An Introduction to Overcurrent Protection

Overview - Whitepaper Articles 1.1 – 1.4

Potentially damaging overcurrents occur in electrical circuits due to either sustained overloads or inadvertent transient (fault) conditions. Natural, non-damaging transient overcurrents occur during start-up conditions in many circuits.

This series of four whitepaper articles discusses:

Article Contents

1.1 Overcurrent Protection and Overcurrent Circuit Protectors

Abstract

Low voltage (300 Volts and below) network overcurrent protection consists of a series connection of circuit protectors that both detect the presence and interrupt the flow of circuit overcurrents. Overcurrent circuit protectors operate in a cascading manner, with each designed to function at a set level and duration of overcurrent flow. Standard low voltage protection devices are: fuses, thermal circuit breakers, magnetic circuit breakers, thermal-magnetic circuit breakers, and solid-state switches.

1.2 The Physics of Circuit Interruption

Abstract

All electro-mechanical overcurrent circuit protectors require physical separation of current carrying contacts; and utilize the rapid collapse of the conduction mechanism within an electric arc at a zero current condition to interrupt the flow of circuit current.

1.3 Overcurrent Clearing Times

Abstract

The total clearing time or operating time of an overcurrent circuit protector is defined as the time duration from overcurrent initiation to complete cessation of current flow. This total operating time is divided into two principal sub-periods: the detection time period and the interruption time period. The detection time period is engineered to be commensurately shorter as levels of overcurrent are higher. It is this period that determines the ability of circuit protectors to coordinate with, or back up, one another. The interruption time period is the "action" period in which the device forcibly opens the path of overcurrent flow.

1.4 Device Physical Characteristics

Abstract

Overcurrent circuit protectors are available in a variety of different housings and functional arrangements. Whether or not a particular circuit protector is suitable for a particular application is dependent both on the device performance capability and the available physical characteristics for the device.

Article 1.1 August 29, 2011

Overcurrent Protection and Overcurrent Protectors

Abstract

Low voltage (300 Volts and below) network overcurrent protection consists of a series connection of circuit protectors that both detect the presence and interrupt the flow of circuit overcurrents. Overcurrent circuit protectors operate in a cascading manner, with each designed to function at a set level and duration of overcurrent flow. Standard low voltage protection devices are: fuses, thermal circuit breakers, magnetic circuit breakers, thermal-magnetic circuit breakers, and solid-state switches**.**

Beginnings

Overcurrents and circuit protectors are not new subjects. Soon after Volta constructed his first electrochemical cell, or Faraday spun his first disk generator, someone else graciously supplied these inventors with their first short circuit loads. Patents on mechanical circuit breaker devices go back to the late 1800's, and the concept of a fuse goes all the way back to the first undersized wire that connected a generator to a load.

In a practical sense, we can say that no advance in electrical science can proceed without a corresponding advance in protection science. An electric utility company would never connect a new generator, a new transformer, or a new electrical load to a circuit that cannot automatically open by means of a circuit protector. Similarly, a design engineer should never design a new electronic power supply that does not automatically protect its solid-state power components in case of a shorted output. Protection from overcurrent damage must be inherent to any new development in electrical apparatus. Anything less leaves the apparatus or circuit susceptible to damage or total destruction within a relatively short time.

Typical System Example

Examples of overcurrent protection devices are many: fuses, electromechanical circuit breakers and supplementary protectors, and solid-state power switches. They are utilized in every conceivable electrical system where there is the possibility of overcurrent damage. As a simple example, consider the typical industrial laboratory electrical system shown in Figure 1.1

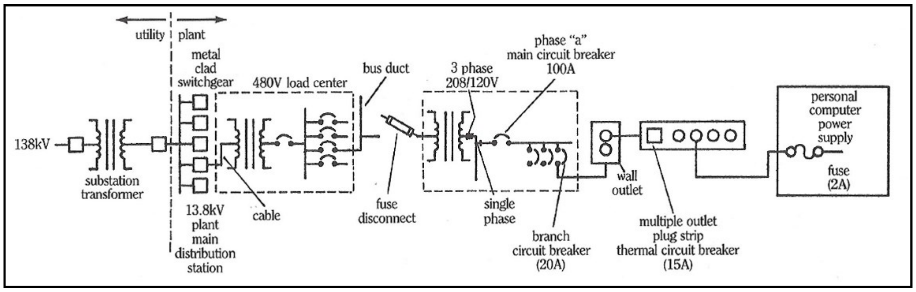


Figure 1.1 __One Line Diagram of a Typical Industrial Laboratory System__

Figure 1.1 is a one-line diagram of the radial distribution of electrical energy, starting from the utility distribution substation, going through the industrial plant and ending in a small, laboratory personal computer. The system is said to be radial since all branch circuits, including the utility branch circuits, radiate from central tie points. There is only a single feed line for each circuit. There are other network type distribution systems for utilities, where some feed lines are paralleled. But the radial system is the most common and the simplest to protect.

Overcurrent protection is seen to be a series connection of cascading current-interrupting devices. Starting from the load end, we have a dual-element, or slow-blow fuse at the input of the power supply to the personal computer. This fuse will open the 120-volt circuit for any large fault within the computer. The large inrush current that occurs for a very short time when the computer is first turned on, is masked by the slow element within the fuse. Very large fault currents are detected and cleared by the fast element within the fuse.

Protection against excess load at the plug strip is provided by the thermal circuit breaker within the plug strip. The thermal circuit breaker depends on differential expansion of dissimilar metals, which forces the mechanical opening of electrical contacts.

The 120-volt single-phase branch circuit, within the laboratory that supplies the plug strip, has its own branch breaker in the laboratory's main breaker box or panel board. This branch circuit breaker is a combination thermal and magnetic (or “thermal-mag”) breaker. It has a bi-metallic element which, when heated by an overcurrent, will trip the device. It also has a magnetic-assist winding which, by a solenoid type effect, speeds the response under heavy fault currents.

All of the branch circuits on a given phase of the laboratory's 3-phase system join within the main breaker box and pass through the main circuit breaker of that phase, which is also a thermal-magnetic unit. This main circuit breaker is purely for back-up protection. If, for any reason, a branch circuit breaker fails to interrupt overcurrents on that particular phase within the laboratory wiring, the main circuit breaker will open a short time after the branch circuit breaker should have opened.

Back up is an important function in overload protection. In a purely radial system, such as the laboratory system of Figure 1.1, we can easily see the cascade action in which each overcurrent protection device backs up the devices downstream from it. If the computer power supply fuse fails to function properly, then the plug strip thermal circuit breaker will respond, after a certain coordination delay. If it should also fail, then the branch circuit breaker should back them both up, again after a certain coordination delay. This coordination delay is needed by any back-up device to give the primary protection device—the device that is electrically closest to the overload or fault—a chance to respond first. The coordination delay is the principal means by which a back-up system is selective in its protection.

Selectivity is the property of a protection system by which only the minimum amount of system functions are disconnected in order to alleviate an overcurrent situation. A power delivery system that is selectively protected will be far more reliable than one that is not.

For example, in the laboratory system of Figure 1.1, a short within the computer power cord should be attended to only by the thermal circuit breaker in the plug strip. All other loads on the branch circuit, as well as the remaining loads within the laboratory, should continue to be served. Even if the supplementary protector within the plug strip fails to respond to the fault within the computer power cord, and the branch circuit breaker in the main breaker box is forced into interruptive action, only that particular branch circuit is de-energized. Loads on the other branch circuits within the laboratory still continue to be served. In order for a fault within the computer power cord to cause a total blackout within the laboratory, two series-connected circuit breakers would have to fail simultaneously—the probability of which is extremely small.

Trip Curves

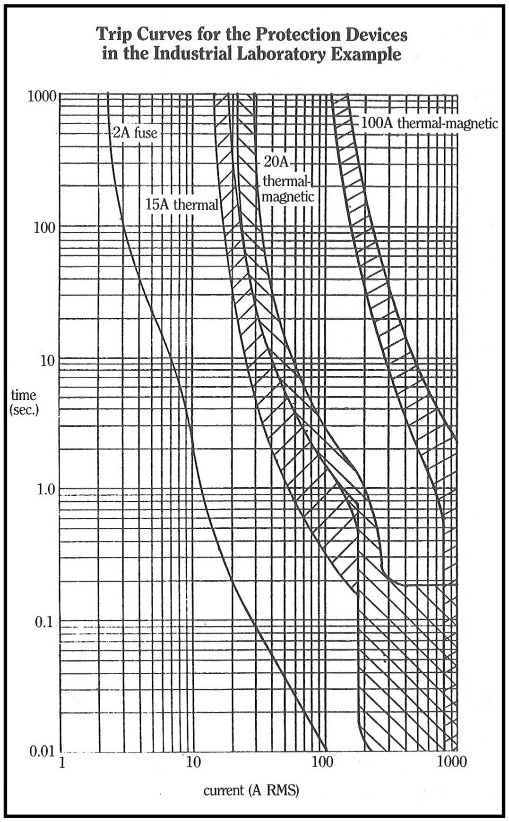
The ability of a particular circuit protector device to interrupt a given level of overcurrent depends on the device sensitivity. In general, all overcurrent circuit protectors, no matter the type or principles of operation, respond faster when the levels of overcurrent are higher.

Coordination of overcurrent protection requires that application engineers have detailed knowledge of the total range of response for particular protection devices. This information is contained in the "trip time vs. current curves," commonly referred to as the trip curves. A trip time-current curve displays the range of, and the times of response for, the currents for which the device will interrupt current flow at a given level of circuit voltage. For example, the time-current curves for the circuit protectors in our laboratory example are shown superimposed in Figure 1.2.

The rated current for a device is the highest steady-state current level at which the device will not trip for a given ambient temperature. The steady-state trip current is referred to as the ultimate trip current. The ratings for the dual-element fuse in the computer power supply, the plug strip thermal circuit breaker, the branch circuit thermal-magnetic breaker and the main circuit thermal-magnetic breaker are 2, 15, 20 and 100 amps, respectively. Note that, except for the fuse curve, each time-current curve is shown as a shaded area, representing the range of response for each device. Manufacturing tolerances and material property inconsistencies are responsible for these banded sets of responses. Trip time-current information for small fuses is usually represented in a single-value average melting time curve.

Figure 1.2

Trip Curves for the Protection Devices in the Industrial Laboratory Example



Even with a finite width to the time-current curves, we can easily see the selectivity/coordination between the different circuit protectors. For any given steady-state level of overcurrent, we read up the trip time-current plot, at that level of current, to determine the order of response.

Consider the following three examples for the laboratory wiring, plug strip, and computer system.

Example 1: Component failure within the computer power supply

Assume that a power component within the computer power supply has failed—say two legs of the bridge power rectifier—and that the resulting fault current within the supply, limited by a surge resistor, is 70 amps.

We see from the fuse trip curve that it should clear this level of current in approximately 20 milliseconds. If the fuse fails to interrupt the current—or worse, if the fuse has been replaced with a permanent short circuit by a gambling repair person—the thermal breaker in the plug strip should open the circuit within 0.6 to 3.5 seconds. The branch thermal-magnetic breaker will open the entire branch circuit within 3.5 to 7.0 seconds, should the plug strip thermal circuit breaker also fail to respond.

Note that no back up is provided for this particular fault after the branch circuit breaker. The main laboratory 100-amp thermal-magnetic unit would respond only if the other loads within the entire laboratory totaled greater than 30 amps at the time of the 70 amp power supply fault.

Example 2: Plug strip overload

Assume that the computer operator has spilled a drink, and to dry up the mess plugs two 1500-watt hair dryers into the plug strip. The operator then flips them both on simultaneously, drawing a total plug strip load current of approximately 30 amps.

From the thermal circuit breaker trip curve, we see that the plug strip unit should clear this overload within 5 to 30 seconds. If the thermal circuit breaker fails, then the branch circuit thermal-magnetic breaker should open within 30 to 130 seconds.

Note the similarity between the trip curves of the plug strip thermal unit and the branch circuit thermal-magnetic unit in the region of 100 amps and below. This is because, for these levels of currents, the thermal portion of the detection mechanism within the thermal-magnetic branch breaker is dominant.

Example 3: Short circuit within the computer power cord

Assume a frayed line cord finally shorts during some mechanical movement. Assume also that there is enough resistance within the circuit plug strip, and line cord system to limit the resulting fault current to 300 amps.

This level of current is 2000% (20 times) of the rated current of the plug strip thermal circuit breaker, and is beyond the normal range of published trip time specifications for thermal breakers (100% to 1000% of the rated current). Thus the exact trip time range of the thermal unit is indeterminate.

At high levels of fault current, greater than 150 amps in this case, we can see the inherent speed advantage of magnetic detection of overcurrents. This is evidenced by the fact that the response curve for the thermal-magnetic branch circuit breaker knees downward sharply at current levels between 150 and 200 amps. At these and higher currents, the magnetic detection mechanism within the thermal-magnetic unit is dominant.

The response curve for the unit crosses over the plug strip thermal circuit breaker response curve (assuming that it extends past its 1000% limit), and coordination between the two interrupters is lost. The range of response for the thermal-magnetic breaker at 300 amps is 8 to 185 milliseconds. Should both the plug strip circuit breaker and the branch circuit breaker fail to operate, the main laboratory breaker should clear the fault within 11 to 40 seconds.

Next: Article 1.2 The Physics of Current Interruption

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Article 1.2 August 30, 2011

The Physics of Current Interruption

Abstract

All electro-mechanical overcurrent circuit protectors require physical separation of current carrying contacts; and utilize the rapid collapse of the conduction mechanism within an electric arc at a zero current condition to interrupt the flow of circuit current.

Interrupting a Circuit

The voltage and current in a complete electrical circuit obey Kirchhoff's voltage and current laws. These laws simply stated are: the rises and drops in voltage around any closed circuit (a circuit loop) must sum to zero; and the total current flow into any one junction (connection point) must also sum to zero. If we wish to interrupt the current in a circuit, we must do so in accordance with these laws.

Although it sounds simple—interrupt the circuit, break the conduction path, or open the switch—it is not. Forcing a conducting circuit to a steady-state condition of zero current is anything but simple. Many times, the actual detailed physics of the process of current interruption is obscured by the seeming triviality of the switching action—such as simply flicking off a flashlight but consider what actually happens when a flashlight is turned off.

DC Interruption

A steady-state direct current (DC) is flowing from the batteries to the bulb as the switch contacts begin to move. At the last microscopic points of electrical contact, the current density becomes high enough that portions of the metallic surfaces actually melt due to resistive heating; and a liquid metal vapor plasma state continues the electrical conducting path as the contacts physically part. As the contacts pull further apart to distances of several microns electrons from the contact into which the current is flowing, the cathode contact, are emitted into the inter-contact space region due to thermal emission (they boil off) and field emission (they are ripped from the cathode metal by electrostatic attraction forces).

A portion of these electrons emitted from the cathode collides with air molecules within the contact gap and ionize the molecules. This frees still more electrons, which in turn ionize still more air molecules. This self-perpetuating action is an electrical breakdown phenomenon commonly referred to as an arc. It is the arc that enables the switch to open the circuit. The arc forms just as the contacts part, and continues to conduct the circuit current as the contacts move further and further apart.

The voltage drop across the arc—which is proportional to the arc length and inversely proportional to the arc cross-sectional size—is in series with the voltages in the circuit loop that contains the switch. The arc voltage grows as the physical movement of the contacts lengthens the arc, and the arc cross-section is diminished as the arc is cooled by contact with un-ionized air molecules.

The arc voltage in low voltage DC circuits grows at such a rate that it soon exceeds, or at least matches, the source voltage in the circuit (in a flashlight the initial arc voltage exceeds the battery voltage). When this occurs, the circuit current is driven to zero in short order. All circuits contain a small but finite inductance, so the current cannot be driven to zero instantaneously. When the current does reach zero, no further arc ionization takes place, and the arc is cooled even more rapidly, since it has no energy input. If it is cooled momentarily to such a state that it is no longer a conducting medium, then the interruption process is complete and the circuit has been opened. It is important to remember that it is the arc that forces the current to zero. The opening of the switch forms the arc, but it is the arc that enables the circuit to be interrupted.

AC Interruption

A switch or circuit protector that is intended to open alternating current (AC) circuits has a somewhat easier chore than its DC counterpart. In AC circuits, there is no need to force a current-zero condition. Since the current alternates about zero already, there is a natural current-zero twice in each AC cycle. Any arc, which forms in an AC switching device, does not have to be stretched and cooled to the extent that the arc voltage exceeds the magnitude of the circuit source voltage. However, this can be done if one wishes to limit the magnitude of an over-current by driving it down to an unnatural current-zero.

AC currents can be interrupted at a natural current-zero, which is primarily determined by the circuit alone and practically unaffected by the presence of the circuit protector. Alternatively, AC currents can be interrupted at forced current-zeros, which are imposed by the action of the circuit protector. Figure 1.3 illustrates these concepts of natural and forced current-zeros in an AC circuit.

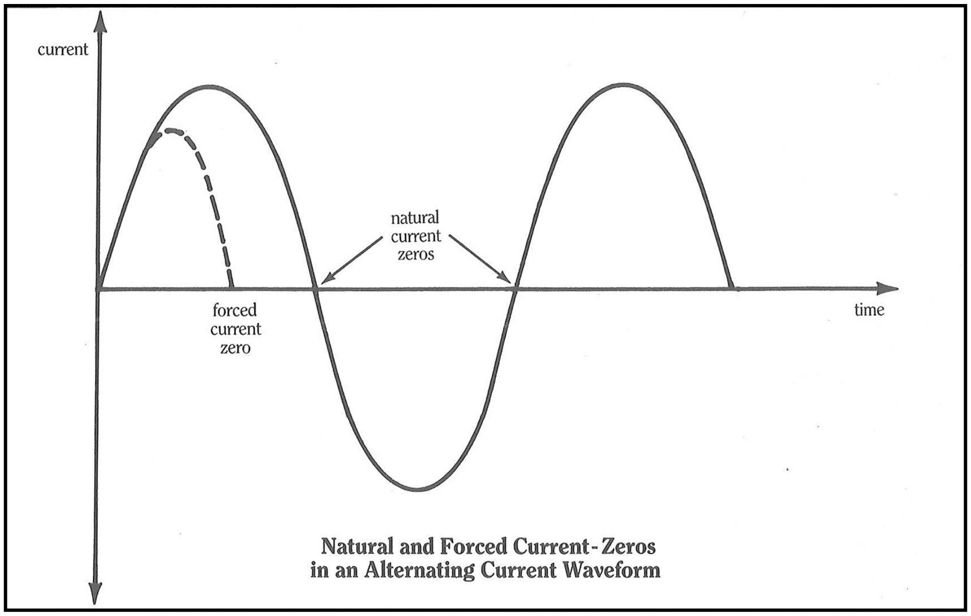

Figure 1.3 Natural and Forced Current Zeros in an Alternating Current Waveform

Solid State Interrupters

All mechanical switches and mechanical circuit protectors depend on the rapid cooling of an arc medium to open an electrical circuit Solid-state switches do not need an arc to break a circuit since they supply their own conducting medium, the semiconductor material itself. A semiconductor can conduct current only as long as mobile carriers (electrons and holes) are provided from supply or injection regions within the device. If the injection of mobile carriers in a semiconductor switch is turned off, then the semiconductor material will revert to an insulating state and block the flow of current—that is, the semiconductor switch will turn off.

The allowable current density within a semiconductor switch is much lower than that which can safely flow in a metal contact/arc switch. Thus, the cross-sectional size of a semiconductor switch, for equal rating devices, will always be larger than that of a mechanical switch. Even with this disadvantage, the ease with which a semiconductor switch can be controlled, and the reliability of a device with no mechanically moving parts, portend a bright future for solid-state power switches and circuit breakers.

Next: Article 1.3 Overcurrent Clearing Times

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Overcurrent Clearing Times

Abstract

The total clearing time or operating time of an overcurrent circuit protector is defined as the time duration from overcurrent initiation to complete cessation of current flow. This total operating time is divided into two principal sub-periods: the detection time period and the interruption time period. The detection time period is engineered to be commensurately shorter as levels of overcurrent are higher. It is this period that determines the ability of circuit protectors to coordinate with, or back up, one another. The interruption time period is the "action" period in which the device forcibly opens the path of overcurrent flow.

Overload Detection

Our discussion of the physics of current interruption in the previous article (1.2 The Physics of Circuit Interruption) did not address the question of detection of an over-current state. Before the interruption process is initiated—that is, when the contacts start to open or the injection of mobile carriers into a semiconductor switch is restricted—the circuit protector must first make a trip/no-trip decision. The period of time between the initiation of an overcurrent condition within a circuit and the initiation of interruptive action by the circuit protector is termed the detection period. The different types of circuit protectors detect overcurrents in different ways. Thus, they can have different detection periods for the same overcurrent conditions.

The detection mechanism in a fuse is the melting and the vaporization of a fusible link. In a thermal circuit breaker, dissimilar metals, bonded together along a single surface, expand differently under the direct or indirect resistive heating of the overcurrent. This forces a lateral mechanical movement, perpendicular to the bonded surface, which releases a latched contact separation mechanism. In some types of thermal circuit breakers, the contact mechanism can be formed using the bi-metal material itself. In these devices, the bi-metal arms/contacts snap open when they absorb sufficient energy from the circuit overcurrent. Another form of thermal circuit breaker utilizes the longitudinal expansion of a hot wire, which carries the overcurrent, to release a contact latch.

The detection portion of a magnetic circuit breaker is comprised of an electromagnet driven by the circuit current. An overcurrent will develop, within the electromagnet, enough magnetic pull to trip a spring restrained latch that, as in the thermal circuit breaker, allows the spring-loaded contacts to separate.

A solid-state switch detects overcurrents electronically, in many cases by simply monitoring the voltage drop across a low-value resistance that carries the circuit current.

Obviously, the faster a circuit protector can detect an overcurrent the shorter the detection period. But, in the majority of cases, the fastest possible detection speed is not desirable. The speed of detection must be controllable and inversely matched to the severity of the overcurrent.

Trip Time

As noted in Article 1.1 (Overcurrent Protection and Overcurrent Protectors), series-connected circuit protectors must be coordinated. For a given level of overcurrent, the device nearest to, and upstream from, the cause of the over-current must have the fastest response. Devices that are further upstream must have a delayed response, such that the minimum circuit removal principle is adhered to.

When we speak of response, we are referring to the total response time, or total clearing time, of the circuit protector, from the time of the overcurrent initiation to the final current-zero at which interruption is completed. Since it is far easier to engineer the extent of the detection period for a given level of overcurrent than it is to control the extent of the actual current interruption process, the total response time of any circuit protector is, by design, determined principally by the size of, and the time required to detect the overcurrent state.

The interruption period is defined as the length of time between the start of interruptive action—for example, when the contacts start to part—and the final current-zero. The sum of the detection period and the interruption period is then the total clearing time, or total trip time, of the circuit protector. These different time periods are shown in Figure 1.4.

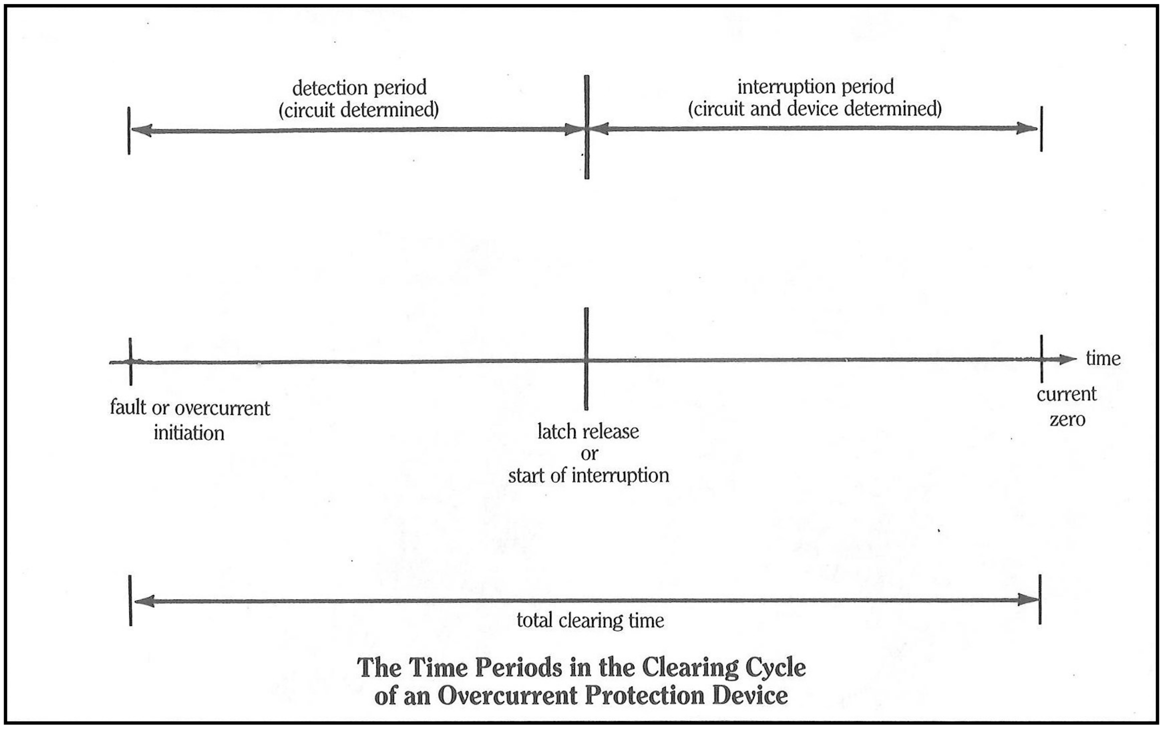

Figure 1.4
<u>Time Periods in the Clearing Cycle of an Overcurrent Protection Device</u>

In contrast to the detection period, the interruption period cannot be engineered to decrease as the intensity of an overcurrent increases. The interruption period is, however, almost always designed to be as short as possible, since during this period the circuit protector is absorbing energy, due to the over-current flowing through the voltage drop across the contacts (or terminals in the case of a solid-state device). If circuit protectors, other than fuses, do not clear the overcurrents fast enough during this period, they can be destroyed due to their own power dissipation. Of course, fuses by design are always destroyed when they interrupt a circuit.

In AC circuits, the interruption period will last to either the first forced current-zero or the first natural current-zero at which the switching medium (arc or solid-state material) can reach its non-conducting blocking state. In DC circuits, the current-zero state is always a result of a forcing action by the circuit protector.

There are additional time periods of interest during the current interruption process, such as contact travel time, arc restrike voltage transient time, thermal recovery time, and charge storage time (for solid-state devices). These times are discussed in other articles detailing the actions of particular interruption devices.

Next: Article 1.4 Device Physical Characteristics

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Article 1.4 August 30, 2011

Physical Characteristics

Abstract

Overcurrent circuit protectors are available in a variety of different housings and functional arrangements. Whether or not a particular circuit protector is suitable for a particular application is dependent both on the device performance capability and the available physical characteristics for the device.

Typical Circuit Protectors

This whitepaper deals with the physical characteristics of circuit protectors. Different types of circuit protectors have their associated limitations and features. A summary table of physical characteristics is given in Table 1.1.

Fuses

Fuses are now offered in a variety of configurations. Sizes range from small surface mount devices without leads or fuse clips to large cartridges. Other configurations include standard fuse clips, holders, blade types (originally for the automotive industry) and those with wire leads for automatic board insertion equipment Dual element fuses, indicator and alarm options are available. Fuses cannot be reset and can only be used to clear a fault or overload condition once.

Thermals

(a.k.a. CBEs, Circuit Breakers for Equipment)

Thermal circuit breakers are available in small card mountable packaging, a variety of bezel mounts (including snap in) and with different bushing configurations. They are available in automatic reset configurations and in a wide selection of circuit breaker switches and/or indicator configurations including rockers, push/pull, toggle, illuminated and push-to-reset circuit breakers usual numbers of poles are 1 to 3. Terminals can be wires for card mounting, quick connect blades, screw terminals, Edison base plug type, or fuse clip terminals. Other configurations include "fuse holder" style cartridges. Shunt trip, relay trip, alarm circuits and 3 and 4 terminal devices are available.

Magnetics

Magnetic circuit breakers are available with many options. Time delay options, inrush tolerancing, relay trip, shunt trip, dual coil (voltage and current), auxiliary switch, rocker handles, toggles, illumination and bat handles. Many color combinations are available. Six pole assemblies are available from some manufacturers. Mounting includes small breakers that are card mountable, quick connect blades, screw terminals, buss mounted and bezels that are snap in or screw mounted.

Thermal-magnetics

Reset configurations are mainly push button or toggle. Trip indicators range from lights to handle position to exposed symbols or flags. Mounting is usually with either bezel screws or buss clips.

Solid-state

Although no configuration is typical a range of solid-state protection devices could be from a black box replacement for a thermal or magnetic circuit breaker with terminals, mounting and status indication to a completely integrated set of components on a printed circuit board.

Table 1.1
Typical Values and Ranges for Protection Devices Rated Below 30 Amperes

Typical Values and Ranges for Protection Devices Rated Below 30 Amperes

	Fuse	Thermal	Magnetic	Thermal-Mag	Solid State
Parameters sensed	current, temp.	current, temp.	current,	current, temp.	current, voltage, temp.
Manufacture's listing of useful ambient temperature range (C⁰)	—	-40 to 70 -55-121(a)	-40 to 85	-10 to 60	-55 to 85
Ultimate Trip Derating with Temperature	yes	yes no(a)	no	yes	no
Overload Trip Derating with Temperature	yes	yes no(a)	yes	yes	no
Minimum current rating (amperes)	.002	.05	.02	.5	.001
Interrupting capacity, fail safe (amperes)	1,500–10,000	1,000–6,000	1,000–5,000	1,500–10,000	(b)
Power loss	low	low	low	low	med.
Voltage drop at rated current:					
@ 2 amperes	.16	.75	.50	.60(c)	.20(d)
@ 10 amperes	.12	.03	.13	.13(c)	.30(d)
Cycle life at rated current	(e)	5,000	10,000	10,000	1,000,000
Switchable	no	yes	yes	yes	yes
Remotely controllable	no	no	no	no	yes
Position sensitive	no	no	yes	no	no
Vibration and shock tolerance	high	high	med.	med.	very high
Cost	low	low	med.	med.	high
Maintenance	high	low	low	low	low

(a) Temperature compensated thermal circuit breaker
(b) solid state circuit protectors are not current withstand devices, they are current limiting
(c) applies to AC only
(d) applies to DC only
(e) not a switchable device

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