Protecting semiconductor devices: circuit breakers vs fuses

Fuses are faster and cheaper, but circuit breakers may be fast enough and cost-effective, and they offer several advantages over fuses

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☐ Ask a design engineer to protect a silicon controlled rectifier, triac, power diode, or solid-state relay, and more than likely he will immediately think of a fuse. That response, however, may not always be the right one. In many applications, especially in circuits using 48 volts or less, where the fault current is not apt to exceed their maximum interrupting-current capacity, magnetic-hydraulic circuit breakers may be truly cost-effective as well as fast enough—they may take as little as 2 milliseconds to open.

In the long run, circuit breakers often prove less expensive than fuses. For one thing, their inherent ability to provide a visual indication of the breaker condition saves time and effort in locating the circuit at fault, minimizing expensive equipment downtime. For another, even though fuses usually cost less than circuit breakers—say, $4 compared with $7—blown ones have to be replaced, and $20 worth of fuses can be used in just one troubleshooting procedure.

Magnetic-hydraulic circuit breakers can also limit di/dt transients—an important feature in protecting semiconductor switches—which fuses do only by opening. In addition, some models offer simultaneous polyphase operation, and others can control the current in one circuit by sensing the current in another.

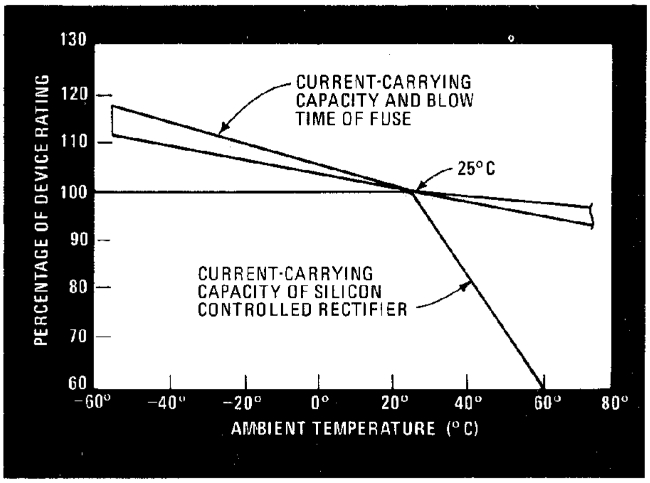
Finally, the belief that circuit breakers are dangerous because they can be held closed manually against an overload is generally not true. Most circuit breakers are designed so that the breaker will remain open when there is an overload or fault, even if the toggle is manually held in the on position. (This "trip-free" feature is specified in the manufacturers' literature; if a breaker lacks it, that fact is usually noted on the data sheet.)

Three choices

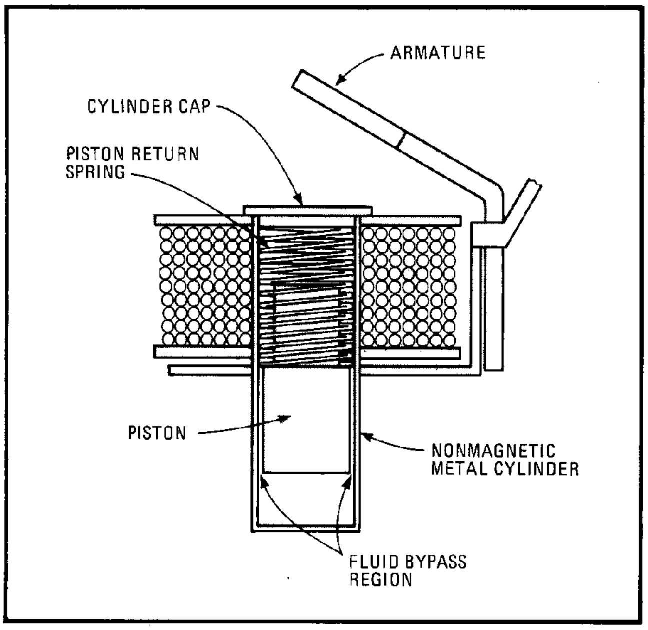
Current-limiting fuses and thermal as well as magnetic-hydraulic circuit breakers are often used to protect in-circuit electronic components. Of the breaker types, the magnetic-hydraulic is faster acting and therefore better suited to protect a semiconductor. A thermal breaker, however, is less expensive and may be sufficient for circuits in which the semiconductor switch is considered expendable (see "Thermal circuit breakers," p. 165). Also, the design of magnetic-hydraulic breakers is such that they are sensitive to current, not temperature. The performance of fuses and thermal breakers, on

COMPARING CIRCUIT PROTECTORS

	Current-limiting fuse	Circuit breakers	
		Thermal	Magnetic-hydraulic
Initial price range	$1 – $6	$2 – $10	$4 – $10
Reusable	no	yes	yes
Maximum interrupt capacity	200,000 A	3,000 A	2,000 A
Visual indication	no	yes	yes
Usable as switch	no	yes	yes
Temperature-sensitive	yes	yes	no
Position-sensitive	no	no	should not be mounted upside-down
Multiphase control	no	yes	yes
Ampere rating checkable by testing	no	yes	yes
I^2T protection	excellent	none	poor to fair
di/dt protection	none	none	fair to excellent
Failure from fatigue	yes	no	no
Replacement stock required	yes	no	no
dc resistance	insignificant	$< 0.5\ \Omega$	$0.004 - 300\ \Omega$
Vibration-sensitive	no	<25 g at 10 – 55 Hz	>50 g at 10 – 55 Hz



1. Temperature-dependent. If the fuse rating is chosen to protect a silicon controlled rectifier, triac, or power diode at 25°C, the circuit will not be adequately protected at lower temperatures and will be overprotected at higher temperatures.



2. Magnetic-hydraulic breakers. Both instantaneous-trip and time-delay circuit breakers trip mechanically when heavy overloads create sufficient magnetic flux in the breaker coil. Instantaneous-trip types have no fluid in the cylinder and open in 2 to 11 milliseconds.

the other hand, is definitely affected by temperature. The table compares the characteristics of current-limiting fuses and both types of circuit breakers.

None of the foregoing means that fuses should not be considered as protection for semiconductors. On the contrary, there are applications where a fuse is desirable. (Indeed, because of their use with semiconductor devices, they are sometimes referred to as "semiconductor fuses.") It may be helpful to discuss fuses first, before giving the details of magnetic-hydraulic-breaker operation and use.

Current-limiting fuses are used in circuits where the potential fault current is greater than the nonrepetitive surge on-state current (I_{TSM}) rating of the semiconductor switch or the interrupting-current capacity of the breaker, or where a circuit-clearing time of 1 millisecond or less is required.

The current-limiting fuse is a tubular device containing a fusible link surrounded with tightly packed silica sand. When there is an overcurrent, the link melts, creating a void that the sand immediately fills, absorbing and extinguishing the arc—usually fast enough to prevent damage to the semiconductor junction. Current-limiting fuses are thereby capable of interrupting fault currents of tens of thousands of amperes, whereas most circuit breakers can interrupt a maximum of only 2,000 amperes without being damaged.

Temperature sensitivity

Since fuses, unlike magnetic-hydraulic circuit breakers, are affected by temperature, they may be a poor choice for semiconductor protection. Usually, the current-handling capability of semiconductors, as well as fuses, is specified at 25°C. The curves in Fig. 1 show that a silicon controlled rectifier's current rating is constant from −55°C to +25°C, at which temperature it derates linearly. However, the current rating and circuit-clea ing, or blow, time of a current-limiting fuse vary wit temperature over the same range, and this fact must t accounted for in the design.

For example, a fuse rated at 10 A will carry 10 A 25°C and may open in 1 ms on a 1,000% overloa However, at −40°C, both the current rating and tl time it takes the fuse to blow may increase by 17% of tl 25°C rating. Thus, at the lower temperature, the fu may actually carry as much as 11.7 A and at a 1,000 overcurrent may take 1.17 ms before blowing. I contrast, at 60°C, it may carry only 9.5 A and may blo at 0.95 ms. Therefore the fuse may take too long to blo at lower temperatures, while at higher temperatures may blow prematurely.

Since the fuse's link is not visible, voltage or resistanc measurements are necessary to determine its conditio Should the measurement require a service technicia the equipmment will remain inoperative until he arrives

On the other hand, if a circuit breaker trips to the o position, anyone can quickly spot it and reset it. I however, the breaker should continue to trip and technician is called, his work is simplified because h does not have to troubleshoot fuses, unscrew or unsold them, and install new ones. Moreover, with a circu breaker, there is no chance of running out of the corre fuse and having to use one of the wrong rating simply t get the equipment back in operation.

Magnetic-hydraulic breaker operation

In a magnetic-hydraulic circuit breaker, the curre flowing through the windings of a coil creates a flu thus attracting an armature to the cylinder cap ar thereby snapping open the breaker's contacts. As show in Fig. 2, the breaker's coil is wound around a hollo cylinder that houses a piston. On heavy overloads ar fault currents, sufficient flux is generated to quick snap open the contacts.

On relatively weak overcurrents, however, the flu generated is in itself insufficient to attract the armatur but is enough to attract the piston resting in the botto of the cylinder and pull it upward. As the piston mov up, it adds to the permeability of the magnetic circui causing an increase in flux density and thereb increasing attraction on the armature. The time it tak the piston to travel to the top of the cylinder is dete mined in part by the viscosity of a silicon fluid in t sealed cylinder. Should the overcurrent be remove before the piston nears the top of the cylinder, t breaker will not trip and a return spring will push t piston back to the bottom.

Such breakers, termed "time-delay," are typical used with circuits where brief, small overcurrents a expected, especially on start-up—with motors an lamps, for example. They exhibit interrupting-time (tri or circuit-clearing) characteristics like those shown Fig. 3a, which charts the time delay as a function of t overcurrent, given as a percentage of the breaker rating. The smaller the overcurrent, the longer it tak the breaker to open.

The non-time-delay version, often called "instanta neous-trip," contains no silicon fluid in the cylinder. It

Thermal circuit breakers

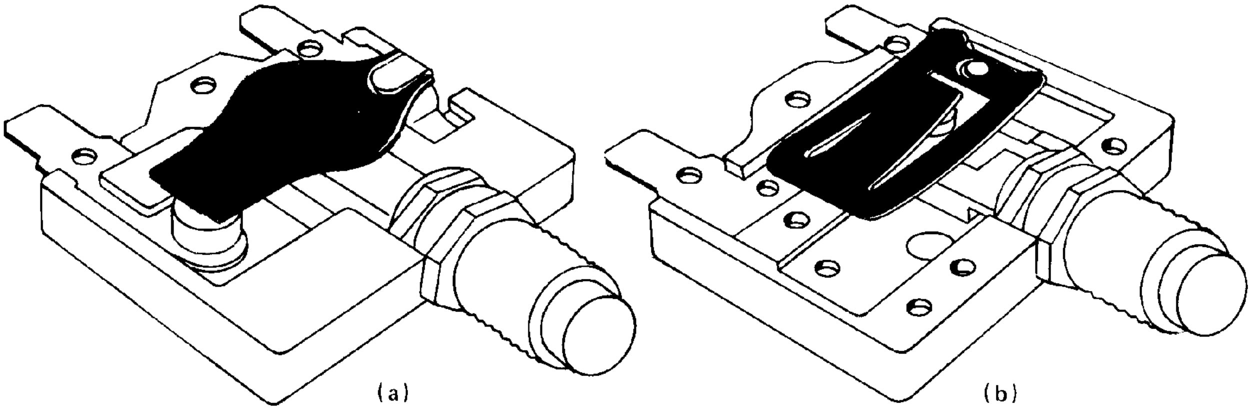
A thermal breaker, like a fuse, is a strictly heat-sensitive device. Its operation is based on the opening of a bimetallic blade through which load current flows, releasing a latch and causing the contact to snap open. Because of their slow response, thermal breakers are generally used to protect wiring from overheating and subsequent insulation deterioration, and not to protect semiconductor devices. But some thermal breakers, like all the magnetic-hydraulic types, may be used as power switches, thus saving the expense of a separate switch.

The thermal breakers that cannot be used as power switches are usually the least expensive type, those that have a recessed reset button that cannot be manually pulled out to the off position. They have no latching mechanism, since the bimetallic blade serves as the movable contact arm.

There are two kinds of thermal circuit breakers, depending on the kind of blade structure used. In the first kind (a), as overcurrent heat increases, the bimetallic blade bends upward, causing the pressure between the contact surfaces to decrease, until the blade finally snaps open and separates the contacts. As contact pressure decreases, considerable heat rise due to overcurrent results, which can lead to early failure—even contact welding.

The second kind (b) has a "positive-pressure" blade designed so that, as overcurrent heat increases, contact pressure also increases. When the critical point is reached, the blade snaps open instantly and the arc is extinguished.

Thermal circuit breakers, like their magnetic-hydraulic counterparts, offer definite circuit resistance that helps limit circuit fault current.



(a)

(b)

designed so that even on small overcurrents it will clear a circuit in from 2 to 11 milliseconds—often fast enough for use with semiconductor switches.

Circuit-breaker manufacturers do not pinpoint the actual clearing time of a breaker. Rather, they specify a window of values within which all breakers of that model will open a circuit. Therefore, in determining whether or not to use such a breaker, it is best to assume the worst-case clearing time of 11 ms, even though the actual time may be much less.

The trip characteristics of an instantaneous-trip breaker are shown in Fig. 3b. The curves show that the breaker will carry 100% of its rating, but will trip somewhere between 101% and 125% at about 50 or 60 hertz over an operating temperature range of −40°C to +85°C. Note that the clearing time is the same for overcurrents from a relatively low 400% of breaker rating to 1,200%. In fact, although it is not shown, the clearing time for breakers remains constant to the breaker's maximum interrupt capacity.

Resistance helps

Depending on the ampere-turns of the breaker coil and the rate of rise of the fault current, the impedance of the coil can limit fault current until the breaker opens the circuit. In some cases, the calculated impedance may be enough to save the expense of adding a saturable reactor to the circuit simply to limit fault di/dt. Without such di/dt limitation, the semiconductor switch may be destroyed on severe fault currents or overcurrents.

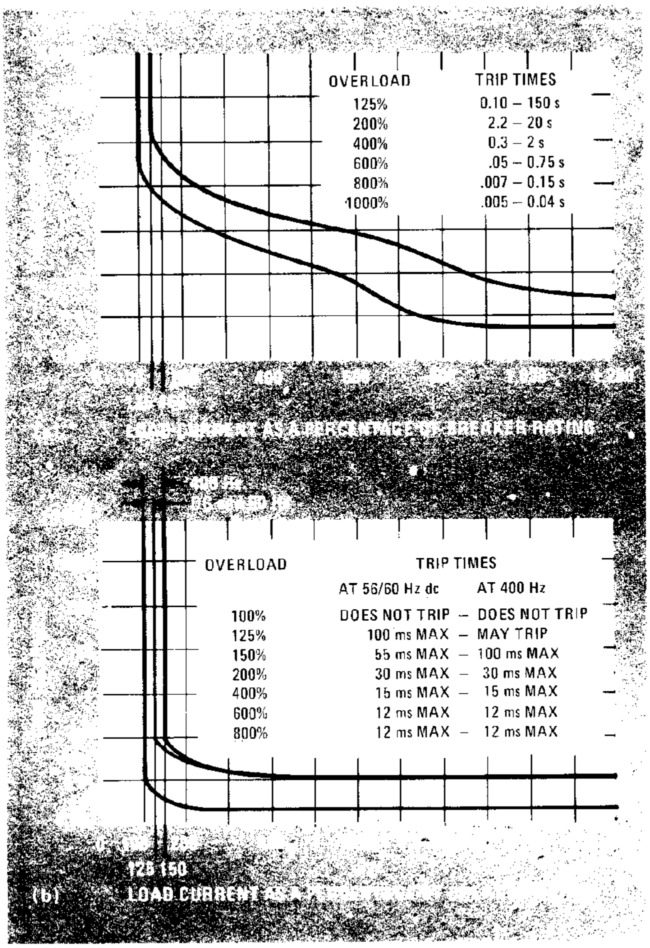
As shown in Fig. 4, the lower the current rating of the breaker, the greater its dc resistance; and the higher the frequency, the greater its impedance. For example, the dc resistance and impedance of a 1-A breaker is approximately 1.1 ohm at 60 Hz, but almost twice that at 400 Hz. Likewise, a 10-A breaker has about 14 milliohms of resistance at dc and at 60 Hz and an impedance of about 23 mΩ at 400 Hz. In fact, coil impedance for a steeply rising fault current may be very high. However, the value must be determined empirically, because no circuit-breaker manufacturer has so far published such data for his products.

Finding the fault current

To determine whether to use a fuse, an instantaneous-trip circuit breaker, or a combination of the two, consider the following:

- Worst-care, root-mean-square, and peak value of the potential circuit fault current.
- Single and perhaps even subcycle surge-current ratings of the semiconductor switch.
- Circuit-clearing time required before component or circuit damage occurs.

Calculating the potential rms and peak circuit fault



OVERLOAD	TRIP TIMES
125%	0.10 – 150 s
200%	2.2 – 20 s
400%	0.3 – 2 s
600%	.05 – 0.75 s
800%	.007 – 0.15 s
1000%	.005 – 0.04 s

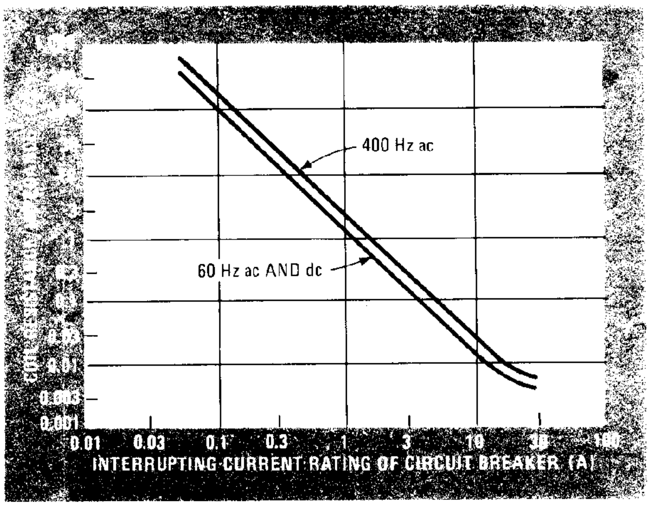
OVERLOAD	TRIP TIMES AT 56/60 Hz dc	TRIP TIMES AT 400 Hz
100%	DOES NOT TRIP	DOES NOT TRIP
125%	100 ms MAX	MAY TRIP
150%	55 ms MAX	100 ms MAX
200%	30 ms MAX	30 ms MAX
400%	15 ms MAX	15 ms MAX
600%	12 ms MAX	12 ms MAX
800%	12 ms MAX	12 ms MAX

3. Matching breaker to application. Curve (a) typifies response of time-delay circuit breakers designed to handle higher-than-normal load current without opening prematurely. Instantaneous-trip breakers (b) are used in circuits that cannot tolerate overcurrents.

current is simply a matter of dividing the circuit voltage by the total of all resistances or impedances in the circuit. In so doing, consider the resistance of the circuit breaker. Even though the decision has not yet been made to use one, its resistance may significantly limit circuit fault current.

Also, the resistance of the wiring and terminal points should not be neglected. A 50-foot run of two-wire no. 12 AWG copper (100 ft total) has 0.162 Ω of resistance at 25°C—enough to limit the fault current in a 48-V circuit to about 300 A, even though the transformer can deliver considerably more. To determine actual circuit resistance, it is best to use either a milliohmmeter or a Wheatstone bridge.

Such measurements will not yield the impedance of the semiconductor itself under fault current conditions. This value must be approximated from curves, such as the one shown in Fig. 5 for an SC260 triac. First, however, the approximate circuit fault current must be known, which can be determined using only the dc circuit resistance.



4. Estimating resistance. Resistance and impedance ratings of magnetic-hydraulic circuit breakers with current-interrupting ratings of from 0.050 to 30 A allow designers to estimate how much coil and contact resistance the breaker will introduce into the circuit.

If, for example, calculations indicate a fault current of 300 A, then the impedance of the semiconductor can be approximated by determining the resultant voltage drop across it. The 115°C junction-temperature curve in Fig. 4 shows that a 300-A current causes a 3.5-V drop across the device. Based on the E/I relationship of these values, the semiconductor may thus be considered to represent an impedance of 11.7 mΩ in this case.

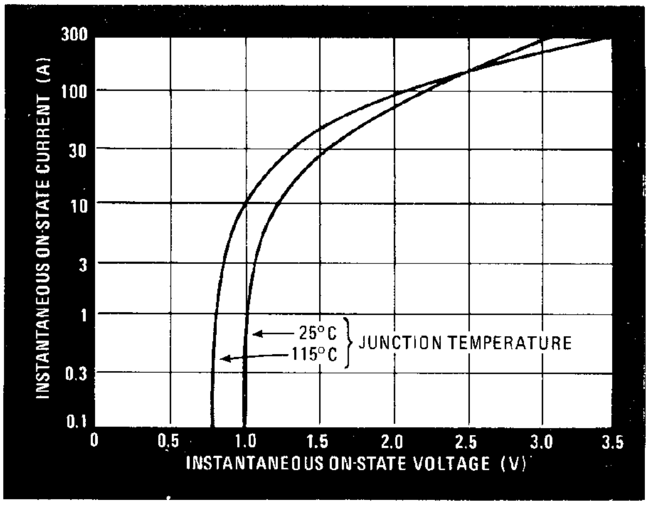
If the calculated fault current based solely on the dc resistance of the circuit, including the resistance of the breaker, is greater than the maximum current shown on the curves given for the semiconductor, chances are that the semiconductor junction will be damaged as a result of overcurrent heating. For this case, a circuit breaker will not adequately protect the semiconductor. (Obviously, though, without the breaker resistance in the circuit, potential fault current would be even greater.) But even the fastest fuse may not adequately protect the semiconductor, and therefore the only solution may be to choose a semiconductor with greater surge-current-handling capability, in which case the circuit breaker would prove adequate.

Keep in mind that, because of the impedance of the semiconductor, the actual fault current will be less than that calculated for the dc resistance only. However, the calculated semiconductor impedance will also be less, simply because the fault current is not as great.

Figure 6 shows a circuit in which a 25-A triac controls a 24-V, 5-A load and a 5-A circuit breaker protects both triac and load. Circuit resistances are calculated from manufacturers' data, and triac impedance from the curves in Fig. 5:

transformer secondary at 25°C	0.055 Ω
circuit breakers at 25°C	0.050 Ω
10 ft of no. 14 AWG copper wire at 25°C	0.026 Ω
SC260	0.012 Ω
approximate circuit impedance	0.143 Ω

The impedance of the transformer secondary may be considerably higher than its dc resistance on steeply rising fault currents; however, for this example, these instances will not be considered. If such impedance values are required, they can be obtained from the transformer manufacturer.



5. Rough cut. Graph of maximum on-state voltage versus on-state current of a commonly used triac, the SC260, gives the designer an idea of the impedance. The fault current must be known, and the voltage across the semiconductor at this current measured.

The approximate fault current for the circuit at 25°C is:

$$I_{rms} \approx (24\text{ V}/0.143\ \Omega) = 167.8\text{ A}$$

$$I_{peak} \approx 167.8 \times 1.414 = 237.3\text{ A}$$

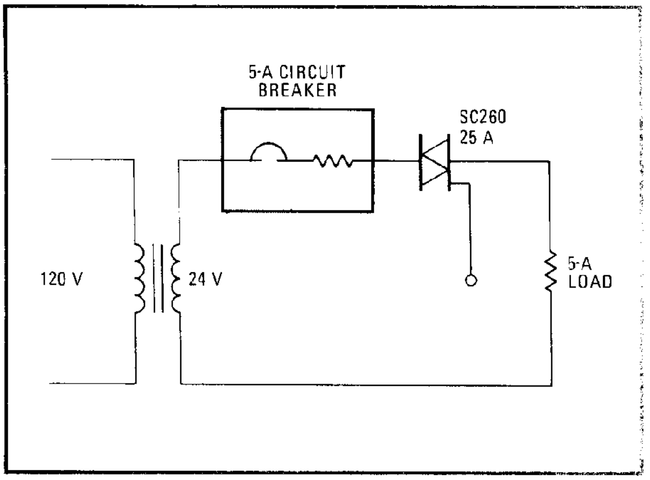
Naturally, many circuits operate at temperatures higher than the 25°C design center of many components. In such cases, component resistances are even greater, and fault current proportionately lower.

To determine if the triac can withstand a peak current of 237.3 A, the I_{TSM} rating must be checked. The manufacturers' data on the SC260 shows an I_{TSM} rating of 250 A, or an rms current of 176.8 A, for 16.6 ms. The interruping-time curve of the breaker (Fig. 3b) shows that the breaker will open the circuit fast enough (2 to 11 ms) to protect the triac.

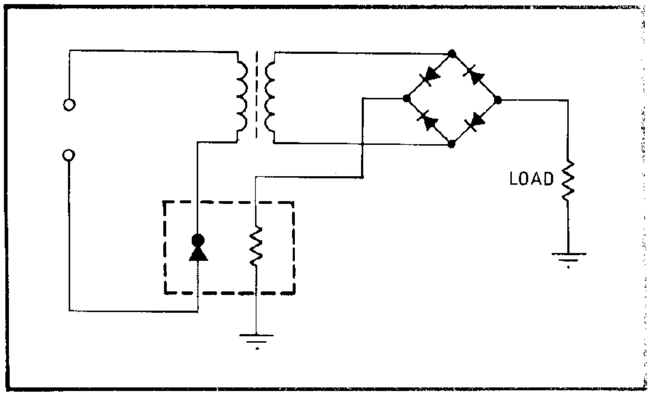
To use the curve, first determine what percentage of breaker rating the fault current represents. For the example given, the breaker has a rating of 5 A and a 167.8-A rms overcurrent represents a 3,356% overload. Even though the curve in Fig. 3b is not plotted beyond the 1,200% overload point, it does not change out to the breaker's 2,000-A interrupt capacity, as mentioned earlier. Thus circuit-clearing time for a 3,356% overload remains between 2 and 11 ms.

In circuits where a breaker cannot provide worst-case fault-current protection for the semiconductor switch, a fuse can be used as backup protection. If, for example, there is no transformer secondary to help limit fault current and 120 V is applied directly to the semiconductor, the peak current will come close to the interrupt capacity of the breaker. Manufacturers' data shows that a fuse can protect the thyristor from the peak current of nearly 2,000 A, but the rating of the fuse should match that of the thyristor, not the rating of the load. Otherwise, the fuse could blow on start-up and other surge currents.

When deciding whether to use a fuse, a breaker, or a combination of the two, the designer may find that circuit-protection costs are prohibitive. In some cases, he may consider the thyristor expendable and simply use an inexpensive thermal circuit breaker to protect the load and wiring.



6. Dual protection. Shown is a typical circuit in which a magnetic-hydraulic circuit breaker protects both solid-state switch and load.



7. Relay-trip circuit. By sensing the dc load current in the secondary winding of the transformer and opening the primary side when an overcurrent exists, the breaker not only protects the load, but ensures that the transformer does not remain unloaded.

Additional circuit breaker advantages

Besides being reusable on repeated overcurrents, circuit breakers can of course serve as on-off switches. Furthermore, some models of both magnetic-hydraulic and thermal breakers offer other features not obtainable with fuses. The most notable is the ability of a multipole breaker to open all legs of a polyphase line when an overcurrent is sensed in any one of the lines. Circuit breakers are available ganged to 10 poles or more so that all poles will open almost simultaneously if any of the individual breakers detect an overcurrent.

An auxiliary single-pole, double-throw snap-action switch incorporated in some models makes possible another desirable feature. The switch is mechanically connected to, but electrically isolated from, the breaker contacts, enabling the breaker to control auxiliary circuits or panelboard lamps that indicate circuit condition. In addition, magnetic-hydraulic circuit breakers come in versions that enable the breaker to open one circuit when it senses an overcurrent (Fig. 7). □