ELECTRIC FUSES

Toward the end of the nineteenth century, Thomas Alva Edison intentionally introduced a weak element into his design for electrical circuits. The sole purpose of this weak element was to protect the other parts of the network. Thus was born the *fuse.* One of the simplest and least expensive forms of protective device, the fuse has become an almost indispensable part of network design. A fuse is an alloy element that is normally connected in series with a device that protects the circuit components of the electrical equipment in the event of an excessive overload. Currents beyond the network's rated capacity may be caused by an unanticipated increase in the load, or due to malfunctioning of equipment, such as a short circuit. The most commonly used, general-purpose, low-cost fuse element is made out of a mixture of lead and tin. This combination has a low melting point but is fairly hard, unlike a soldering alloy which is soft. However, different manufacturers use different alloy combinations, depending on the specific need and desired applications. The design of a fuse is fairly simple because it does not involve complex engineering methodologies.

Ohm's law stipulates $I = V/R$ where I = current, V = voltage, and R = resistance. If, for any reason, R tends toward zero, I tends toward infinity. The objective of using a fuse is to ensure that such an unacceptable increase in current is prevented. For example, a fuse is normally made out of an alloy with a low melting point. Under circumstances of excessive currents, the alloy fuse element melts and creates a physical break in the circuit. Under these conditions, the fuse is said to have "blown." It is necessary that the response of the activation of the fuse be at least inversely proportional to the magnitude of the overload current. In other words, the fuse should blow faster in response to how much higher the current is than what it is rated for.

Figure 1(a) represents how a fuse is incorporated in a series circuit as a protective device. Circuits are always designed with multiple levels of protection. These levels must be carefully coordinated. If the first line of protection fails, the second line of protection should take over. If the second line of protection also fails, then the third line of protection should be automatically activated, and so on. In some cases, several fuses may serve the different levels by possessing different inverse time characteristics. Referring to Fig. 1(a), the series field of a motor receives power from the line via a manually operated bus safety knife-switch T, a fuse, a normally open contactor M, and an overload coil OL. For sake of convenience, let us assume that the neutral is grounded.

When the motor is operational, the bus safety switch is closed, the contactor M is closed, the overload bimetallic strip is not overheated for activation, and the fuse is "healthy" or "not blown." In this case, the protective devices may be coordinated like this: M would be first line of protection, OL the second, and the fuse the third and last line of protection. If the motor experiences an overload, there should be a feedback mechanism that senses it and sends a signal to open the contactor automatically. If this fails, the overload bimetallic strip should respond to thermal overheating and create a break in the circuit. If this second line of protection also fails, then only the fuse should blow and protect the circuit and the motor.

CHARACTERISTICS OF FUSES

Figure 1(b) shows a commonly used symbol for fuse. Figures 1(c) and 1(d) are pictures of commonly used cartridge fuses. Figure 1(e) shows a collection of indicating fuses. Figure 1(f) provides a family of characteristics. Figure 2 represents a typical characteristic expected of a normal fuse, called the current–time characteristic or the I–t characteristic. [In this case, time is measured on the x-axis, although it is common to have current on the x-axis. It is commonly designated the time–current characteristic (TCC) curve.] Figure 3(a) shows a family of current–time characteristics. The fusing factor may be defined as the ratio of minimum fusing current and the rated current-carrying capacity of the fuse. It should be noted that the graph is a full-log graph. [Both the x-axis (time) and the y-axis (current) are plotted on a logarithmic scale.] Figure 3(b) shows a collection of UL-listed power fuses, which tell the operator immediately which circuit is open. There are fast-acting fuses, which interrupt the circuit in about a millisecond. Delayed action fuses may take as long as 20 s. The range of time interval for medium-action (medium-fast or medium-slow) fuses may vary from a few milliseconds to a few seconds. Utility companies make use of high-voltage fuses that may have a rating as high as 250 kV and 50,000 A. When such a fuse blows, a huge arc is struck between the two terminals and a tremendous amount of energy is released that results in the formation of high-pressure gases. The arc needs to be quenched at the appropriate time using an expulsion technique. Although current plays a vital role in the fuse activation, fuses designed to operate on a 60 Hz alternating current (ac) supply may not be suitable for use in 50 Hz ac or direct-current (dc) supply systems. There are other types of fuses such as automotive fuses and electronic fuses. Figure 3(c) shows a collection of automobile fuses.

Another way of classifying fuses would be: current-limiting fuses and non-current-limiting fuses. All fuses limit the passage of excessive currents. However, a current-limiting fuse interrupts the circuit before the first peak of the short-circuit current is achieved. This is shown in Fig. 4(a). The symmetrical short-circuit current waveform will reach its first peak in time t_p. However, the fuse has already melted at time t_1, which is less than t_p. The process for creating a break in the circuit has already commenced. An arc has been struck and is being extinguished between time t_1 and t. A non-current-limiting fuse will take more than one-half cycle for breaking the circuit.

After interruption, the fuse or the fuse-holder [Figs. 4(b) and 4(c)] should be able to safely withstand the rated voltage of the system across its terminals. Therefore, it is important that the fuse be rated not only on its safe current-carrying capacity (normally referred to as the continuous current rating or simply current rating), but also on its voltage rating. A fuse should be capable of being operated continuously at or below its rated values without any deterioration to its properties. The wattage involved is $P = I^2R$, and this could be very high. As such, open-type or rewireable fuses are not very com-

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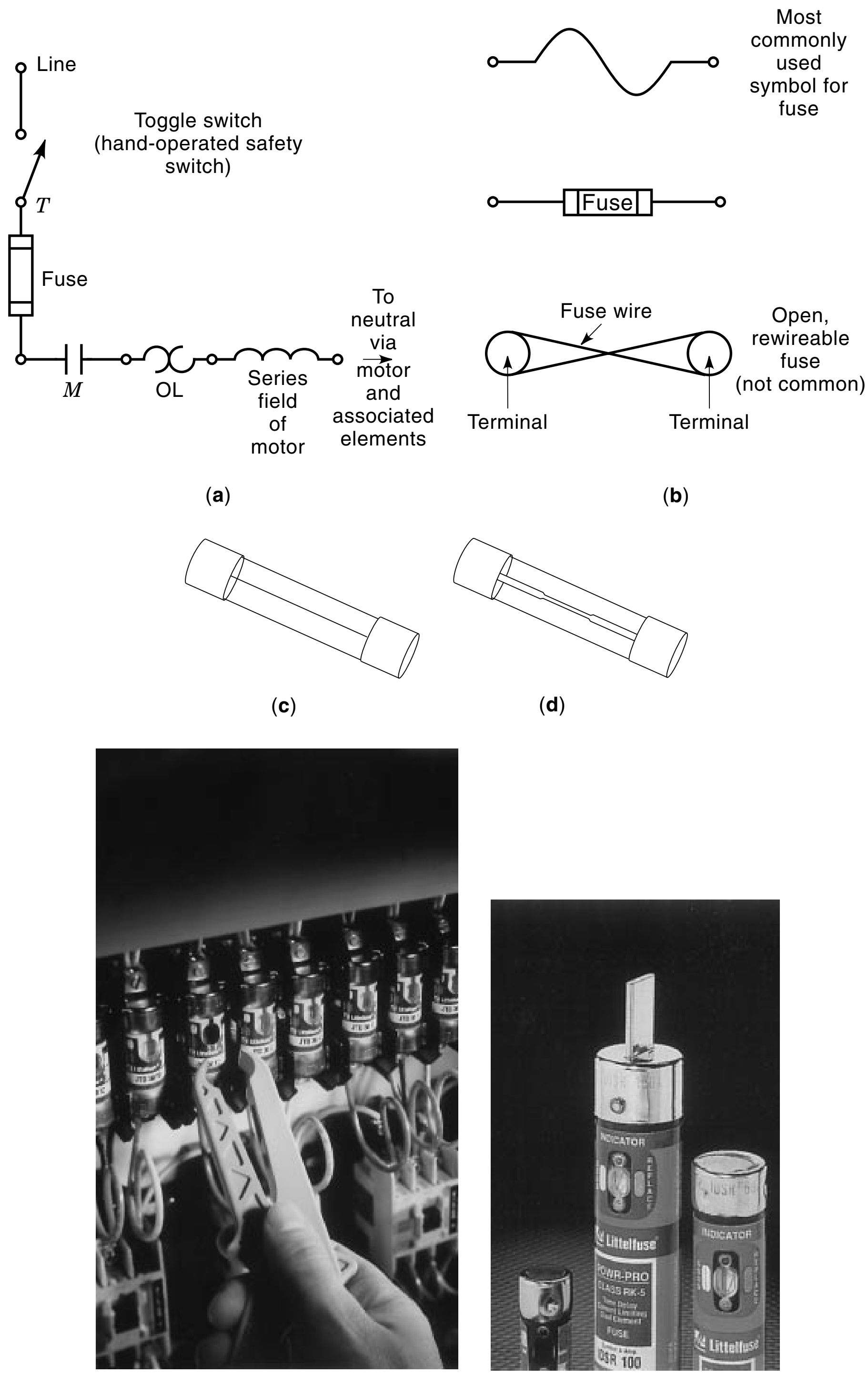


Figure 1. (a) Series connection of fuse in a circuit. Current flow is permitted only if T is closed, fuse is not blown, M is closed, and OL is not activated. M, normally open contractor; OL, overload device (example: a bimetallic strip). (b) Symbols used for fuse in electrical drawings. (c, d) Commonly used cartridge fuses. (e) Indicating fuses, offering a time delay in handling repeated motor startups. (f) Time-current characteristics of FLNR ID-type fuses. Courtesy of Littelfuse, Inc., Des Plaines, IL.

mon. Most general-purpose fuses are enclosed in a glass, fiberglass-epoxy, or a ceramic cartridge. This helps to contain the energy released. High-rupturing-capacity (HRC) cartridge fuses or high-voltage fuses may use a silver or silver alloy element as a fuse that is enclosed in a ceramic cartridge filled with pure quartz powder, which has excellent arc quenching properties. An example is shown in Fig. 5, although constructional details vary from manufacturer to manufacturer, depending upon the need, characteristics, and applications. When the fuse melts, the generated heat melts the quartz as well. The energy is thus dissipated. The channel of melted metal and sand creates an increased resistance bath. Thus, current is reduced and the arc is ultimately extinguished.

A fuse is used in series with a circuit. It carries the same current as the circuit does. It is a protective device, and therefore the voltage drop across the fuse should be negligible. A simplified design methodology follows.

Since $V_{\text{fuse}} = I_{\text{fuse}}R_{\text{fuse}}$ and V_{fuse} has to be small, a fuse must possess very little resistance.

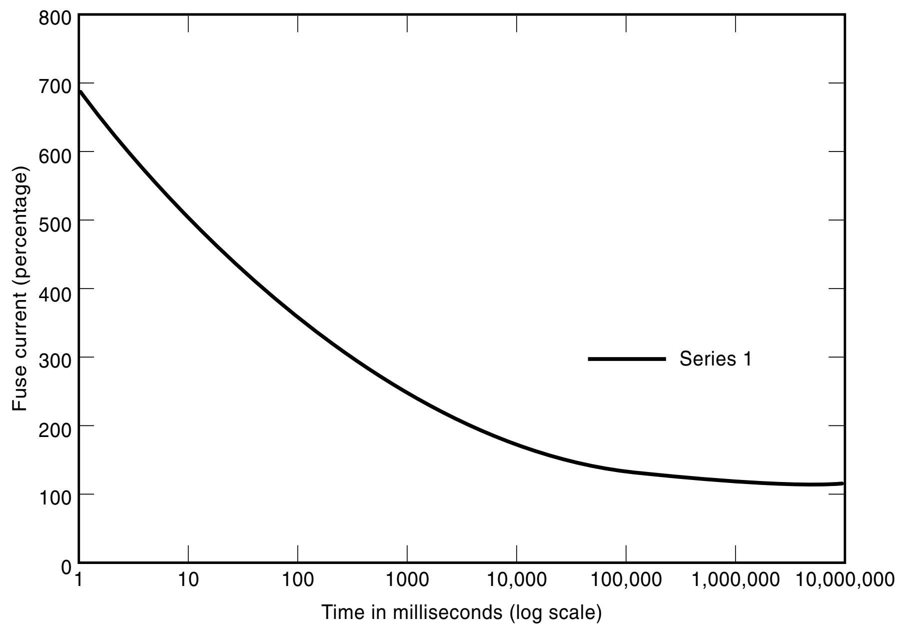


Figure 2. Current–time characteristic of a fuse.

The heat generated is directly proportional to the power P of the fuse element at the time of interruption. If I is current interrupted by the fuse and R is resistance of the fuse, then

$$P = I^2R$$
$$R = \rho l/A$$

where ρ = specific resistance of the fuse material, l = length of the fuse link element, and A = area of cross section of the fuse element = $(\pi d^2)/4$ if the fuse has a circular cross section whose diameter is d [Fig. 6(a)].

Resistivity (ρ) of Various Materials ($\mu\Omega \cdot$ cm)

Silver	1.65
Copper	1.72
Aluminum	2.83
Tungsten	5.5
Zinc	6
Tin	11
Lead	22
Nichrome	100

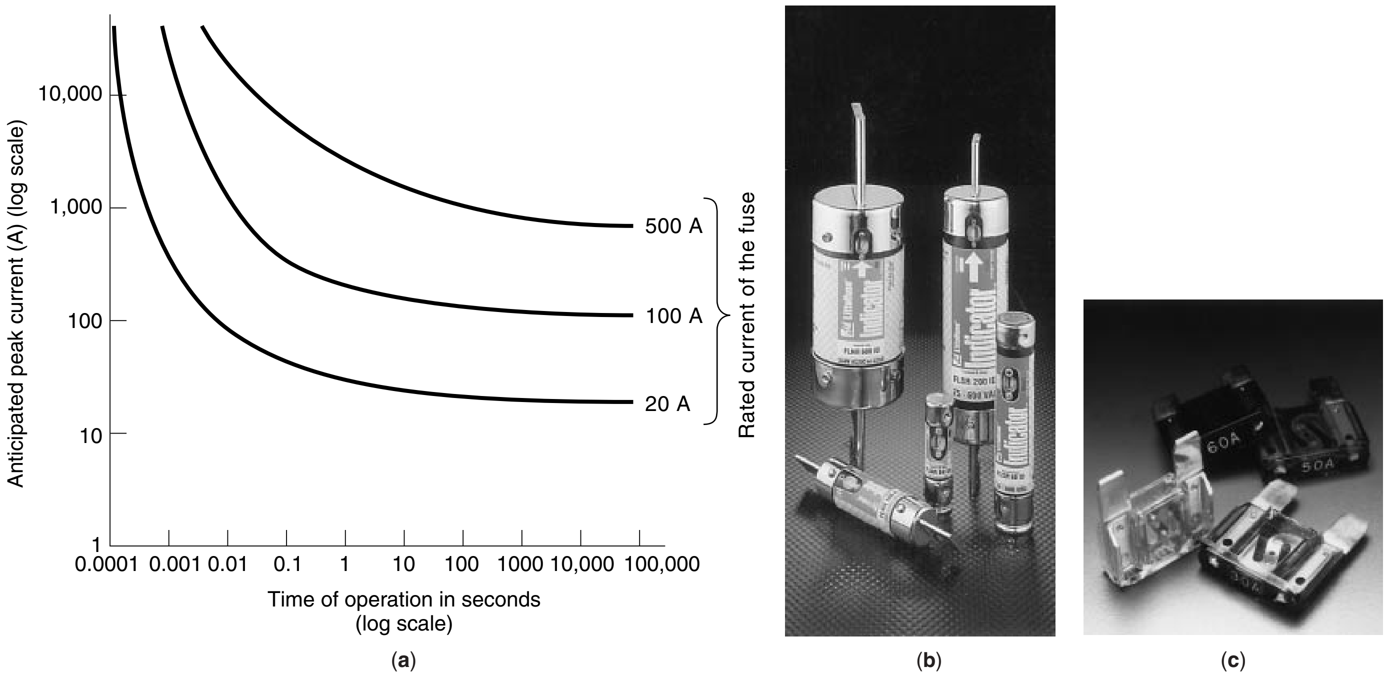


Figure 3. (a) Current–time (I–t) characteristics of three fuses. (b) UL-listed power fuses which indicate to the operator which circuit is open. (c) Automobile fuses (JCase high-current fuses). Courtesy of Littelfuse, Inc., Des Plaines, IL.

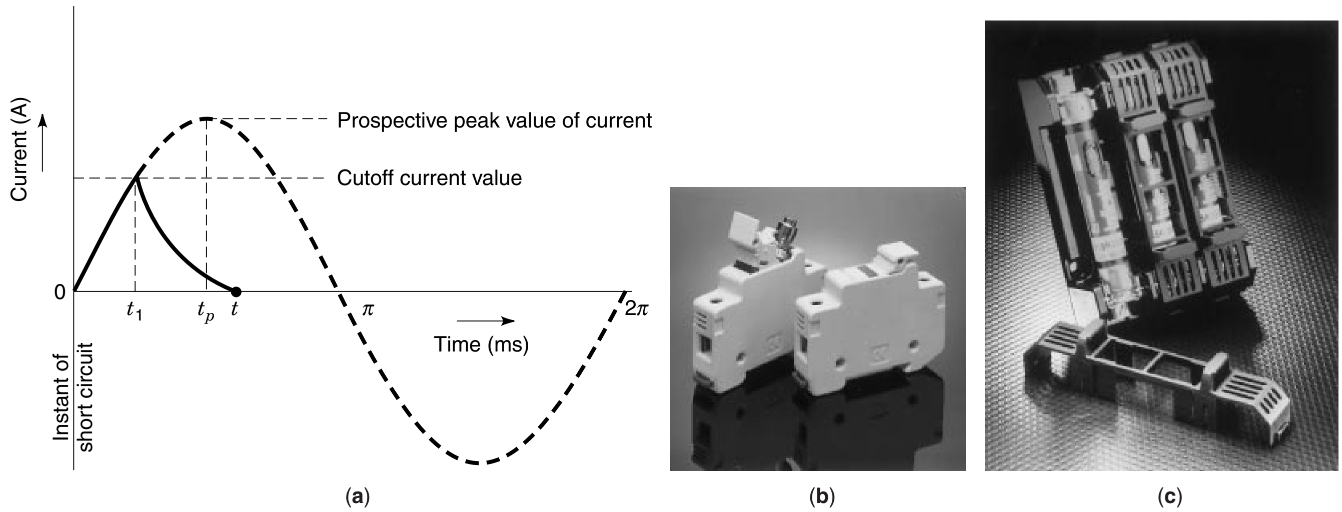


Figure 4. (a) Current waveform: Performance of a current-limiting fuse. Fuse melts before the first peak of the current waveform is attained. (b) Power-safe "dead front" fuse holders provide optimum personnel protection. (c) Power covers and fuse block covers are ventilated to dissipate heat. Courtesy of Littelfuse, Inc., Des Plaines, IL.

The heat generated has to be dissipated in the medium in which the fuse is located. This could be, for example, silica or, for an HRC fuse, quartz powder. The surface area involved is dl and therefore the heat dissipated $= dl(C)$, where C is a constant that defines the medium and other parameters associated with it:

$$\text{Heat generated} = \text{Heat dissipated}$$
$$[(4I^2\rho l)/(\pi d^2)] = [dl(C)]$$
$$I^2 = (C\pi d^3)/(4\rho)$$

For a chosen material, a chosen design, and a chosen heat dissipation mechanism, we obtain

$$I^2 = Kd^3$$

where K is another constant. This indicates that the diameter of the fuse element plays a vital role in the current interruption capacity. Furthermore, it can be shown that the current interruption capacity of the fuse depends upon the geometry of cross-sectional area (square, rectangular, thin strip, etc.) as well. The current interruption capacity also depends upon whether the fuse is a "single-element" or is a "multiple-element" or is "stranded." The above example may appear oversimplified. Current technology would entail much more detailed mathematical analysis.

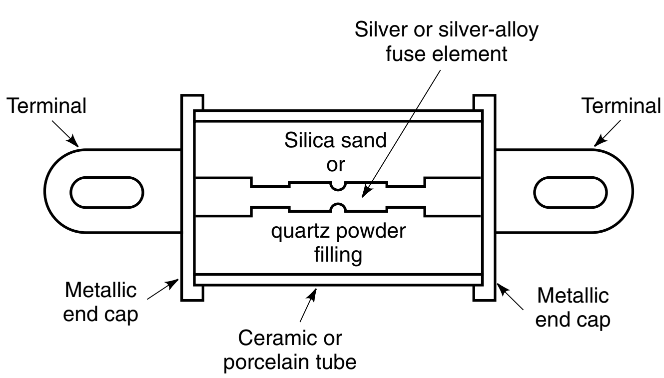


Figure 5. High-rupturing-capacity fuse.

The energy involved is $w = I^2Rt$, where t is the total time required for the operation of the fuse. As shown in Fig. 6(b), this is the sum of melting time (also called pre-arcing time) and arcing time. Since the resistance R of a fuse is small, the factor I^2t, called the "thermal energy let-through," plays a dominant role in defining the characteristic behavior of the fuse. Two I^2t values may be defined for a given fuse. One is

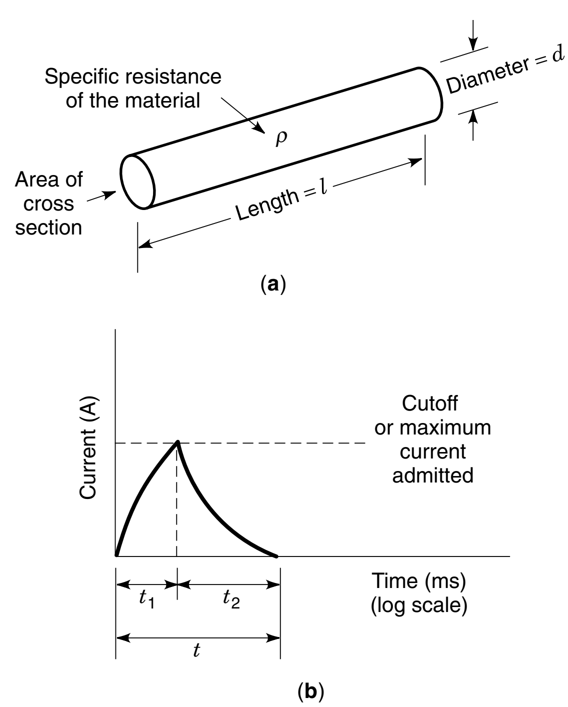


Figure 6. (a) Cylindrical fuse element parameters. (b) Fuse current waveform. t_1 = melting time (pre-arcing time), t_2 = arcing time, t = $t_1 + t_2$ = time taken for interruption (operating time or clearing time).

based on the current alone, which is called the melting I^2t, and the other is based on the voltage as well as the power factor, called the clearing I^2t. The arc created by the melting fuse needs to be extinguished effectively so as to withstand the system voltage it has been designed for.

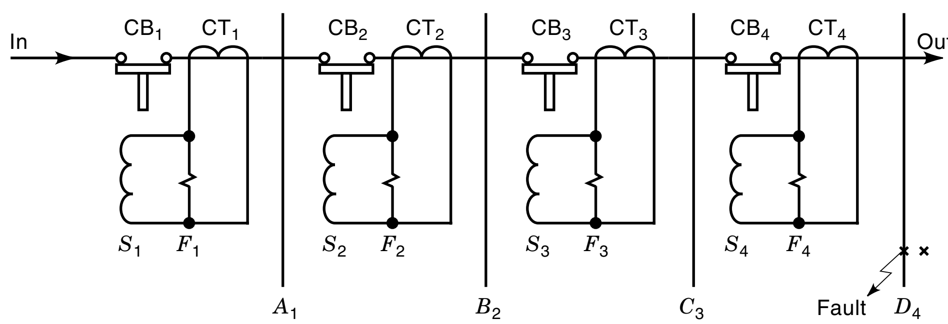
COORDINATION OF FUSES

Network design often incorporates fuses that possess different current–time characteristics. Proper coordination of a set of fuses helps to identify or isolate the fault location and thereby provides needed discriminatory properties. In the simplified representation of a network shown in Fig. 7(a), current flow is from left to right, from "in" to "out." When all the four circuit breakers CB_1, CB_2, CB_3, and CB_4 are closed, the current flow is continuous. Different equipment is located at stations A_1, B_2, C_3, and D_4. The circuit breakers CB_1, CB_2, CB_3, and CB_4 are activated by solenoids S_1, S_2, S_3, and S_4, respectively. CT_1, CT_2, CT_3, and CT_4 are current transformers whose secondary terminals are connected to the terminals of the respective solenoids. In addition, fuses F_1, F_2, F_3, and F_4 are also connected across the solenoid terminals.

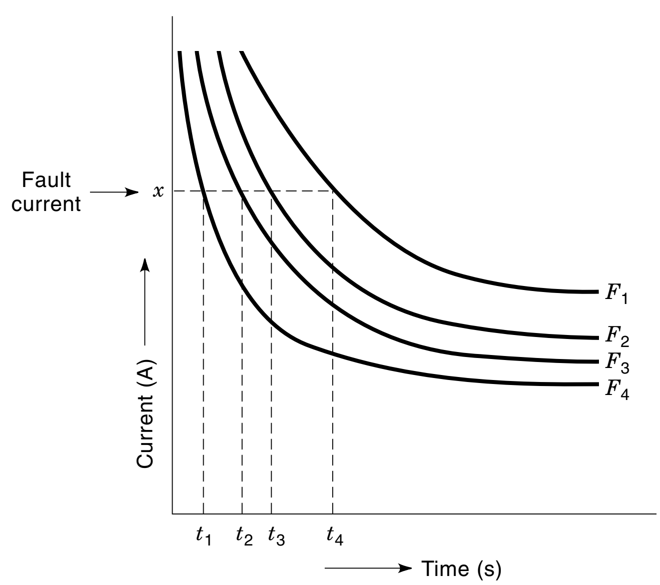
Under normal conditions, the current in the secondary of the current transformer follows the path of least resistance, which in this case is the fuse. Therefore the solenoid will not receive any current. When the fuse blows, the current in the secondary of the current transformer flows through the solenoid. The magnetic field created by the solenoid will attract the plunger down, thereby interrupting the circuit.

Consider a dead short circuit at the location X as shown in the figure. If all the four fuses were identical, they all blow at the same time and service to all the four stations A_1, B_2, C_3, and D_4 is interrupted. Instead, let us consider a system of fuses that are coordinated judiciously. This can be understood by referring to the current–time characteristics of the four fuses shown in Fig. 7(b). It can be seen that the fuses F_1, F_2, F_3, and F_4, react to the fault current "X" by response times t_1, t_2, t_3, and t_4. Only the system equipment connected at location D_4 is disconnected from the main supply. The dead short-circuit fault is thereby isolated, and the service to systems A_1, B_2, and C_3 is retained and remains unaffected or uninterrupted.

The same logic applies to coordinating a fuse with an overload circuit breaker. Unless the fault is extremely severe—that is, cannot be successfully cleared by the overload circuit breaker—the fuse should not be called upon to respond. The current–time characteristics of an overload circuit breaker coil and the fuse associated with the same circuit is shown in Fig. 8. For example, if the current is excessive, say 100 times the safe normal value, the fuse immediately responds. However, if it is a "normal" overload, say the current is twice the rated capacity, the overload circuit breaker will respond and clear the overload.



(a)



(b)

Figure 7. (a) Coordination of fuses. CB, circuit breakers; CT, current transformers; S, solenoids; F, fuses. A_1, B_2, C_3, and D_4 are systems or stations or equipment locations. (b) I–t characteristics of the four fuses.

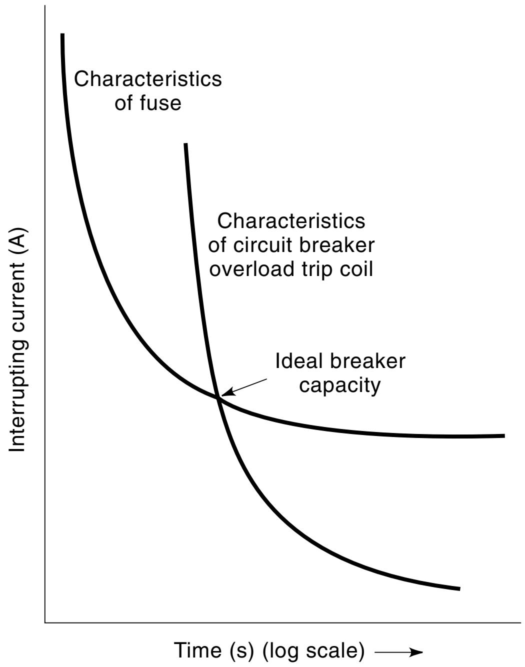


Figure 8. Coordination between a fuse and an automatic reusable current interrupting device.

LOW- AND HIGH-VOLTAGE FUSES

Low-voltage (to 600 V) fuses are generally designed to meet the demands of household consumers. Standard low-voltage fuses are tested and classified by Underwriters Laboratories Inc. There are letter classifications such as G, H, J, K (fast), L, R, and T (slow) in addition to plug fuses, electronic appliance fuses, dc fuses, and mine-duty fuses. For example, a G-class fuse may be capable of handling 300 V, up to 60 A. As a contrast, an L-class fuse may handle 600 V up to 6000 A. They may have a minimum of 10 kA interrupting capacity.

High-voltage fuses are used by utility companies and large customers. Large industries and industrial complexes consume electricity at high voltages and establish their own power distribution network systems. High-voltage fuses are usually rated above 600 V and are used for isolating electrical distribution systems from dangerous faults and deadly short circuits. For example, open-type expulsion cutouts, although violent in operation, may have a 30,000 V rating and 25,000 A asymmetrical interrupting capacity. Many applications prohibit the use of open-type cutouts, and safety codes may warrant the use of enclosed-type cutouts instead. In contrast, liquid fuses are nonviolent but may have only about 10,000 A interrupting capacity. Nonviolent, general-purpose current-limiting fuses may possess very high current interrupting capacities, but they are expensive. Power fuses aim at reducing arc energy; they are also expensive. Oil-immersed protective links are inexpensive but suffer from the major disadvantage of oil contamination.

SPECIAL APPLICATIONS

Time-delay fuses are designed not to blow while responding to inrush currents or transient overloads. A time-delay fuse can permit the passage of large transient spikes that occur over short durations and are harmless for most electrical

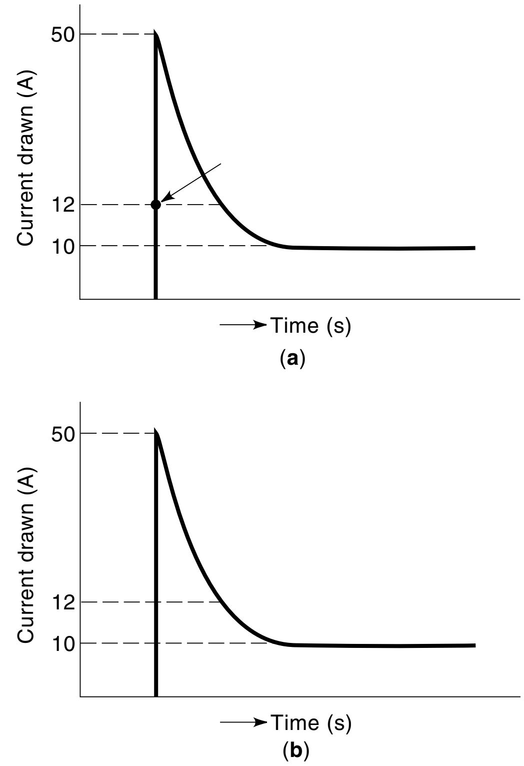


Figure 9. (a) Fuse with no time delay. Fuse interrupts circuit at location shown by arrow. (b) A time-delay fuse will not interrupt the circuit and can be used in motor protection circuits.

equipment. For example, a 10 A motor's starting current may be five times its rated value of 50 A. It should not require the use of a 50 A fuse. A 12 A time-delay fuse may be appropriate for the application because the time-delay fuses follow the philosophy of averaging and therefore it will not blow and disconnect the motor [Figs. 9(a) and 9(b)].

Transformer inrush currents also warrant the use of fuses with special shapes, for example, K links in utility fusing ap-

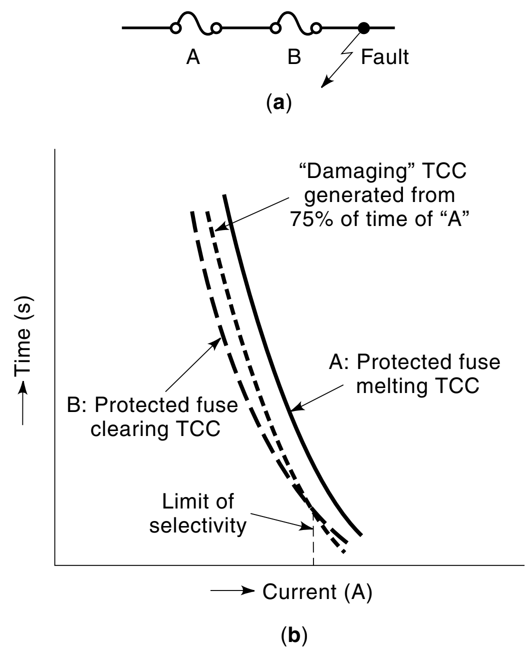


Figure 10. (a) Two fuses in series. (b) Fuse-to-fuse coordination.

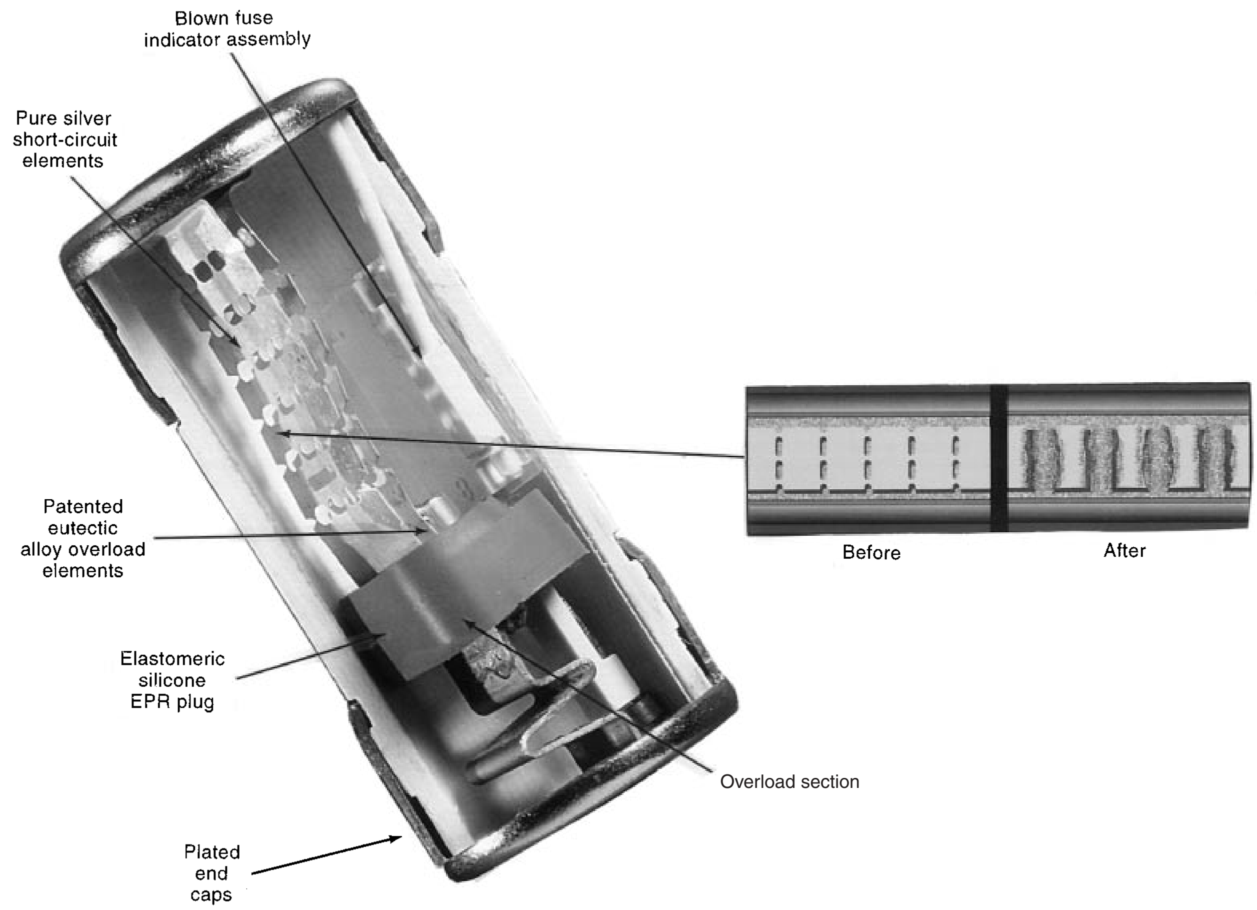


Figure 11. Salient features of a time-delay fuse. Courtesy of Littelfuse, Inc., Des Plaines, IL.

plications. Fuses that protect transformers must be specially designed to meet several requirements. They need to provide satisfactory protection against anticipated overloads and respond appropriately in the presence of close-in secondary faults and catastrophic failure on internal transformer faults. Time-delay fuses should not be used for protecting electronic circuits and devices because transient voltage spikes cause damage to electronic circuitry.

Capacitors and capacitor banks need fuses with special characteristics. The fuse link should be capable of continuously carrying at least 135% of rated current. It should be able to withstand the transients that appear during charging or discharging. The TCC of the fuse should be appropriately coordinated with tank-rupturing time current characteristics of the capacitor.

To ensure some service to at least a partial group of customers in a large electrical distribution network, more than one fuse is used in a series configuration [Fig. 10(a)]. Fuse A is the protected fuse and fuse B is the protecting fuse. Melting time of fuse A is provided by the manufacturer and is plotted on the TCC graph [Fig. 10(b)]. (This TCC is plotted with current on the x axis.) A suitable factor of safety is applied to this melting-time graph, and another graph called the damaging time curve is generated (75% of melting time in seconds). The total clearing-time curve for the protected fuse B is also plotted on the same TCC. The limit of selectivity is established by the point of intersection as shown on Fig. 10(b).

Care should be exercised to avoid excessive peak arc voltages when selecting current-limiting fuses for high-voltage applications. Salient construction features of a current-limiting fuse are shown in Fig. 11. The philosophy of design is to make the element longer than that of a normal, regular fuse, to create arcs in many places, and to achieve a voltage that opposes the flow of current.

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