Since static exciters do not sustain short-circuit current, protective devices on the system will not operate properly, or at all. Static exciters, therefore, are not recommended. Static exciters with current boost should be specified for applications requiring static excitation.
- Round-rotor generators with brushless exciters, typically above 10 MVA, can sustain short-circuit current for several seconds. Salient-pole generators less than 10 MVA, also with brushless exciters, will typically sustain short-circuit current at 300 percent of generator full load amperes.
- *Synchronous motors.* When a short-circuit occurs upstream of a synchronous motor, the system voltage goes to zero, and the motor begins losing speed. As the motor slows down, the inertia of the load is actually turning the motor and causing it to act like a generator. The synchronous motor has a dc field winding, like a generator, and actually delivers short-circuit current into the fault until the motor completely stops. As with a generator, the short-circuit current is limited only by the synchronous motor impedance and the circuit impedance between the motor and the fault.
- *Induction motors.* With one slight difference, a short-circuit upstream of an induction motor produces the same effect as with a synchronous motor. Since the induction motor has no dc field winding, there is no sustained field current in the rotor to provide flux as

is the case with a synchronous machine. Consequently, the short-circuit current decays very quickly.

- *Supply transformers.* Supply transformers are not sources of short-circuit current. Transformers merely deliver short-circuit current from the utility generators to the fault point. In the process, transformers change the voltage and current magnitudes. Transformer impedances will also limit the amount of short-circuit current from the utility generators. Standard tolerance on impedance is plus or minus 7.5 percent for two-winding transformers and plus or minus 10 percent for three-winding transformers. The minus tolerance should be used for short circuit studies and the plus tolerance for load flow and voltage regulation studies.

Time Variation of Short-circuit Current

Since short-circuit current from rotating machines varies with time, it is convenient to express machine impedance (inductive reactance) as a variable value. This variable reactance will allow calculation of short-circuit current from a rotating machine at any instant in time. For the purpose of simplification, three values of reactance are assigned to rotating machines for the purpose of calculating short-circuit current at three specified times following the occurrence of a fault. These three values are called subtransient, transient, and synchronous reactances.

- *Subtransient reactance (X_d'').* Subtransient reactance is a value used to determine the short-circuit current during the first few cycles after a short-circuit occurs. This is the short-circuit current value to be used in all short-circuit studies.
- *Transient reactance (X_d').* Transient reactance is a value used to determine the short-circuit current from the first few cycles up to about 30 cycles after the short-circuit occurs (depending upon the design of the machine). This value is often used in voltage regulation studies.
- *Synchronous reactance (X_d).* Synchronous reactance is a value used to determine the short-circuit current when the steady state condition has been reached. Steady state is reached several seconds after the short-circuit occurs. This value is often used to determine the setting of generator backup overcurrent relays.

Symmetrical and Asymmetrical Short-circuit Currents

"Symmetrical" and "asymmetrical" are terms used to describe the symmetry of the short-circuit current waveform around the zero axis. If a short-circuit occurs in an inductive reactive circuit at the peak of the voltage waveform, the resulting short-circuit current will be totally symmetrical. If a short-circuit, in the same circuit, occurs at the zero of the voltage waveform, the resulting short-circuit current will be totally asymmetrical. If a short-circuit, in the same circuit, occurs at some time between the zero and peak of the voltage waveform, the resulting short-circuit current will be partially asymmetrical. The amount of offset or asymmetry depends on the point when the fault occurs. In circuits containing both resistance and inductive reactance, the amount of asymmetry will vary between the same limits as before. However, the X/R ratio (ratio of inductive reactance to resistance looking upstream from the fault point) will determine the rate of decay of the DC component. As X/R increases, the rate of decay decreases. Interrupting current

ratings may have to be derated for high X/R values. Practically speaking, most all short-circuit currents are partially asymmetrical during the first few cycles after a short-circuit occurs. Modern personal computers can now be used to easily calculate symmetrical and asymmetrical current values at various times after a fault. Low-voltage protective devices are rated on a symmetrical basis but tested on an asymmetrical basis. Medium-voltage switchgear has a momentary and an interrupting rating. The momentary rating is the short-circuit duty during the first cycle after a fault, and defines the equipment's ability to close and latch against worst-case mechanical stresses. The interrupting rating is the short-circuit duty as the equipment contacts part, and is expressed in symmetrical amperes or MVA. Medium-voltage fuses have interrupting ratings expressed in symmetrical amperes.

Overcurrent Protection Devices

General

Design of power system protection requires the proper application of overload relays, fuses, circuit breakers, protective relays, and other special purpose overcurrent protective devices. This course provides detailed information about various protective devices, illustrates their time-current characteristics, and identifies information required to design coordinated power system protection.

Motor Overload Relays

- Thermal overload relays. The most common overcurrent protective device is the thermal overload relay associated with motor starting contactors. In both low-voltage and medium-voltage motor circuits, thermal overload relays detect motor overcurrents by converting the current to heat via a resistive element. Thermal overload relays are simple, rugged, inexpensive, and provide very effective motor running overcurrent protection. Also, if the motor and overload element are located in the same ambient, the thermal overload relay is responsive to changes in ambient temperature. The relay trip current is reduced in a high ambient and increased in a low ambient. The curves level off at about 10 to 20 times full-load current, since an upstream short-circuit device, such as a fuse or circuit breaker, will protect the motor circuit above these magnitudes of current. The thermal overload relay, therefore, combines with the short-circuit device to provide total over-current protection (overload and short-circuit) for the motor circuit.
- Melting alloy type overload relays, as the name implies, open the circuit when heat is sufficient to melt a metallic alloy. These devices may be reset manually after a few minutes are allowed for the motor to cool and the alloy to solidify.
- Bimetallic type overload relays open the circuit when heat is sufficient to cause a bimetallic element to bend out of shape, thus parting a set of contacts. Bimetallic relays are normally used on automatic reset, although they can be used either manually or automatically.
- Standard, slow, and quick-trip (fast) relays are available. Standard units should be used for motor starting times up to about 7 seconds. Slow units should be used for motor starting times in the 8-12 second range, and fast units should be used on special-purpose

