PDHonline Course E499 (5 PDH)

Protection of Low Voltage Circuits

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Joseph E. Fleckenstein

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Low Voltage Circuit Protection

1.0 Circuit Protection - General

This course treats protection of electric circuits under 1,000 VAC. Although the course treats primarily three phase circuits, much of what is discussed is also applicable to single phase circuits.

The basic objective of circuit protective devices is to protect personnel and property. It is important that a person understands that while circuit protective devices may in most instances act to protect personnel and property, there is no guarantee that in all cases these devices will have the capability of reacting in a manner that will avoid injury or damage to property.

In most applications, a circuit protective device will act to isolate a circuit from its source of electrical power whenever an overcurrent condition is detected. There are, however, notable exceptions. In some instances it is best to avoid circuit isolation - as discussed below.

Fuses and circuit breakers are the commonly used types of circuit breakers. Both types of devices have been in use for many years and it appears both will be around well into the foreseeable future.

1.1 Basic Considerations

Circuit protective devices intended for low voltage circuits are commonly called Overcurrent Protective Devices (OCPD). According to the National Electric Code (NEC), there are two basic types of OCPD's: circuit breakers and fuses. Many chapters in the NEC treat electrical circuit protection and prescribe the criteria for the selection and sizing of OCPD's.

While the NEC is widely mandated for many installations, it is pertinent to note that not all installations within the USA are required to follow the guidelines of the NEC. Most large municipalities in the USA have passed regulations that require new installations follow the NEC but many small towns and urban areas have no such requirements. Power plants and industrial installations are exempted from following the requirements of the NEC. Many municipalities within the USA impose codes and special procedures applicable to electrical installations but many may not necessarily invoke the NEC. Very often a construction specification will require that an installation should be made in compliance with the NEC. This practice becomes a convenient means of presenting the minimal requirements of an installation.

The IEEE's *Buff Book*, while not primarily concerned with the specifics of installation or the safety of personnel, is a well-recognized and authoritative textbook on the subject of circuit protection. The *Buff Book* consists of over 700 pages and it treats the subject of circuit protection in great detail. The IEEE publication can be particularly helpful in resolving unique or special protection problems.

According to the IEEE *Buff Book*, the objectives of OCPD's are to:

- Limit the extent and duration of service interruption whenever equipment failure, human error or adverse natural events occur on any portion of the system.
- Minimize damage to system components involved in the failure.

In order to meet these objectives, the *Buff Book* states, systems should include the following design features:

- Quick isolation of the affected portion of the system while maintaining normal operation elsewhere
- Reduction of the short circuit current to minimize damage to the system, its components and the utilization equipment it supplies
- Provision of alternate circuits, automatic throwovers, and automatic reclosing devices

Circuit breakers and fuses each have unique characteristics and properties. In many instances an electrical circuit may have both fuses and circuit breakers, one being upstream of the other or in parallel circuits. Most low voltage circuit breakers are furnished with an operating handle that also allows the circuit breaker to be used as a disconnect switch. The operating handle also permits convenient resetting after a fault condition has occurred. High voltage circuit breakers, which are not furnished with an operating handle, are operated by means of remote pushbuttons which activate electromechanical devices within the circuit breaker that shift the CB's contacts from one position to the opposite position.

In some regards fuses are not as convenient as CB's. To de-energize a circuit downstream of a fuse, a fuse must be removed from its holder. Removing and installing fuses in high voltage circuits can present a dangerous condition to personnel who may not be adequately trained in the procedure. Replacing a fuse in a circuit that has a short circuit can be especially hazardous. An overcurrent event opens a fuse and replacement of the fuse will be required to again energize the circuit. One blown fuse in a three phase motor circuit can lead to undesirable single phasing of a motor and possible damage to the motor. Briefly stated, circuit breakers and fuses each have unique features and drawbacks that usually cause one or the other to be a better fit to a specific application.

Protective devices of any type add expense to the cost of a circuit. A variety of protective devices available in the marketplace are capable of guarding against numerous types of postulated fault conditions. Some of these are described below. A relatively inexpensive circuit that connects to relatively inexpensive gear may warrant only an inexpensive OCPD. On the other hand, a circuit that serves relatively expensive equipment, as a large and expensive motor or a large and expensive transformer, will warrant a greater expense. Personnel protection may become another cause for greater protection. Briefly stated, circuit protection should be commensurate to the application.

Several special terms are commonly used when referring to circuit overcurrent protective devices. Following are some of the commonly recognized terms:

- Overcurrent – current flow that is excessive for some reason. (An overcurrent condition could in consequence to a current above the design level, a short circuit or a ground fault.)
- Overload – current flow that is above predetermined, safe levels. (The term is generally used in reference to a current flow that is somewhat above desired levels – perhaps in the region of 1% to 400% of an approved level.)
- Short circuit – an unintended connection allowing current flow: (1) from one phase to another, or (2) from one phase to neutral, or (3) from one phase to ground (which would be the same as a ground fault). (Short circuit currents are drastically larger than overload currents – possibly in the range of 1,000 to 10,000 times larger.)
- Ground fault – a current flow from one phase to ground. (As with a short circuit current, a ground fault current would generally be much larger than an overload current.)

1.1.1 Grounding

Proper grounding is needed if circuit protective devices are to perform the role for which they are intended. There are various types of grounds and grounding practices.

1.1.1.1 Definitions

There is a variety of terms used with regard to grounding practices. If those terms are not understood by a person, confusion and misunderstandings may result. If grounding practices are to be followed, an understanding of the commonly-used terms is necessary.

In recent years any English speaker involved with electrical power would have encountered the words “ground”, “grounding”, “earth” and “earthing.” In North America the terms “ground” and “grounding” have been widely used. Elsewhere “earth” and “earthing” are generally used. For the purposes of this course, the words “ground” and “grounding” are used. Nevertheless, it is recognized that equivalent words are, respectively, “earth” and “earthing.”

Following are a few additional, common terms associated with the subject of grounding.

- Ground - The NEC defines “ground” as follows:

“GROUND. A conducting connection, whether intentional or accidental, between an electrical circuit or equipment and the earth or to some conducting body that serves in place of the earth.”

- Equipment Grounding Conductor - The NEC defines “equipment grounding conductor” as follows:

“EQUIPMENT GROUNDING CONDUCTOR. The conductor used to connect the non-current-carrying metal parts of equipment, raceways, and other enclosures to the system grounded conductor, the grounding electrode conductor, or both, at the service equipment or at the source of a separately derived system.”

According to the NEC, ground conductors are to be colored green. An equipment grounding conductor is not necessarily insulated.

- Neutral Conductor - The term “neutral conductor” is associated with grounding although the NEC does not directly define neutral conductors. Nevertheless, a definition is implied as:

NEUTRAL GROUND CONDUCTOR. A neutral conductor is one that may under normal circumstance be a conductor of electrical current. For example the neutral wire of a four wire wye circuit will be conducting current if the circuit is unbalanced. While not considered a ground conductor, a neutral conductor must necessarily be connected to a ground conductor and at most times it will be at or very near ground potential. Neutral conductors are insulated and, according to the NEC, may be colored white or gray but never green.

1.1.1.2 Grounding Paths

Many electrical circuits are provided with a neutral conductor that, under normal circumstances, will provide a path to ground for current flow. Likewise, most electrical installations will be furnished with a metallic path to ground for abnormal conditions. A non-current-carrying ground includes the "equipment ground conductor" (as defined by the NEC) that connects equipment to a ground. A typical application would be a metallic cabinet that houses electrical equipment and which is connected to an equipment ground conductor. The primary purpose for grounding of the cabinet is to avert a potentially hazardous condition to personnel in the event that a live conductor of an electrical circuit would inadvertently contact the metallic cabinet. If a live conductor would come in contact with metallic components connected to the equipment ground conductor, the circuit protective device would be tripped thereby avoiding a condition potentially hazardous to personnel. In short, the purpose of the equipment ground is primarily personnel safety. Proper wiring practices dictate that equipment grounds not be connected in a "daisy-loop" fashion. If so connected, a short to one grounded item would momentarily charge all devices. Rather, equipment grounds should be separately connected to a ground. While a conductor is often a part of a ground path, wiring codes also allow the ground path to include metallic wireways.

1.1.1.3 Reasons for Grounding

According to common practice that was followed years ago, many electrical installations were not grounded. Perhaps the need for adequate grounding was not fully recognized, understood or considered necessary. Today, grounding is considered important to most, but not all, electrical installations. Yet, the importance of proper grounding is often neglected. In fact, the USA Office of Safety and Health Administration reports that the most common safety violation is the improper grounding of equipment or circuits.

An electrical ground prevents conductor voltages from exceeding the rating of the respective conductor insulation. Equipment grounding prevents equipment, as cabinet enclosures and motor cases, from becoming charged to a potential above ground potential.

Whereas grounding is considered necessary to most electrical circuits, there are many circuits that, for a variety of reasons, are definitely not to be grounded. Specifically, the NEC (Article 250.7) requires that (for safety reasons) the following circuits are to be ungrounded:

- Cranes
- Health Care Facilities (some restrictions)
- Electrolytic Cells

In a system that is specifically not grounded, the first inadvertent grounding becomes the ground point for the circuit. A feature of an ungrounded system is that the first, inadvertent grounding will not trip the overcurrent protective devices. This characteristic is sometimes important to a process or procedure that might be harmed by the immediate isolation from the source of electrical power. An ungrounded system also minimizes the chances of a serious arc flash that might otherwise result if a system is grounded. Ungrounded systems are often fitted with a ground fault detector that will provide notification of a ground fault condition and in some instances may simultaneously initiate a trip of the circuit.

1.1.2 Overcurrent

A prolonged overcurrent condition in an electrical circuit has the potential to cause significant damage to electrical equipment as well as to other nearby equipment. The rise in temperature resulting from a relatively high current flow causes the greatest challenge in the design of electrical components of all types. Insulated cables are a typical example. An insulated copper wire of a certain diameter has a specific current carrying rating. At that specific rating the temperature of the wire will rise to some extent because of current flow but no higher than a value that would prematurely deteriorate the insulation. So, it becomes important for the purpose of ensuring an adequate life of an electrical product, that currents should not be allowed to rise above predetermined acceptable limits. A basic function of an overcurrent protective device (OCPD) is to prevent the high currents that cause excessively high temperatures. An overcurrent condition could be due to a current that is only slightly greater than an acceptable continuous current. Or, an overcurrent can be due to a fault condition that might be thousands of times greater than a circuit's continuous rating.

Aside from the potential damage that might result from high temperatures, there is also the prospect for mechanical damage due to the forces generated by short circuit currents. The magnetic fields surrounding a short circuit current can be very strong and in many instances capable of bending and twisting steel components. In particular, the internal components of transformers are subject to mechanical stress and distortion that could result from a high level short circuit. Accordingly, a secondary function of an OCPD is to guard against forces that can cause mechanical damage.

1.1.3 Faults

In a three phase circuit the most commonly considered faults are:

- A ground fault from one phase to ground
- A ground fault of two phases to ground
- A short circuit of one phase to another phase
- A short circuit of all three phases one to the other

Of these four types of faults, the most common are ground shorts. The four possible configurations of shorts are represented in Fig. 1.1. Any of these possible scenarios may result from one of several possible causes. The cause could be mechanical in nature with the result that a live conductor is brought in contact with either another live conductor or ground. An overvoltage condition may breakdown the circuit's insulation or insulation may deteriorate because of age. A fault might then follow. Of the mentioned types of faults, the phase to ground is by far the most commonly encountered form. A fault can also be classified as "bolted" or "arching." A bolted fault assumes that the resulting current is the same as would result from a conductor connected to either a ground or to another conductor by a bolted, low resistance connection. Bolted shorts can at times result in very high currents. An arcing short differs from a bolted short in that the current flow to either ground or another conductor is through air or another medium and the resistance to current flow is much higher than what would occur in a bolted short. Consequently the current flow in an arcing short is generally less than a bolted short. In some regards an arching short has the potential to cause considerably more damage than a bolted short. An arcing short might continue undetected and at a rate below a current rate needed to trip the circuit protective device. A continuing, arcing short can irreparably damage the insulation of all of the circuit that is common to the point of the fault. An arcing short can also start a fire or cause an explosion.

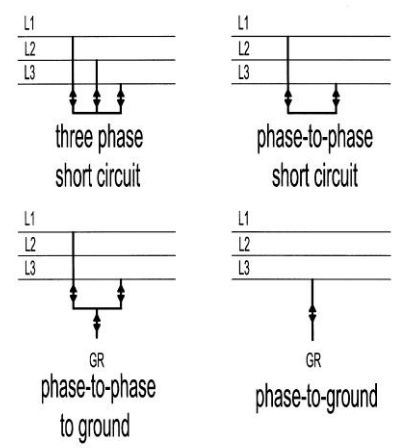

Fig. 1.1 – Possible Short Circuits

The computation of the maximum fault current is important so as to establish the required interrupting capability of the OCPD's. When an OCPD is selected the interrupting capability should be one of the criteria. For example, a manufacturer may offer a 50 amp breaker with a 10,000 amp interrupting capability, 30,000 amp capability and 60,000 amp capability. The higher the interrupting capability the larger the physical size of the device and the higher the associated cost. For this reason, it is generally desirable to use an OCPD that is adequate for the application but one that does not have an interrupting rating unnecessarily higher than what is needed. It is usually recommended that a short circuit study be conducted to establish the required interrupting capability of an OCPD. The subject of short circuit studies is treated in greater detail in below Section 5.0, Interrupting Capabilities.

2.0 Circuit Breakers

A circuit breaker is an electromechanical type of OCPD that is designed to protect an electrical circuit. In the event of a detected overcurrent condition, contacts within the circuit breaker are opened to deactivate the circuit protected by the circuit breaker. There are a large variety of circuit breakers intended for a multitude of applications and an array of configurations. Circuit breakers guard against both a circuit overload and a short circuit condition. For low voltage applications the commonly recognized types of circuit breakers are the molded case circuit breakers (MCCB), the insulated case circuit breakers (ICCB) and the low voltage power circuit breakers (LVPCB). Metal clad circuit breakers are used in medium and high voltage applications.

Worldwide, the number of manufacturers of circuit breakers is small. No doubt this condition is largely due to the high costs of developing, testing, manufacturing and marketing a wide range of products. All of the manufacturers of circuit breakers provide detailed information regarding their products and this information is needed by those persons considering devices for circuit protection. When viewing manufacturers' literature it is pertinent to note that the recommendations, practices and terms used by one manufacturer may vary considerably from those used by others in the industry. In this course, the terms and concepts used are largely common to all of the manufacturers of circuit breakers.

2.1 Molded Case Circuit Breakers

Molded case circuit breakers (MCCB's) are the most widely-used type of circuit breaker for applications under 1,000 volts. This is due to the simple design of the devices and their relatively low cost. MCCB's have all of the operating parts contained within a case that is fabricated of a non-conducting material which is usually a thermoset plastic and which is "molded." Practically all MCCB's are fitted with an operating handle which serves as a disconnect switch. When the operating handle is in the "off" position the circuit is open and he voltage source is blocked from the downstream circuit. In the "on" position the circuit is closed and the CB is engaged to protect the circuit. The energy required to open the contacts is provided when the operating handle is manually moved to the closed position. There are several types of common MCCB's. The most common types are the thermal-magnetic circuit breaker, the magnetic only circuit breaker and the electronic circuit breaker. (The electronic circuit breakers are also called the "solid state circuit breakers.") The thermal-magnetic MCCB's are used on all types of circuits although to a lesser extent on motor circuits. Magnetic-only MCCB's are intended primarily for motor circuits. The electronic CB's are less commonly used than the other types, mostly because of their higher costs, but are often used to meet special circuit requirements not readily met with other types of circuit breakers.

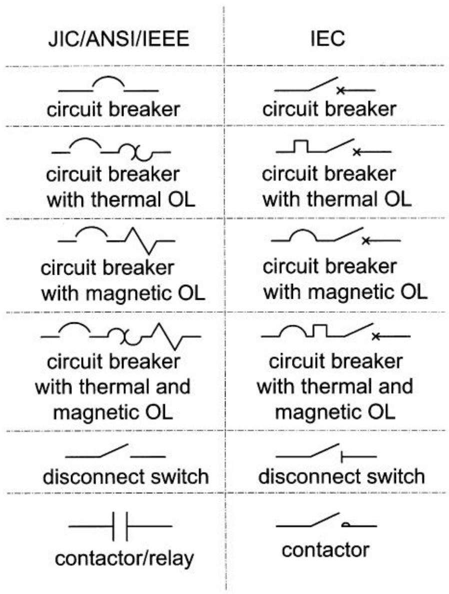

Fig. 1.2 – Types of MCCB's

The drawing symbols representative of the various types of CB's are shown in Fig. 1.2. It is pertinent to note that (European) IEC symbols differ significantly from the (North American) JIC/ANSI/IEEE symbols.

2.2 Thermal Magnetic Circuit Breakers

Thermal magnetic circuit breakers are a very common type of MCCB, perhaps the most common. A MCCB is designed such that the monitored current passes through components contained entirely within the enclosure of the MCCB. Essentially, thermal magnetic CB's house two types of sensing elements each of which has a distinctly different function. Thermal components of a thermal magnetic CB guard against an overload in the monitored circuit. As the monitored current increases, the temperature of the thermal element increases much in a manner that simulates the temperature increases of the protected devices. Today the most common type of thermal sensing element is the bimetallic element. As suggested by the name, a bimetallic element is constructed of two different types of metals, each having a different coefficient of expansion. When the monitored current passes through the bimetal element each of the two metals expand but the metal with the higher coefficient of expansion will elongate more than the other metal. A typical bimetallic element is represented in Fig. 1.3. Common metals used in bimetallic elements are invar and brass. Invar, which is an alloy of nickel and iron, has a relatively low coefficient of expansion at the temperature range within which it is used in MCCB's. Brass has a much higher rate of expansion with temperature. As current passes through the bimetallic element it becomes heated due to the I^2R effect and the brass grows with respect to the invar. Movement of the type shown in Fig. 1.3 results. The bimetallic element is essentially a means of converting current flow to mechanical movement. At a point the increasing current flow and the resulting movement of the bimetallic element trips the MCCB's contacts to the open position.

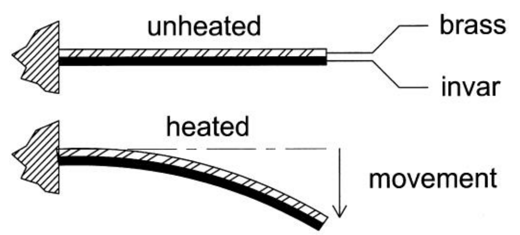

Fig. 1.3 – Bimetal Element

Unless a CB is marked "independent trip" or "no common trip" an overload in any of the monitored conductors will cause a trip of the MCCB and an opening of the contacts. Thermal magnetic CB's have an inherent time delay and an inverse tripping characteristic. In other words, the greater the overcurrent level the shorter the time to trip. Thermal magnetic CB's are available in designs of one pole, two poles, three poles and, in some areas outside North America, four poles. Code requirements mandate that some ungrounded circuits must be isolated. Each pole must be monitored for an overload condition. A three pole CB would have three separate thermal elements. A commonly recognized standard for CB's is the UL Standard 489 which calls for calibration of the CB's at 40ºC. Since the bimetallic element within a CB depends on ambient air for cooling, the trip setting of the CB will shift somewhat with shifts in ambient temperature. The higher the ambient temperature, the lower the value of the current required to cause a trip and vice-versa. According to the NEC code requirements, thermal magnetic CB's intended for service above 40ºC must be rerated.

Under a short circuit condition the "magnetic" components of a thermal-magnetic CB act to open the monitored circuit as quickly as possible. Each pole of the

MCCB has two contacts: one that is stationary and one that is movable. When the MCCB is "closed" and the monitored current is within predetermined limits the contacts are pushed tightly one against the other. The design of MCCB contacts is a specialty and every manufacturer strives to develop rugged, durable yet inexpensive designs. Contact material must present a low resistance when the contacts are closed. Otherwise, constant heating and a premature trip will result. Yet, when the contacts are opened the heat generated by the arc must not melt or significantly deteriorate the surface of the contact material. A common material used for contacts is silver-cadmium oxide.

The common mechanical design of thermal magnetic CB's is such that the magnetic field of the monitored current acts to assist in the opening of the CB's contacts. The higher the current, the more forceful the assisting forces. Since short circuit currents can be relatively high, the contribution from the magnetic field of the short current can be significant. Some thermal-magnetic MCCB's contain two sets of contacts electrically connected in series. One set of contacts is to open in consequence to thermal sensing and one is to open when an instantaneous opening is required.

Some manufacturers provide what are termed a Current Limiting Circuit Breaker. These types of CB's are for overcurrent protection on AC circuits subject to high fault currents. These CB's are a specific form of the thermal magnetic CB.

2.3 Magnetic-Only Circuit Breakers

Magnetic-only MCCB's are used primarily in motor control circuits. Unlike thermal-magnetic MCCB's, the magnetic-only MCCB's have only magnetic elements and no thermal elements. Magnetic MCCB's are provided to open the circuit only in the event of a short circuit. Motor controllers alone guard against a motor overcurrent. Since motor controllers are designed specifically to guard against a motor overload, they are better suited to protect a motor than a thermal-magnetic circuit breaker. Magnetic CB's also include a manual switch that allows the CB to be used as a disconnecting means. Magnetic-only CB's are set to trip at a current setting that by necessity must be above the locked rotor current of the motor. However, codes impose an upper limit on the settings of magnetic-only CB's.

2.4 Electronic Circuit Breakers

Unlike thermal-magnetic circuit breakers, electronic circuit breakers do not contain thermal elements to measure current flow. Rather, current flow is measured by current transformers contained within the enclosure of the CB and the determination to trip is made by electronic computing components. Electronic circuit breakers are fitted with a variety of adjustments that allow shaping of the time-current characteristics to meet unique circuit requirements. Typical variables that can be controlled by adjustments on electronic circuit breakers are:

- Continuous current – The allowable level of the breaker's continuous current rating that will not trip the CB. Typically adjustable in the range of 20% to 100% of the breaker's continuous rating.
- Long time delay – Controls the variation in tripping due to a current level above the allowable continuous current, namely a current in the "overload" region.
- Instantaneous pickup – Determines the level of current at which the breaker will open without a significant delay. The level of instantaneous pickup is typically in the region of 2 to 40 times the breaker's continuous rating. The instantaneous setting overrides all other settings.
- Short time pickup – Determines the level of current below which a trip is not required. Typically adjustable in the range of 1.5 to 10 times the breaker's continuous current rating. The setting causes a delay in tripping that is often used for coordination with downstream circuit breakers.
- Short time delay – Time delay in the short time pickup range, typically in the region of 0.05 seconds to 0.2 seconds. The time delay facilitates coordination.
- Ground fault pickup – Determines the level of ground fault current that will result in a trip. (Since electronic circuit breakers measure three phase currents, an algorithm within the breaker can readily determine that a ground fault has occurred and then call for a trip.)

A significant feature of the electronic circuit breakers is that the devices facilitate coordination with other breakers by purposely delaying a trip, allowing the downstream CB to open. In a way, an intentional delay seems contradictory to the purpose of an OCPD. There are arguments pro and con for this practice. It is difficult to generalize since circuits vary greatly in design and purpose. Obviously a delay in trip allows a greater amount of energy to pass through the CB before the circuit is opened. Although this is certainly true, in many instances it is immaterial. If the downstream CB is capable of interrupting a short circuit current, then why not allow it to complete the task while the upstream CB is holds closed? The results would enhance, or ensure, the prospects of coordination. Of course a delay in response by the upstream CB may allow a greater amount of energy to pass through to the downstream circuit. Should there be a short in the circuit between the two CB's, energy let-through would not have been restricted to the lowest possible level. This would be a consideration if an arc flash is a concern. On the other hand, if the two CB's are located in the same panel, which is very often the situation, experience indicates that the chances of a short in the interconnecting circuit are very low. Briefly stated, these are some of the considerations in the use of electronic circuit breakers.

Some electronic circuit breakers are capable of additional features not commonly available in other types of circuit breakers. Special features available in some models of electronic circuit breakers are:

- Shunt trip – A shunt trip permits tripping of the circuit breaker from a remote circuit as determined by logic external to the CB. For example, a remote ground fault detector could be used to trip an electronic circuit breaker in the event of detected fault.
- Under voltage trip – An under-voltage trip can be provided with the CB to call for a trip in the event of a detected low voltage condition. (Some electronic circuit breakers can be provided with a built-in under-voltage trip which can be a relatively inexpensive way to provide an under-voltage tripping feature.)
- Remote on-off-reset – This accessory allows remote activation of the CB to "on", "off" or "reset." (This feature is especially desirable if a person might be in proximity to the OCPD and there is a potential for an arc flash.)
- Auxiliary contacts – Auxiliary contacts to remotely indicate the CB's position as "closed" or "open."

2.5 Insulated Case Circuit Breakers

Insulated case circuit breakers (ICCB) are similar in many regards to molded case circuit breakers and are manufactured to meet the same standards common to molded case circuit breakers. Insulated case circuit breakers are physically larger than MCCB's and are generally capable of interrupting higher energy levels. Some models of ICCB's are suitable for potentials up to 1,000 VAC and continuous currents of 6,400 amperes. As suggested by the name, insulated case circuit breakers are contained within an insulated case. Much as electronic molded case circuit breakers, ICCB's are furnished with a number of adjustments that allow shaping the time-current characteristics to meet the needs of a specific installation. ICCB's are also available in designs with drawout capability. That is to say, the ICCB's can be readily isolated from the circuits for testing, maintenance or for the readjustment of settings. The isolation is accomplished merely by moving the ICCB "in" or "out" and no conductors need to be disconnected or reconnected. With the drawout feature an ICCB can be withdrawn a few inches from its "in" (or "closed") position to a "test" (or "open") position within its cradle (mounting mechanism) thereby separating the CB from both the incoming cables and the outgoing cables. Insulated case circuit breakers are most commonly used in motor control centers and power distribution centers.

2.6 Low Voltage Power Circuit Breakers

Low voltage power circuit breakers (LVPCB) are similar to ICCB's but generally offer a few more features. LVPCB's are generally available for the same range of voltages and currents as insulated case circuit breakers although some models offer higher interrupting currents. LVPCB's are manufactured and tested to standards that are different from those used for MCCB's and ICCB's which appears to be the primary explanation for the different titles. Much as the electronic CB's, the time-current characteristics of LVPCB's can be programed to meet special TCC needs and, as ICCB's, are available in a drawout design.

2.7 Metal Clad Circuit Breakers

Metal clad circuit breakers are intended primarily for interrupting currents at energy levels that start where the ICCB's and LVPCB's end. Metal clad circuit breakers are used primarily for medium and high voltage applications, i.e. well above the 1,000 VAC point that is often used to define low voltage. By definition a metal clad circuit breaker is housed entirely within a metallic enclosure. Metal clad circuit breakers are furnished with the drawout feature that facilitates periodic testing and maintenance. Metal clad circuit breakers have a variety of mechanisms designed to extinguish the arc that occurs when the breaker's contacts are opened. In some designs compressed air is used to assist in blowing the arc away from the path between the breaker's contacts. Other designs use vacuum contacts and yet others use special gases to quench the arc. Because of their large physical size, metal clad circuit breakers cannot react with the speed of the smaller insulated case or low voltage power circuit breakers. Medium sized metal clad circuit breakers cannot open in less than approximately three to five cycles. Larger breakers require more time yet to interrupt a circuit. Because of the forces required, metal clad circuit breakers are indexed to the ready position by motors within the breaker's cubicle. A metal clad circuit breaker can be "racked in" so that it is operative, or it can be "racked-out" for testing or maintenance.

3.0 Fuses

3.1 Basic Design

Fuses have been used to protect electrical circuits almost since the advent of electrical circuits in the 19th Century. A fuse differs from a CB in the way it protects a circuit. Fuses contain a metal element that provides a conducting path through its internal parts, and which allows current flow through the metal at current levels below the rating of the fuse. Increases in current flow warm the metal and when the current flow rises to a relatively high level the metal melts to open the circuit. In past years zinc had been used as the common metal in fuses. If fuses with zinc were cycled numerous times at normal currents, the zinc would fatigue over time and inadvertently open. Today fuses use metals that melt at a higher temperature and fatiguing of the metal is no longer an issue. Some fuses contain a spring that assists to separate melting metal and which thereby shortens the time needed for circuit interruption.

A fuse is a sacrificial device that requires replacement once it has opened to interrupt current flow. Whereas CB's provide a convenient and compact means of disconnecting a circuit, a circuit protected with fuses lacks the same convenient feature. A blown fuse requires the procurement of a replacement fuse. To isolate a fuse-protected circuit, either a disconnect switch is required upstream of the fuse or the fuses must be removed to disconnect the circuit. While the replacement of a fuse can entail delay and inconvenience, the use of fuses in lieu of circuit breakers can often translate to considerably less initial cost. Often fuses are selected in circuits, rather than CB's, for the reason that coordination can more readily be ensured. Common fuse symbols are shown in Fig. 1.4.

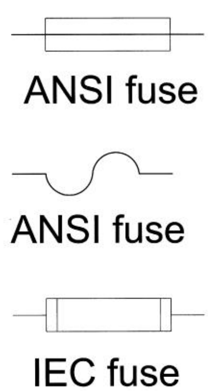

Fig. 1.4 – Fuse Symbols

3.2 Standard-Delay Fuses

Fuses are available with a variety of time-current characteristics. The standard fuse for power applications has a slight delay before opening. These types of fuses are suitable, say, for the protection of conductors and circuits that do not have a prolonged inrush. However, they would not function satisfactorily for circuits that serve a motor or a transformer. (For electronic circuits, special types of quick-blow fuses are commonly used. Electronic components can be damaged more readily by current surges than most devices found in power applications.)

3.3 Slow-Blow Fuses

For circuits that serve a motor or a transformer, slow-blow fuses are typically used. Slow-blow fuses have a larger mass than standard fuses and will hold until the initial current inrush following activation has returned to the circuit's continuous draw.

4.0 Sizing Circuit Protective Devices

4.1 Sizing MCCB's

Several considerations enter into the sizing of a molded case circuit breaker for a specific application:

- The CB must remain closed when the monitored current is below the CB's nominal overload rating. From a safety consideration, no problem is created in the monitored circuit if the circuit breaker inadvertently opens while the monitored current is below its nominal rating. Nevertheless, inadvertent openings are undesirable because of the inconveniences and safety issues that might result from premature isolation of a circuit.
- A CB must isolate the circuit if the monitored current rises to or exceeds the overload value - although after a time delay that is an inverse function of the degree of overcurrent.
- The sizing of a CB should be such that it has an adequate interrupting capability, i.e. the capability to open the circuit against a fault current.
- Coordination is possibly an issue

A specific example might better explain some of the principles that are involved in the sizing of a CB for a normal load and for an overload.

Example 1.1

Use of 50 amp MCCB

Consider a case in which a circuit breaker is to be selected to protect a three phase heater with a continuous current rating of 40 amps. For the purposes of this example the voltage is immaterial. Consider the use of #8 AWG conductors to be extended from the MCCB to the heater. Procedures outlined in the applicable wiring code will determine the allowable amperage of the conductors. Assume that the authority having jurisdiction (AHJ) requires that the guidelines of the NEC are to be followed. Under some conditions the NEC allows #8 AWG copper conductors rated 75ºC to continuously carry 50 amps. However, derating of conductors is possibly required for a number of reasons. Assume that a derating factor of 0.94 is applicable because of an anticipated high ambient temperature. Applying the derating factor, the current carrying capability of the #8 AWG conductors (called the conductor's "ampacity" by the NEC) is reduced to 47.0 amps. The code allows selection of the next higher standard size breaker which in this case is 50 amps. If manufacturer's catalogs are reviewed, it will be found that a number of three pole 50 amp thermal-magnetic circuit breakers are available. However, the NEC has a rule concerning the loading of a MCCB. That rule states that unless the MCCB is suitable for continuous amperage at the rated value (and so clearly marked) the MCCB is not to be used with a continuous current above 80% of its rating. Using a 50 amp MCCB with a nominal rating of 50 amps, the usage would be at (40 amp/50 amp) (100%) or 80%. So the installation would satisfy that rule of the NEC. One of the variations is the interrupting capability of the CB. So, having determined that a nominal 50 amp breaker will suffice, a MCCB with an adequate interrupting must be selected. The procedure for determining the required interrupting capability of a circuit breaker is discussed in detail below in Section 5.1, Short Circuit Studies.

(Note: The sizing of conductors and OCPD's is a subject that is treated in wiring codes as the NEC. Often, local and state codes impose additional requirements. These codes provide critically important guidelines that are intended to ensure a safe electrical installation.)

The brief computations shown here illustrate the importance of codes. The computations also demonstrate that intimate knowledge of the code is needed to properly select conductors and the associated OCPD's.)

4.2 Sizing for Interrupting Capability

Protective devices are described in part by their capability to interrupt fault currents. The highest current that can be interrupted is called the device's "interrupting rating" or its "ampere interrupting rating" (AIR). A CB must be capable of opening its contacts without permanent damage in the event that a fault current should occur at the level of the CB's AIR. As would be expected, interrupting ratings of a CB's are drastically higher than the rated overload current. Listed interrupting currents for MCCB's are typically in the range of 5,000 amps to

200,000 amps. Naturally, the higher the interrupting rating the larger the physical size of the unit and the greater the expense. So, there is reason to select a MCCB with an adequate interrupting rating but one that is no larger than what is required. How to determine the required interrupting capability?

It is generally accepted that the only way to properly determine required interrupting currents of a CB is by means of a short circuit analysis. The IEEE provides several documents that outline procedures for conducting a short circuit analysis. Some manufacturers of CB‘s also provide brief descriptions of methods for determining interrupting requirements. There are also a number of PC programs available that can serve as a helpful guide in determining interrupting requirements. These PC programs offer a convenient means to document selections. Some textbooks suggest that the utility supplying the electrical service, upon request, may provide the interrupting capacity at the meter. (Transformer capability would constitute an upper current limit to some extent.) It will generally be found that small users of a single phase service may have an interrupting requirement of, say, only 5,000 amps. However, most three phase users will require OCPD’s with much higher interrupting capabilities.

A circuit protective device should be adequately sized to interrupt the highest current that may result from a short circuit. Should a fault current exceed the interrupting rating of a protective device that device may violently explode thereby generating a potentially hazardous condition. It is particularly important to note that the cause of a MCCB’s explosion could be the result of an individual moving the MCCB’s operating handle from the off position to the on position. In a scenario of this type an individual would be in close proximity to the exploding device and in an especially dangerous position.

Series Ratings of MCCB

Often it is desirable to have coordination between OCPD’s located in series. If coordination is not necessary the associated interrupting rating of a CB can be selected on the basis of the series rating of two OCPD’s. A series rating allows use of an OCPD with an interrupting rating less than the available short circuit current. The reduced rating is applicable to the OCPD downstream of another OCPD. The merits are that the downstream CB would generally be less expensive and physically smaller. Series ratings can be determined only through reference to a manufacturer’s listing of the available series ratings.

4.3 Coordination of Circuit Protective Devices

According to the NEC the definition of "selective coordination" is, "Localization of an overcurrent condition to restrict an outage to the circuit or equipment affected, accomplished by the choice of overcurrent protective devices and their ratings or settings." Most personnel who deal with protective devices merely use only the term "coordination" rather than the full "selective coordination." Some manufacturers in the industry have coined the phrase "total selective coordination" to describe a configuration that is coordinated throughout a selected range of possible fault currents. It can be argued that this phrase is a misnomer since the NEC definition implies that "selective coordination" requires coordination throughout the entire range of possible fault currents. It is true that many possible configurations can be coordinated throughout a specific range of possible fault currents but to satisfy the NEC definition of "selective coordination," coordination must be throughout the entire range of possible currents. If the coordination is correct, a fault condition will result in isolation of the affected circuit but no other circuits downstream of the upstream OCPD.

The coordination of two OCPD's actually has nothing to do with circuit protection. The lack of coordination may result in an inconvenience and possibly a dangerous condition. Nevertheless, it is assumed that the two OCPD's of concern have been properly selected to protect their respective downstream circuits. Yet, coordination is generally preferred and is in fact mandated for some applications. So, it is fair to state that coordination can be an issue in the selection of OCPD's. For this reason, the subject of OCPD's coordination is considered here.

Example 1.2

Coordination

This example treats the subject of OCPD coordination. Consider the three phase circuit arrangement represented in Fig. 1.5. In the representation there are four overcurrent protective devices (OCPD's) shown. For the present assume the four OCPD's could be either circuit breakers or fuses. A feeder delivers power to main overcurrent protective device

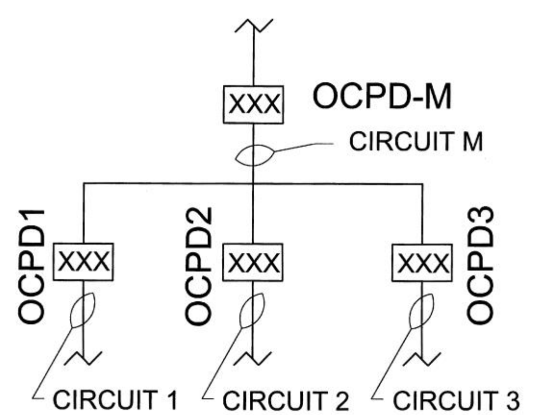

Fig. 1.5 - Circuit with OCPD's

OCPD-M which protects Circuit M. Circuit M transfers electrical power to three downstream OCPD's: OCPD1, OCPD2 and OCPD3. OCPD1 protects Circuit 1. OCPD2 protects Circuit 2 and OCPD3 protects Circuit 3. Should a fault occur, say, in Circuit 1, OCPD1 will trip (open) and separate Circuit 1 from Circuit M. Without proper coordination, OCPD-M may also trip thereby deenergizing not only Circuits 1, but Circuits 2 and 3 as well. In consequence to the trip of OCPD-M the devices served by Circuits 2 and 3 might have been unnecessarily made unavailable. If there had been coordination between OCPD-M and the three sub-OCPD's, only OCPD1 would trip in the event of a detected fault on Circuit 1 whereas OCPD-M, OCPD 2 and OCPD3 would hold closed and Circuits 2 and 3 would remain energized.

If the OCPD's of Fig. 1.5 are not coordinated a short on any circuit will trip the respective OCPD and all three circuits will possibly be isolated. Another form of a lack of coordination would be an overcurrent condition involving fuses when only one fuse opens and allowing the other two phases to remain energized. A condition of this description presents another set of unique problems as discussed below.

The traditional method of determining CB coordination involves a procedure that examines the time-current characteristics of proposed protective devices. If the circuit is to have selective coordination, as required by the NEC for some applications, all possible short currents are assumed for downstream protective devices. Then it is determined if those currents and the associated time delays would result in a trip of an upstream protective device. If the analysis determines that a short of any magnitude would result in both protective devices opening then there is a lack of coordination. If coordination is truly required, different OCPD's should be considered for the application.

Coordination is primarily concerned with the loss of availability and not damage to property. However, in some installations the lack of coordination can have serious and adverse consequences. Starting in 1993, the requirements for protective circuit coordination began to appear in codes. The first requirements were for elevator circuits. In subsequent years additional requirements were imposed for other applications as essential electrical systems for health care facilities. Code requirements for coordination have been the source of controversy, liabilities and in many instances the reasons for exceptions to the NEC by the authorities having jurisdiction (AHJ).

4.3.1 Circuit Breaker Time-Current Characteristics

The manufacturers of circuit protective devices provide the time-current characteristics (TCC) for their products. (Circuit breaker time-current characteristics are also commonly called “trip curves.”) Time-current characteristics are applicable to both circuit breakers and fuses. An understanding of these TCC’s will be of assistance in determining coordination of two prospective OCPD’s. The time-current characteristics for a circuit protective device presents the time of opening at an assumed specific current. Manufacturers determine the values of TCC’s by tests conducted in accordance with standards by UL or IEC. Since the two agencies have different testing methods, manufacturers generally identify which standard is applicable to their published data.

A typical time-current characteristic for a molded case circuit breaker is shown in in Fig. 1.6. The characteristics are generally made in log-log plots with the multiples of currents on the abscissa and the times to break on the ordinate. Since manufacturers usually offer MCCB’s for a wide range of service, it is common to find only one time-current characteristic plot for, say, a family of MCCB’s. For example, the number “1” for a 50 amp MCCB on the ordinate is the equivalent to 1X50 amps, or 50 amps and 10X50 is the equivalent to 500 amps. The characteristics of Fig. 1.6 show both a thermal sensing region and an instantaneous region. The thermal region in the representation is from approximately “1.0” to “10.0.” For several reasons MCCB time-current curves are generally shown with a range, or band, of values. The left, or lower, side represents the minimum trip time and the right, or upper, side of the band represents the maximum trip time. The band of published time-current characteristics illustrate that MCCB’s are not precise devices. The principles involved in the application of MCCB’s can best be illustrated by a specific example.

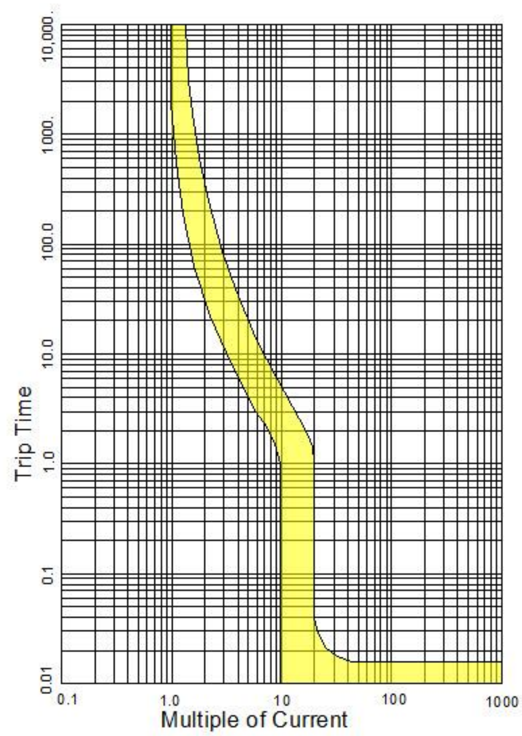

Fig. 1.6 - MCCB TCC

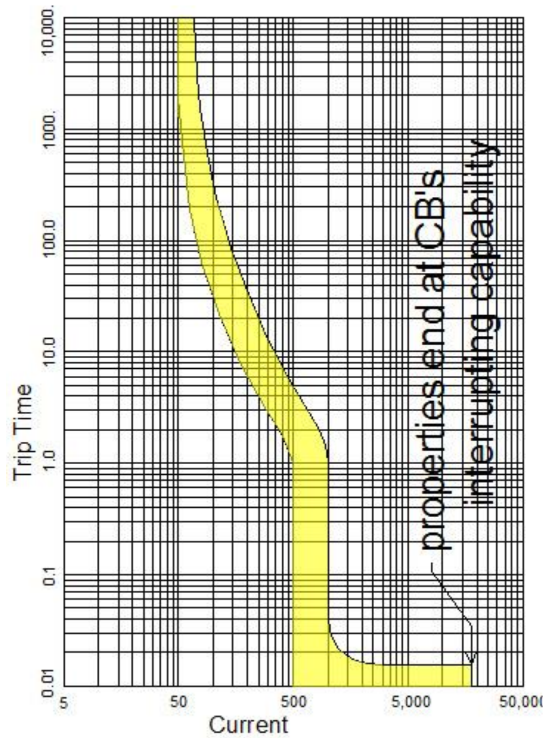

Fig. 1.7 – TCC for 50 amp MCCB

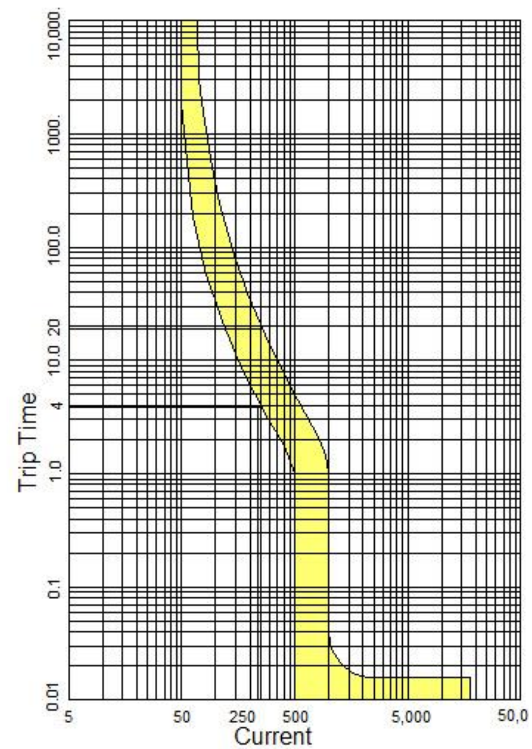

Fig. 1.8 – Trip Times at 250 amps

Example 1.3

50 amp MCCB

Fig. 1.6 is modified to show the specific values of a TCC for a nominal 50 amp MCCB. The specific values are shown in Fig. 1.7. The currents are shown on the abscissa and the times to trip are shown on the ordinate. The TCC of Fig. 1.7 shows that the 50 amp MCCB will hold indefinitely for currents below a value somewhere between 50 amps and 55 amps. According to the TCC, values above 55 amps will definitely cause a trip but after a (inverse) time delay. The TCC of Fig. 1.6 is duplicated in Fig. 1.8 where it is shown that a current of 250 amps will cause a trip of between 4 seconds and 20 seconds.

Coordination Practices

As mentioned above, the traditional method of establishing CB coordination is by comparing the associated time-current characteristic. Again, the principles can best be explained by means of a specific example.

Example 1.4

Using TCC's

To consider a typical coordination study, assume the circuit of Fig. 1.5 is to use all thermal-magnetic MCCB's for the OCPD's as represented in Fig. 1.9. The specific OCPD's become CB-M, CB1, CB2 and CB3. Assume the conditions of Example 1.1 for the downstream CB's, namely CB1, CB2 and CB3. As stated in Example 1.1, the normal loads of Circuits 1, 2 and 3 are 40 amps and CB1, CB2 and CB3 are all nominal 50 amp circuit breakers. The possible continuous current through CB-M is 3X40 or 120 amps. The conductors connecting CB-M to CB1, CB2 and CB3 must be capable of at least 120 amps since CB-M must be sized to handle a continuous current of 120 amps. According to the NEC the AWG #1, 75ºC conductors are capable of 130 amps so the AWG#1 conductors merit consideration. Allowing for an elevated ambient temperature, as in Example 1.2, a derating factor of 0.94 is applicable. The ampacity of the conductors connecting CB-M to CB1, CB2 and CB3 then becomes 0.94X130 or 122.2 amps. The next higher standard rating of MCCB's is 125 amps. However, in applying the 80% rule (per Article 210.20 A), the allowable current must not exceed 0.80X125 or 100 amps. Thus, a 125 amp MCCB will not be adequate. The next larger CB's are 150 amp and 175 amps. For coordination, as will be evident, the 175 amp breaker might be a better choice. The use of a 175 amp breaker will require conductors extending between CB-M and CB1, CB2 and CB3 to have an ampacity of at least 175 amps. The AWG#3/0 conductors which have a derated ampacity of 188 amps would suffice. In this case the AWG#3/0 conductors would extend between the 175 amp breaker and the three 50 map breakers. If the configuration of Fig. 1.9 is to be coordinated, CB-M must not trip in the event of a trip at CB1, CB2 or CB3.

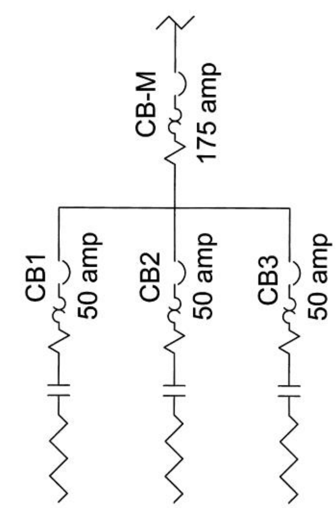

Fig. 1.9 – Example 1.4

The next step requires an evaluation of the coordination of the two types of

MCCB's under consideration. The traditional method of evaluating coordination is to examine the TCC's for the two CB's under consideration. The TCC for the prospective 50 amp CB is shown in Fig. 1.7 and the TCC for the 175 amp CB is shown in Fig. 1.10. The TCC's for both the 50 amp CB and the 175 amp CB are shown together in Fig. 1.11.

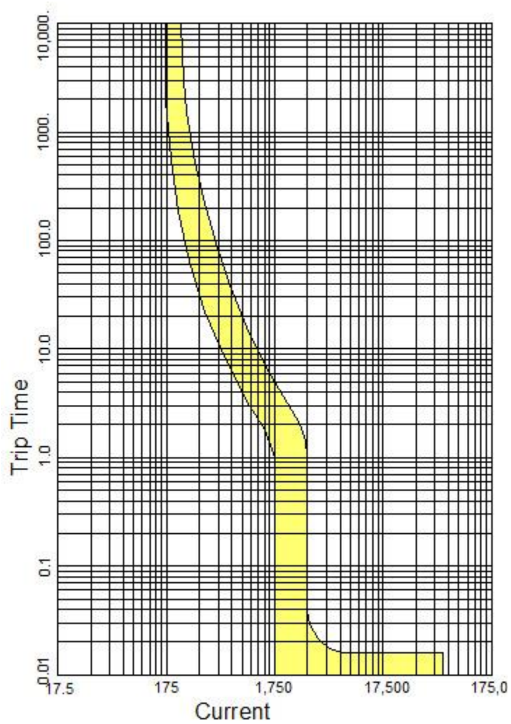

Fig. 1.10 – 175 Amp CB TCC

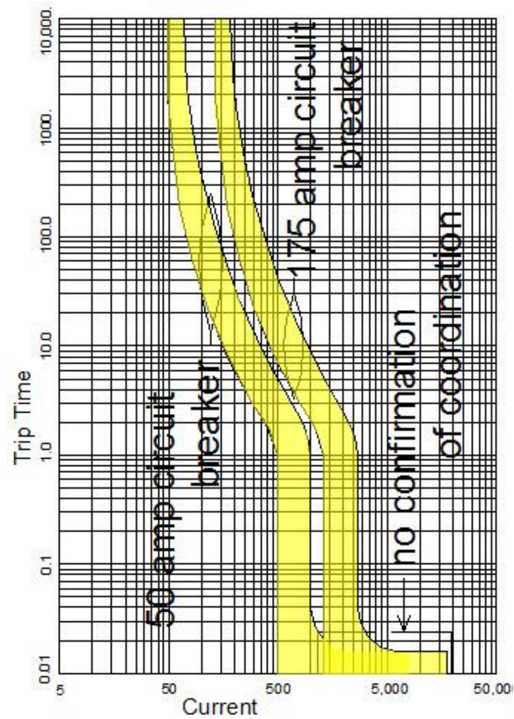

Fig. 1.11 – 50 Amp & 175 Amp TCC's

It may be noticed that use of the 175 amp breaker moved the 175 amp breaker TCC to the right and thereby avoided interference with the TCC of the 50 amp breaker up to 2000 amps. Up to 2,000 amps the two CB's are coordinated. In other words, a current of 2,000 amps or less will allow the 50 amp breaker to open while the 175 amp breaker will hold closed. However, at currents above 2,000 there is ambiguity. A current of, say, 10,000 amps will cause one or possibly both MCCB's to open within 0.017 seconds, but it cannot be predicted which will open first. Therefore it cannot be said that the two MCCB's are selectively coordinated. If coordination is required then an alternative configuration will be required. (The "boot" characteristic of CB TCC's is often the source of a problem when efforts are made to confirm coordination between two CB's.)

(Note: In this example the TCC's for both the 50 amp MCCB and the 175 amp MCCB are shown in a single drawing, namely Fig. 1.10. This was done to allow a convenient comparison of the two TCC's. In practice, it is usually not convenient to show the two TCC's on the same drawing. Rather, the common method of comparison involves having one of the TCC's on tissue paper so that it can be positioned over the other TCC. In this manner the two TCC's may readily be compared to determine coordination.)

4.3.2 Fuse Time-Current Characteristics

Fuses are available for a wide range of voltages, currents and configurations. Much as a circuit breaker the behavior of a fuse can be described by a time-current characteristic. The time-current characteristics of fuses have an overall different appearance than those of circuit breakers. Whereas the time-current characteristics of circuit breakers have many curves and bends the TCC's for fuses more approximate a straight line. Typical TCC's for a 50 amp fuse and a 175 amp fuse are shown in Fig. 1.12. The fuse TCC's do not have the "boot" shape in the area of the low opening times typical of the thermal-magnetic circuit breaker TCC's. In some ways this characteristic simplifies the task of establishing essential coordination. The times-to-open at the bottom of the TCC are less ambiguous than what is characteristic MCCB's. As CB's, fuses also have a maximum short circuit interruption capability.

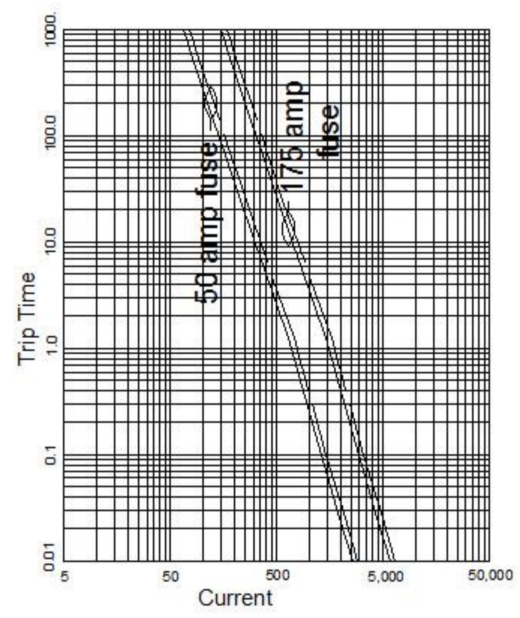

Fig. 1.12 – TCC's for Fuses

The TCC's of Fig. 1.12 indicate that coordination of the two fuses in the plot can readily be demonstrated on paper. It will be apparent that the coordination of two fuses can be confirmed since the two curves essentially are side-by-side and do not overlap at any point. It will be apparent that with a fuse downstream and a CB on the line side, selective coordination will be present. However, with a thermal-magnetic CB on both the line side and the load side there would be an overlap and coordination could not be confirmed solely from an analysis of the TCC's. Most fuse manufacturers provide coordination tables that, having been confirmed by tests, identify the combination of fuses that will coordinate one with the other. When selecting only fuses, the coordination tables make the selection process very convenient. However, when a mix of fuses and circuit breakers are involved, use of the respective TCC's will generally be required to confirm coordination.

The value of current to open a fuse is affected by temperature. Elevated ambient temperatures lower the operating point and low ambient conditions raise the operating point.

Example 1.5

Using Coordination Tables

In above Example 1.4 it was found that by using the manufacturer's TCC's it could not be confirmed that coordination would exist with the considered thermal-magnetic MCCB's under consideration. However, a study of the TCC's may not be the final answer. There are alternatives. Manufacturer's TCC's are generated from test results conducted in accordance with the applicable guidelines of either UL (which would be UL Standard 489) or the IEC. These guidelines call for testing of a single CB. While the TCC's may not suggest that any two CB's may be coordinated, in fact the two may actually be coordinated. There are a number of reasons to suspect that a CB tested with another CB of a higher rating may very well display coordination. For this reason, most manufacturers today offer coordination tables that show which specific CB's, when used in series, will be found to be coordinated. These coordination tables are a great convenience to persons responsible for demonstrating coordination of OCPD's. In summary, it would be fair to say that a TCC study may not demonstrate coordination whereas a coordination table may actually show coordination. This was found to be the case for the specific 50 amp and the 175 amp breakers cited in Example 1.4.

Example 1.6

Using an Upstream Electronic Circuit Breaker

Some of the methods of obtaining circuit breaker coordination are discussed above. Another, often mentioned, method involves the use of an electronic circuit breaker upstream of a thermal-magnetic circuit breaker. By the use of an upstream electronic circuit breaker, coordination can be demonstrated using the respective TCC's. In the way of illustration, consider the circuit of Fig. 1.9 and assume the upstream CB is to be an electronic circuit breaker with a rating of 175 amps, essentially the CB of Fig. 1.13. The downstream CB will be the same 50 amp CB used in above Example 1.4. The resulting TCC's are shown in Fig. 1.14. As is apparent in Fig. 1.14 the TCC for the 175 amp electronic circuit breaker is to the right and above the TCC of the 50 amp thermal-magnetic CB - thereby demonstrating coordination of the two breakers.

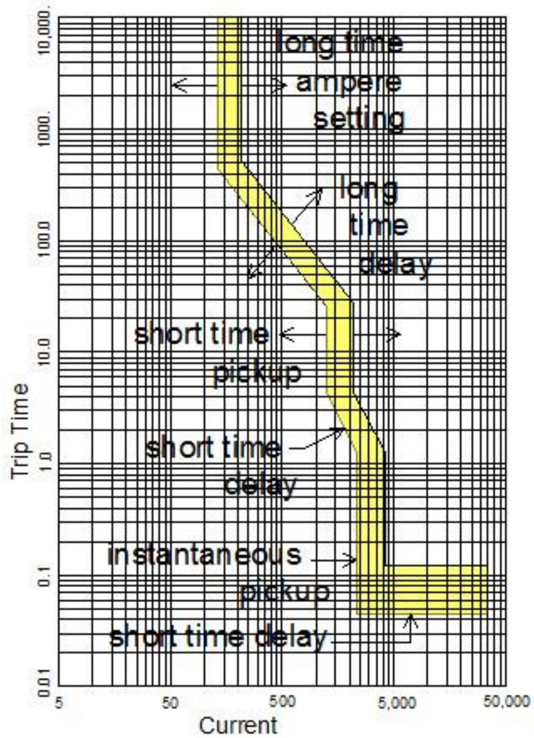

Fig. 1.13 – 175 Amp Electronic TCC

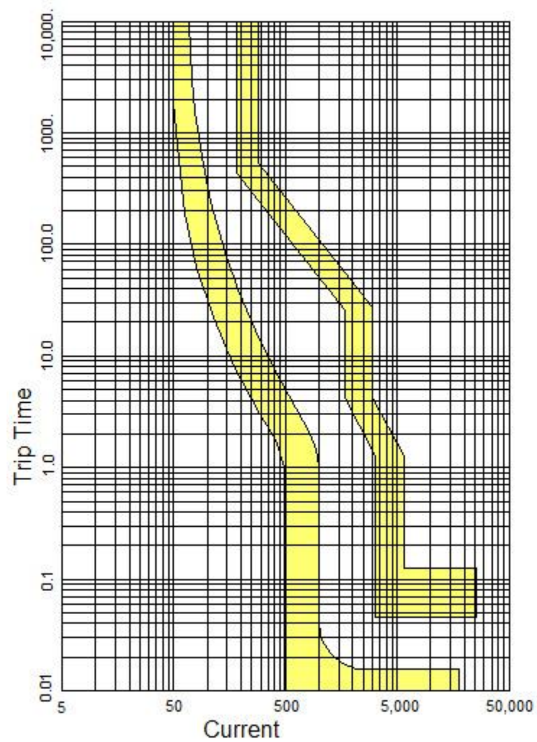

Fig. 1.14 – Coordinated CB's

5.0 Interrupting Capability

In the process of selecting an OCPD, the fault interrupting capability of the device must be taken into account. A short circuit through an inadequate OCPD could be disastrous. The high currents of a fault through an inadequate OCPD can result in the device exploding, scattering molten metal and other component to the surroundings. In order to calculate the maximum, symmetrical current that would result from a short circuit condition, a short circuit study is necessary. However, if a fault-to-ground occurs and the circuit contains reactive elements, the first few cycles could be asymmetrical. In other words, the initial current would be a combination of DC and AC. Because of asymmetrical currents, the maximum current that is calculated by a short circuit study must be adjusted to account for the asymmetrical aspect. Otherwise, an OCPD might be selected with an inadequate interrupting capability.

5.1 Short circuit Studies

There are several commonly recognized methodologies available for determining the possible value of a short circuit current. The computations involved in a comprehensive short circuit study that is conducted manually can be relatively intricate, challenging, time consuming and prone to error. Computer programs specifically tailored to short circuit studies can be very helpful and provide a standardized means of documenting calculations. There are various published aids available to assist in the effort and many manufacturers of OCPD's also offer technical papers that can be of assistance. Aside from a full blown short circuit study that considers all of the possible considerations, in many instances there are alternatives methods that suffice. None of the mentioned, and highly detailed, methods of calculating short circuit currents is reviewed here although a few pertinent considerations are treated. Rather, an abbreviated method is suggested.

The normal procedure that is followed in conducting a short circuit study begins with generation of a one line diagram of the circuit under consideration. A one line diagram represents on paper the important components of a short circuit study and it provides a visual basis for the effort to be undertaken. The one line diagram is to include the source of the electrical power which in most cases is a utility's transformer. An on-site generator might be another possible source. Generally the transformer is the most important element of a short circuit study as it is most often the primary source of the fault current at a facility. To a large extent, the size of the transformer limits the short circuit current. It is pertinent to note, however, that motors in the circuit can increase the value of a fault current. The one line diagram that is made to show all of the possible contributors of current is to also to include the assumed point of the short. Motors or capacitors, if in the circuit, should be clearly shown.

A typical one line diagram of the type necessary for a short circuit study is shown in Fig. 1.15. The representation of Fig. 1.15 includes the same configuration that was used in above Example 1.4 except that the representation is expanded to show a transformer and an assumed load. While the transformer supplying electrical power to the circuit determines the largest part of a short current, the impedances of devices between the transformer and the assumed point of a short circuit will decrease the value of the current made available at the transformer. The longer the distance from the transformer to the point of the short circuit the greater the intermediate impedance. Taking into account the impedance will result in at least some reduction in the required interrupting capability of the OCPD. It is pertinent to consider the prospective range of interrupting currents that might be determined by a short circuit study. Table 1.1 tabulates a summary of typical short circuit currents at various types of installations.

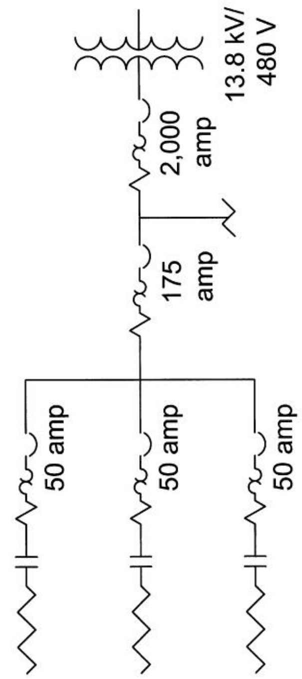

Fig. 1.15 – One Line Diagram for Short Circuit Study

Table 1.1
Typical Short Circuit Currents

Type of Installation	Typical Short Circuit
Small Residential – 100 to 200 amp	10,000 to 15,000 amp
Small Commercial – 400 to 800 amp	20,000 to 30,000 amp
Larger Commercial – 2000 to 3000 amp	50,000 to 60,000 amp
Commercial Building Directly Connected to Utility Grid	200,000 amp and greater

In residential or small commercial installations, most of which have a single phase service, the persons selecting OCPD's typically select an interrupting rating based on what has normally proved to be satisfactory in past installations. Transformers in residential areas tend to be of approximately the same size. Because of the likeness of installations, rarely would a formal short circuit study be conducted in the selection of OCPD's for a residential installation. Unlike residential applications, transformers serving three phase facilities can vary greatly in size from one installation to the next. In larger commercial or industrial installations it is likely that the transformer supplying electrical power might be capable of a relatively high current and the impedances along the path to an assumed short might be relatively low. The consequences could be very high interrupting currents. So, a short circuit study of some degree is appropriate for practically all three phase installations.

As mentioned above, there are several types of short circuits that might occur in a three phase circuit. While the phase-to-ground short circuit is by far the more common type of short circuit, the type that draws the highest symmetrical current is the bolted three phase short circuit. For that reason the three phase short circuit condition is most often used as the basis for calculating symmetrical short circuit current. Shorts other than the bolted three phase short will draw less symmetrical current but with the DC component added may be larger. If the bolted three phase short scenario is used, adjustments will then be needed to account for asymmetrical currents. How then to proceed to determine interrupting current? A good place to start is with the transformer as the transformer's parameters are pertinent. Aside from the types of short circuits mentioned, a short circuit can be either symmetrical or asymmetrical. If the fault is symmetrical it is assumed that all three phases are affected equally and all three phases have equal currents. If only some phases are affected the fault is considered to be asymmetrical. The asymmetrical condition would draw the highest current and therefore merits evaluation.

5.2 Symmetrical Short Circuit Currents

To a large extent the transformer that provides power to a circuit determines the maximum possible symmetrical fault current. (Note that motors can add current to a fault.) Parameters pertinent to the transformer supplying power are critical to any short circuit study. Much of this data is available on the transformer's nameplate. (However, according to UL requirements transformers under 15 kVA are not required to be furnished with a nameplate.) The data on a transformer generally includes the intended primary voltage, secondary voltage, full load secondary current, manufacturer, "impedance percentage" (or "impedance voltage") and very likely additional data. The impedance percentage value is of importance in determining the value of current that the transformer can deliver to a short circuit. The impedance percentage is sometimes shown on the nameplate as merely "%", "Z%." or "% p.u." The impedance percentage is defined as the percent of rated input voltage required at the primary terminals, with the secondary shorted, to produce full load current at the secondary. Having the impedance percentage, the maximum current available at the transformer's secondary for assumed symmetrical conditions can be readily computed. Common percentage impedances for three phase transformers are shown in Table 1.2

Table 1.2
Common Transformer Percentage Impedances

Transformer Size	Percentage Impedance
<200 kVA	3%
200 kVA to 500 kVA	3% to 4.5%
>500kVA	5% to 9.5%

A sample calculation of the maximum transformer's secondary fault current based on a transformer's percentage impedance is shown in below Example 1.7. (A word of caution: Approaching a transformer to obtain nameplate data can be dangerous and should not be attempted by untrained persons. In most instances a call to the utility is all that is needed to obtain needed data. In some instances a utility may provide a transformer's properties.)

Example 1.7

Maximum short circuit (symmetrical) current from transformer.

Following is a sample calculation to determine maximum symmetrical current that can be derived from a transformer based on a transformer's impedance percentage. In the way of illustration consider a transformer with a 480-3-60 secondary, a 3 MVA rating and an impedance percentage of 5%. Let MVA_f be the fault MVA, MVA the transformer's rated (non-fault) mega volt-amperes, I_f the fault current and V_s the transformer's secondary voltage.

$$MVA = 3{,}000{,}000 = (V_S)\ I\ (\sqrt{3})$$

The secondary rated current is:

$$I = 3{,}000{,}000 \div (V_S)(\sqrt{3}) = 3{,}000{,}000 \div (480)(\sqrt{3}) = 3608.4 \text{ amps}$$

If the primary is at rated voltage, the secondary current would become:

$$I_f = (100 \div 5)(3608.4) \text{ amps} = 72{,}168 \text{ amps}$$

So, the maximum (symmetrical) current available from the transformer is 72,168 amps

The computation of Example 1.7 assumes full voltage at the primary terminals throughout a short circuit condition - which would almost always never be the case. In reality, a short on the secondary of a transformer will normally result in significant voltage sag on the primary. This assumption would result in short circuit values of current that would be conservative, i.e. higher than what can be expected. All other factors being equal a decrease in the primary voltage will decrease the available current at the secondary.

When conducting a short circuit study of a circuit that includes a motor it is important to consider the contribution of the motor acting as a generator. The current added by a motor acting as a generator adds to the short circuit current that is provided by the transformer. Generally single phase motors and motors below 50 HP are excluded from consideration. The contribution of current from a motor is taken as the locked rotor amperage (LRA), which is typically computed as: FLA X 8. (A few motors, mostly IEC designs, may be as high as FLAX10.)The current delivered to a short circuit by capacitors is usually neglected for the reason that the current from capacitors is approximately 90º out of phase with the voltage at the short.

It was stated above that the assumption is that the short circuit is symmetrical. Once the maximum possible symmetrical current in a short has been determined, a person is in position to decide the next move. Example 1.7 demonstrates a method of calculating the maximum possible current available from a transformer. Will that value then become the maximum interrupting current of the OCPD's? Not necessarily! It may be necessary to use OCPD's with an interrupting capability higher than what is determined as the largest current available from the transformer as well as any motors in the circuit. The explanation harks back to the method used to test and rate OCPD's. The limitations of OCPD's are related to the asymmetrical currents that occur at the time of a short circuit.

5.3 Asymmetrical Currents

As stated above, the purpose of a short circuit study is to determine the value of the symmetrical current that might occur in the event of a short circuit. The intention of the study is usually for the purpose of sizing a circuit's OCPD's. Actually, a short circuit in an AC circuit normally results in currents that are asymmetrical and that condition introduces a set of unique problems that are not necessarily addressed in a short circuit study. Nevertheless, asymmetrical currents must be considered in the selection of an OCPD.

When typical AC equations are employed, symmetrical voltages and currents are assumed. For example, the following equations are valid only if the RMS AC voltages and currents are symmetrical:

$V = IR$ (single phase)

$P = I^2R$ (single phase)

$P = (\sqrt{3}\,)\ V_L\ I_L\ (PF)$ (three phase)

By definition a symmetrical AC current has symmetry about a zero level and the direction of the current reverses twice every cycle. By definition, an asymmetrical current is one that is not symmetrical. Examples of both symmetrical and asymmetrical currents are shown in Fig. 1.16.

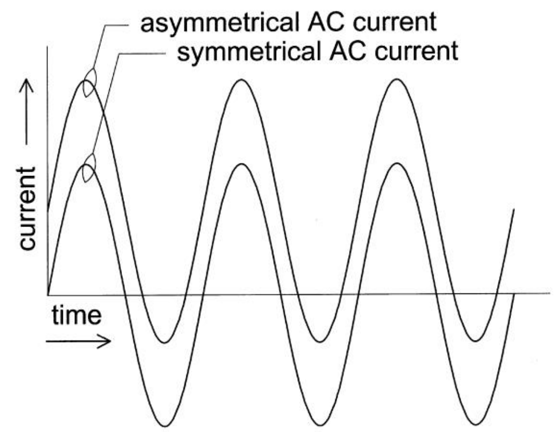

Fig. 1.16 – Typical Symmetrical and Asymmetrical Current Plots

When a short circuit occurs in an AC circuit, the current that results is normally asymmetrical to some extent. This is the case because of the circuit's reactive elements. The immediate, resulting asymmetrical current is larger than what would result if the circuit's elements were purely resistive. A typical asymmetrical current that might result from an AC short circuit is represented in Fig. 1.17. The asymmetrical current of Fig. 1.17 is a combination of an AC component and a DC component. The DC component decays in time and its value with time can be described by the equation,

$I_{DC} = I\,[1 - e^{(-t/T)}]$, where

I_{DC} = DC voltage

(t) = time (sec)

T = time constant (sec)

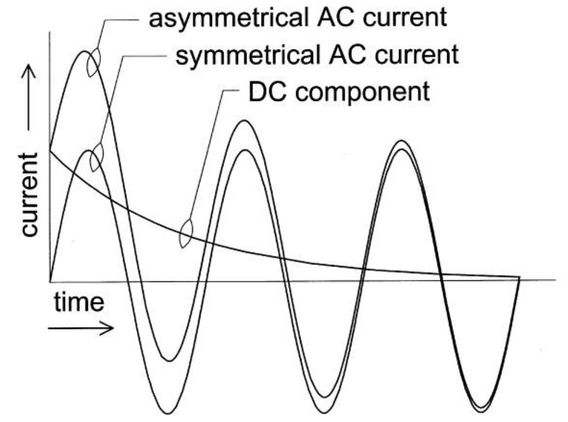

Fig. 1.17 – Asymmetrical Current Showing Symmetrical and DC Components

The time constant, T, determines the decay rate. When ($-t$/T) = 1, the value of I_{DC} will have decreased by 63.2% from its initial value. In Fig. 1.17 there are three full, symmetrical AC cycles represented. For a 60 hz circuit each cycle would be (1/60) sec, or 0.0166 sec, or 16.66 msec, in duration. The 63.2% decrease occurs at 0.01388 seconds. So, the time constant of the DC component in Fig. 1.17 is 13.88 milliseconds. The greater the lag of current with respect to voltage in the circuit, the lower the power factor and the longer the time constant of the DC component.

5.4 Ratio X/R

Power factor in a linear circuit defines the lead or lag of current with respect to the applied voltage. If a reactance diagram is made of a circuit, the power factor is cos (R/Z), where R is the resistive component, $|Z| = [R^2 + X^2]^{½}$ and X is reactance. To determine maximum, asymmetrical currents the terms “X” and “R” are commonly used and the expression (X/R) often appears. Obviously if the power factor is known, the ratio (X/R) can be calculated. The ratio (X/R) is the tangent of the angle which describes the power factor. If the angle describing the lead or lag of current with respect to voltage is θ, then,

$\cos\theta$ = PF, or

$\theta = \cos^{-1}$ PF

$\tan\theta$ = X/R

In short circuit studies the ratio (X/R), rather than power factor, is commonly used with reference to transformers. The ratio is used to determine the capability of an OCPD to interrupt current. The higher the (X/R) ratio the higher a circuit’s reactance and the greater the difficulty an OCPD has in interrupting a current. In this regard, a circuit’s (X/R) ratio is related to a short circuit study. The rating of any OCPD is limited to a specific (X/R) ratio. Circuit breakers bear an interrupting rating that is based on test results that were conducted in accordance with the guidelines of a standard. Molded case circuit breakers are tested in accordance with either a North American or a European standard. Table 1.3 lists a summary of the minimal (X/R) ratios that are mandated by the UL standard for tests on MCCB's. The IEEE provides the minimal requirements for low voltage power circuit breakers. The applicable X/R ratios for power circuit breakers per IEEE are shown in Tale 1.5.

Table 1.3
Properties per UL for MCCB

Breaker's Interrupting Rating in Amperes	Test Circuit Power Factor	Test Circuit Equivalent X/R Ratio
10,000 or less	0.45 to 0.50	1.73
10,001 to 20,000	0.25 to 0.30	3.18
Over 20,000	0.15 to 0.20	4.90

Table 1.4
Properties per IEEE for LVPCB

Type Breaker	Test Circuit Power Factor	Equivalent X/R
Unfused Breaker	0.15	6.60
Fused Breaker	0.20	4.90

A review of Tables 1.4 and 1.5 suggests the obvious question: What if a circuit has a X/R ratio higher than that used in the tests that determined the OCPD rating? That would be a more severe condition than what the device has been proved to be capable of handling. For X/R ratios above an OCPD's rating a derating must be applied. Adjustments can be made by means of a multiplication factor (MF or FM). The multiplication factor is either applied to the symmetrical current that has been calculated (by a short circuit study) and an OCPD selected accordingly - or, the symmetrical rating of a prospective OCPD is derated by dividing its rating by the multiplication factor. How to determine the multiplication factor? The referenced standards provide multiplication factors for X/R ratios that are higher than those used for testing. The multiplication factors are shown in Table 1.5 and Table 1.6.

Table 1.5
Multiplication Factors (F_M) for MCCR's (UL-489)

Power Factor	X/R	≤ 10,000 amp Interrupting Rating	10,001-20,000 amp Interrupting Rating	>20,000 amp Interrupting Rating
0.50	1.73	1.000	1.000	1.000
0.40	2.29	1.078	1.000	1.000
0.30	3.18	1.180	1.000	1.000
0.25	3.87	1.242	1.052	1.000
0.20	4.90	1.313	1.112	1.000
0.15	6.59	1.394	1.181	1.062
0.10	9.95	1.487	1.260	1.133
0.05	19.97	1.595	1.351	1.215

Table 1.6
Multiplication Factors (F_M) for LVPCB

Power Factor	X/R	Unfused Breaker	Fused Breaker
0.20	4.90	1.000	1.00
0.15	6.60	1.000	1.07
0.12	8.27	1.04	1.11
0.10	9.95	1.07	1.15
0.085	11.72	1.09	1.18
0.07	14.25	1.11	1.21
0.05	20.00	1.05	1.26

Obviously, the value of the X/R ratio is needed in order to determine a multiplication factor from Table 1.5 or Table 1.6. If the transformer in question is supplied by a utility, the utility might provide the X/R data. Otherwise the information might be available from the transformer manufacturer. In the absence of the X/R ratio, the IEEE standard allows use of a multiplication factor of 2.7 for determining the value of peak current. In comparison to the values of multiplication factor listed in Table 1.5 and Table 1.6 a value of 2.7 seems very high. It may in fact be applicable if the transformer is relatively large. Typical X/R ratios for transformers are shown in Table 1.7.

Table 1.7
Typical X/R Ratios for Self-Cooled Power Transformers

Range of MVA	Range of X/R
0.05-0.50	1-4
0.5-2	4-8
2-10	8-16
10-50	16-30
50-200	30-45

Consider an example in which a calculated (symmetrical) interrupting current is corrected to allow for the asymmetrical aspect.

Example 1.8

Correction for Asymmetrical Current

Consider an application in which the transformer of Example 1.7 is the sole source of electrical power to a bus that supplies a variety of loads including induction motors with a combined (FLA) current draw of 1 MVA. The interrupting capability of the main OCPD is to be calculated. Assume that an unfused LVPCB is under consideration for the application.

In Example 1.7 a transformer with a 3 MVA rating was considered and it was determined that the transformer was capable of a continuous current of 3608.4 amps and a symmetrical short circuit current of I_f = 72,168 amps. The 1 MVA draw of the motors corresponds to 3608.4/3 amps, or 1202.8 amps. Using a ratio of 8:1 for LRA:FLA, the possible contribution to a fault from the motors would be: 1202.8 X 8, or approximately 9623 amps. The net, possible symmetrical current is the current from the transformer plus the contributions from the motors: 72,168 + 9,623, or 81,791 amps

Assume further that it was found that the transformer's X/R ratio is 10.0. Assume also that for the moment a detailed short circuit study is not to be conducted. Rather, a simple calculation is to be done to consider only the short circuit current available from the transformer without regard to the impedance of circuit elements.

According to Table 1.6 a multiplication factor of 1.18 is applicable. Correcting the symmetrical current, the required interrupting capability of the MCCR must be at least:

I_{int} = 81,791 X 1.18 = 96,513 amps

Circuit impedances and the findings would most likely lower the values to some extent.

In this section consideration is given to the effects of asymmetrical currents on the interrupting ratings of MCCB's and LVPCB's. Briefly stated, short circuit currents are almost always asymmetrical and for this reason computed symmetrical currents must be corrected to allow for the higher energy due to the asymmetrical aspect of current flow. For applications requiring ICCB's, it is recommended that reference be made to the respective manufacturer's literature to correctly select a CB for a specific application.

Discussion above is centered on the North American practices for the selection and rating of OCPD's. The IEC methods are somewhat different.

6.0 Damage Curves

An overcurrent condition will increase to some extent the temperature of the metal conductors contained within an electrical device as a consequence to the I^2R effect. The device's insulation, which is in constant contact with the metal, will in turn be heated by the metallic conductors. If the resulting temperature rise is excessive, the insulation can be either seriously deteriorated or, in the extreme, rendered useless. In consequence to failed insulation a short circuit may result either immediately or after a delay. For this reason the possible effects of an overcurrent condition warrant a careful evaluation. This generality is true of cables, transformers, generators, capacitors and other electrical devices that might be at risk of an overcurrent condition. These electrical devises, much as the OCPD's mentioned above, have an associated unique time-current curve which is known as the device's damage curve. Currents exceeding the respective damage curve are considered as harmful to the device to some degree and should be prevented by a suitable OCPD. An example will demonstrate some of the principles that are involved.

Example 1.9

Conductor Damage Curves

In the way of a specific example, assume that three #6 AWG, THHN (90ºC) copper conductors are to be installed in a conduit as a part of a three phase circuit. The conduit is air cooled. The three conductors will be the only conductors in the conduit. According to NEC Article 310.13 the uncorrected ampacity of the conductors is 75 amps. Because the normal temperature is expected to be no greater than 30ºC no derating is required.

Reference is made to IEEE Standard 242-2001 which states that an overcurrent of 10 seconds or longer is considered as intermediate-to-long term condition and an overcurrent lasting less than 10 seconds is considered a short circuit current. Each of these two time periods is treated separately.

Currents Lasting 10 Seconds or Longer

The values of computed overcurrent vs time are dependent on the assumed value of maximum insulation temperature during a short. The IEEE document maintains that calculations are based on what is said to be a conservative value of 150 ºC. Following the guidelines of IEEE 242-2001 the following values of overcurrent were computed:

Table 1.8
Overcurrent Values per IEEE 242-2001

Time (sec)	Overload Current
10	618
100	209
1000	99
10000	84
18000	83

Currents Lasting Less than 10 Seconds

To determine the maximum allowable short circuit currents of cables, IEEE 242-2001 refers to Standard P-32-382-1999 of the Insulated Cable Engineers Association (ICEA). According to Section 9 of IEEE 242-2001 the applicable equation for periods less than 10 seconds is determined by the ICEA equation which is known as the "Conductor Withstand Formula." The formula states:

$t = 0.0297 \log_{10} [(T_f + 234) / (T_o + 234)] (A/I)^2$ (in ºC), where

t = time of short circuit (sec)

A = conductor area (cmils)

I = short circuit current (amps)

T_o = allowable operating temperature of the insulation (ºC)

T_f = maximum allowable insulation short circuit temperature (ºC)

The values of overcurrent are dependent on the assumed maximum acceptable insulation temperature. General Cable uses a maximum insulation temperature of 250ºC for 90ºC conductors. (Obviously, this temperature is much higher than the 150 ºC temperature used in IEEE Standard 242-2001.) Following are the computed values using the two temperatures.

Table 1.9
Time vs Temperature per IEEE 242-2001

Max Current (amps)	Time (sec) (250ºC)	Time (sec) (150ºC)
10,000	.0356	.0157
5,000	.1425	.0603
3,000	.396	.167
2,000	.891	.377
1,500	1.584	.670
1,000	3.56	1.508
750	6.33	6.035

The above-calculated values of current vs time for the assumed #6 AWG conductor are plotted in Fig. 1.18 along with the TCC for a prospective 40 amp thermal-magnetic MCCB OCPD. The plots indicate that, except for the "boot" area of the MCCB, either the 150ºC assumed insulation temperature or the 250ºC assumed insulation temperature would be acceptable. In the boot area, acceptability is dependent on the interrupting capability of the MCCB. With the 150ºC assumed temperature there is no problem up to an interrupting current of 10,000 amps. With the 250ºC assumed temperature there is no problem up to an interrupting current of 15,000 amps. The damage curves tell much about the prospective combination of the selected MCCB and the #6 AWG conductor. Perhaps the "boot" area of the MCCB suggests a problem with interrupting current. Or, perhaps the assumed temperatures are considered too high for an application that, say, is critically important. There are several alternatives that could be considered. Use of a fuse instead of a MCCB would avoid concern related to the "boot" area of the MCCB. Another alternative would be to use a larger conductor as the next larger size, namely a #4 AWG.

A #4 AWG conductor is considered in Fig. 1.19. Use of the larger conductor shifts the short circuit withstanding capability to 15,000 amps for an assumed maximum of 150ºC and higher for the temperature of 250ºC. The greater amount of copper in the larger conductor acts as a heat sink thereby reducing the insulation temperature for a given short circuit current.

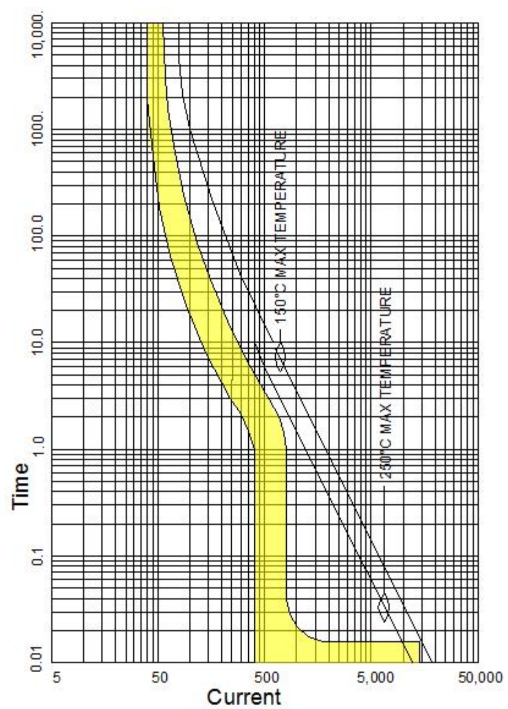

Fig. 1.18 - #6 AWG Conductor and 40 amp Thermal-magnetic MCCB

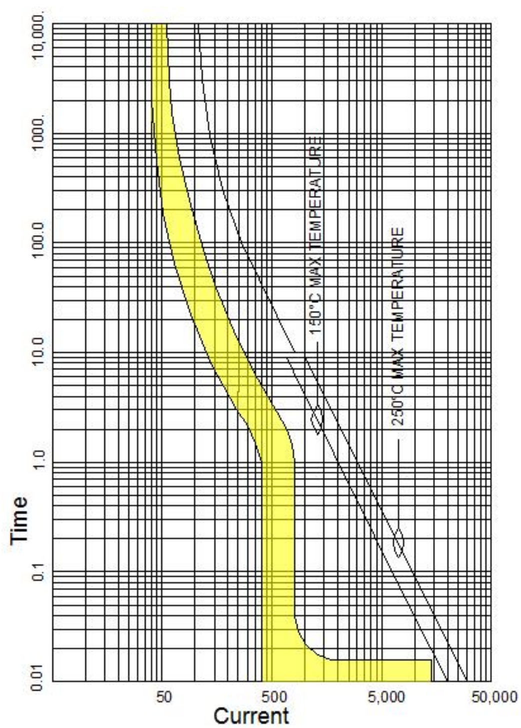

Fig. 1.19 - #4 AWG Conductor and 40 amp Thermal-magnetic MCCB

Example 1.9 demonstrates the typical technique followed when damage curves are used to evaluate potential damage to an electrical device. Primarily, the method is applicable to any electrical device that has insulation that might be subject to deterioration or damage resulting from elevated temperatures. Damage curves are applicable to motors, generators, transformers, conductors and the like. Damage curves are especially helpful when an evaluation is to be made of critically important electrical gear. As illustrated in the example, damage curves provide a convenient means whereby alternatives may be considered.