element14 Essentials: Circuit Protection II

element14 ESSENTIALS

Circuit Protection II:

PCB-Mounted Fuses

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1. Introduction

Fuses are current-sensitive devices designed to serve as the intentional weak link in an electrical or electronic circuit, by providing reliable protection for those circuits or discrete components under overcurrent or overload conditions. While the function of a fuse appears to be rather elementary, is that the end of the story? Should an electronic design engineer or bench technician know anything else about fuses? Some obvious questions to consider include: How do fuses provide overcurrent protection? What happens during an overcurrent transient that "triggers" a fuse to operate, interrupt, or limit the circuit's current flow? When should a resettable fuse be used in lieu of a traditional fuse? What types of fuses are safe to specify for a hazardous environment? This learning module will answer these important questions, and many more.

2. Objective

The objective of this learning module is to provide you with a basic understanding of fuses, including pertinent definitions, theory, applications, standards, and the common types of PCB-mounted fuses.

Upon completion of this module, you will be able to:

- Discuss the purpose, function, and theory of fuses
- Define key terms related to through-hole, surface-mount, and resettable fuses
- Describe the standards utilized for certifying fuses
- Identify the different types of PCB-mounted fuses and their applications

3. History

Before we begin discussing fuse technology, let's briefly digress to mention the evolution of fuses, starting with the question, "Who invented the fuse?" Most people would volley the guess: super-inventor Thomas A. Edison. In truth, Edison wasn't the first to conceive of or invent the fuse.

In 1774, Edward Nairne demonstrated a phenomenon at the time called the Exploding Wire Method, where a steadily increasing current is conducted through a thin electrically conductive wire, producing heat (due to the resistance of the wire), which then vaporizes the wire, causing an arc to occur. This phenomenon was put to some practical use when Nairne tried discharging some Leyden bottles (an early version of the capacitor) connected with thin resistive wires that functioned like a modern day fuse; when high discharge currents occurred, the wire disintegrated into small balls, interrupting the circuit.

Another early instance of fuse technology in a state of evolution occurred in 1847, when Louis-François-Clement Breguet proposed a way to protect telegraph equipment from lightning. He suggested using wires of smaller cross-sections that would melt, and thereby interrupt the telegraph equipment's path to its batteries.

Figure 1: Illustration of the Thompson fuse cutout

In 1879, Professor S.P. Thompson invented a new type of fuse also called a cutout. It was made of two iron wires connected by a metallic ball made of a lead alloy, tin, or other material of low melting point. When circuit current was high enough, the current conducted through the ball would melt it, causing it to drop out; the wires then swung apart and broke the circuit.

Most references in history to fuses occurred in the 1880s. For example, Sir Joseph Swan and Thomas A. Edison demonstrated their own versions of incandescent lamps at nearly the same time. Around that time, Edison applied for a British patent in 1881 for a lead safety wire. Swan had a similar device that consisted of a strip of tinfoil (the fuse) jammed between two brass blocks. In a Swan United Electric Company's 1883 catalog, these early fuses are called safety-fusing bridges.

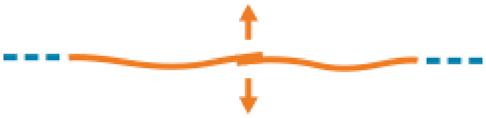


Figure 2: Illustration of the leaf spring fuse invented by CV Boys and HH Cunningham

In 1883, CV Boys and HH Cunningham designed a different version of the Thompson fuse cutout. It consisted of two leaf springs that were soldered at their opposing ends. When a high current passed through this fusible link, the solder melted and the springs flexed in opposite directions to quickly open the circuit.

Figure 3: The ball on wire fuse invented by AC Cockburn

As electric lamps developed, their level of fault volt-amps also increased, presenting a more dangerous situation. As a result, there was a greater need for reliable fuses. It was during this time period that AC Cockburn began conducting what might be considered the first research on the physical properties of fuses. He studied their thermal and electric conductivity properties, and also created his own version of the fuse. In his version, he placed a weight on the wire, but current did not flow through the weight. When a high current melted the wire, the weight would break it. He claimed this approach had better performance. More than anything, the tests that Cockburn conducted found that fuses were not applied in a consistent manner, with minimum fusing currents occurring at many times rated current. He was the first to suggest what may be considered a fusing current standard.

4. Definitions

A fuse performs two essential functions: (i) a passive function to dependably carry normal load current without aging or overheating, and (ii) an active function to "operate" or interrupt circuit current when it exceeds its maximum rating during an overload or overcurrent/short-circuit condition. To fully understand fuse operation, it is useful to become acquainted with fuse terminology. This section provides a list of commonly-used terms relating to fuse operation and technology.

Current Rating: the amount of current a fuse can conduct without melting or exceeding specific temperature rise limits.

Voltage Rating: the maximum voltage (AC or DC) that can be applied to a fuse.

Interrupting Rating: the maximum short-circuit current that a fuse can safely interrupt. (Important Safety Note: This is key, because when a fault current higher than the interrupting current is applied to a fuse, a high internal pressure may make the fuse rupture, causing, in some instances, an explosion).

I^2t: an expression of the available thermal energy or heating effect resulting from current flow. With regard to fuses, the term is usually expressed as melting, arcing, and total clearing I^2t. ***(i) Melting I^2t:*** the thermal energy required to melt a specific fuse element. ***(ii) Arcing I^2t:*** the thermal energy passed by a fuse during the arcing time; the magnitude of arcing I^2t is a function of the available voltage and stored energy in the circuit. ***(iii) Total Clearing I^2t:*** the thermal energy through the fuse from the moment the overcurrent begins until current is completely interrupted. Total clearing I^2t = (melting I^2t) + (arcing I^2t).

Fusing Current: the minimum value of current at which the fuse element melts. The fusing current depends on the fuse element material, length, diameter, the shape of the cross-section of the element, size and location of the terminals, type of surface, and type of enclosure.

Fusing Factor: the ratio of the minimum fusing current to the current rating of the fuse element; this is always greater than 1. The smaller the fusing factor, the greater the difficulty in avoiding deterioration due to overheating and oxidation at rated current.

Prospective Current: the root-mean-square (RMS) value of current which would flow in a circuit immediately following a short-circuit condition, assuming the fuse has been replaced by a link of negligible resistance.

Pre-arcing Time: the time between the beginning of the fault current, which will ultimately cause a break in the fuse element, and the instant that the arc is initiated.

Arcing Time: the time between the end of the pre-arcing time and the instant when the circuit is opened and the current decreases permanently to zero.

Overcurrent: any current which exceeds the ampere rating of wiring, equipment, or devices under conditions of use. The term "overcurrent" includes both overloads and short circuits. An overload is an overcurrent which is limited to normal current paths. An overload occurs when the current exceeds the value for which the wires or equipment are rated. A short circuit is current out of its normal path. It occurs when an accident or malfunction creates an unintended current flow path.

5. Theory

A fuse protects a circuit, or devices in a circuit, from overcurrent conditions. While this function appears to be rather simple, the process by which it is accomplished is perhaps not so. In this section, let us go through what occurs from the moment a fault current occurs, to better understand how a fuse interrupts a circuit current in a fault condition.

Fuses possess one or more elements which are designed to melt when the overcurrent threshold for the fuse has been attained; as the element melts, current is interrupted as it passes through various phases. Let's take a closer look at the fuse element.

The fuse element is a conductor which, when quickly heated due to the overcurrent condition, has a rate of rise in temperature proportional to $\int i^2dt$ ($0 \rightarrow t$), which represents the thermal energy delivered to the circuit by the short-circuit current during time *t*. Often referred to simply as I^2t, it represents the value that is integrated up to the moment of melting. It is also called the pre-arcing I^2t which is maintained at a minimum value, as the fuse designer needs to ensure the fuse has the ability to conduct normal current loading without overheating and thus operating. At the point of melting, the element will vaporize, causing arcs to be formed, which must be extinguished in order to obtain complete circuit interruption.

Under normal conditions, the current flowing through a fuse element is at a magnitude equal to or less than its rated current. Hence, the temperature of the element is well below its melting point. The fuse will continue to conduct current safely without overheating.

In a fault condition, such as when a short circuit condition first appears, the current through the fuse element increases rapidly to a high value, thereby increasing the temperature of the element. If current conducted through a fuse is above its threshold — that is, above the melting point of the element — the circuit interruption process begins.

When a fault occurs, the current begins to increase rapidly. This fault current is asymmetrical, and very large in the first loop, but before achieving its maximum value it generates enough energy to melt the fuse element. The RMS value of the first loop of fault current is called the *prospective current*. While the fault current has a large positive peak, before reaching its peak, the fuse operates and opens the circuit. The current at which the fuse melts is called the *cut-off current*.

The value of the cut-off current is very important, since it doesn't allow the prospective current to reach its peak, preventing the circuit from being subjected to undesirable electro-dynamic stresses. As the fuse element begins to melt, the current continues to flow in the molten liquid element. For a very short period of time, voltage builds up across the element breaks, which leads to ionization and the formation of arcs. Arcing begins when a gap in the fuse element becomes ionized because of a rapid buildup of voltage across it. The arcs persist until current reaches zero.

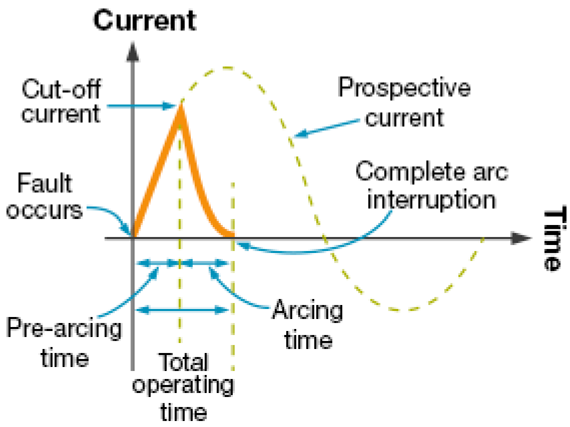


Figure 4: Fuse Operation During Fault Condition

The *pre-arcing period* is the time from the moment when the current exceeds its threshold until the melting and vaporization of the element has occurred prior to arcs being formed. From the time the arcs appear where current still can flow, to the time until arcing interruption has been completely achieved, is called the *arcing period*.

When the arcs are started, there is a significant increase in the voltage drop across them. The voltage then rises as the arcs lengthen, owing to more metal being eroded from the element. Once the arcs are completely quenched, and fault current is zero, the recovery voltage becomes normal.

- 5.1 Resettable Fuses

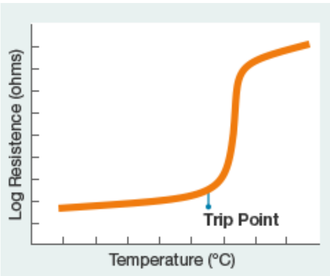
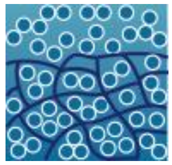
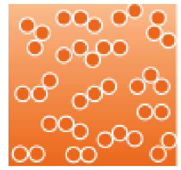


Figure 5: Response of PTC Resistance to Temperature

A resettable positive temperature coefficient (PTC) overcurrent protection device is made with a polymer that responds rapidly to a rise in temperature. Under normal conditions, it has very little resistance, and therefore little impact on a circuit. In an overcurrent condition, a PTC device will change from its normally low resistance state to a high resistance state. After the overcurrent state passes, the device cools and returns or “resets” to its normal, low resistance state.

The structure of a polymer PTC resettable fuse governs its ability to change states. It's made of an organic crystalline insulating matrix consisting of fine carbon particles. In the crystalline state, the carbon particles have electrical conductivity, allowing current to flow. When the current increases beyond a particular threshold (specific to the particular PTC device), the temperature of the device increases, changing the matrix structure from a crystalline to an amorphous (non-crystalline solid) state. In this amorphous state, electrical conductivity between carbon particles is stopped, and the device behaves as an insulator. Only when the temperature of the device decreases to restore its crystalline structure will its conductive properties return.

It should be noted that when a PTC device is in its high resistance or "tripped state," it protects the circuitry by limiting the current flow to a low leakage level. Leakage current can range from less than a hundred milliamps at rated voltage up to a few hundred milliamps at lower voltages. Traditional fuses, on the other hand, completely interrupt the current flow when operated; the open circuit results in no leakage current when subjected to an overload current.

Crystalline State	**Amorphous State**
	
Acts like a conductor	Acts like an Insulator

Understanding the differences in performance between the two types of fuses is important in order to choose the right device for the application. The ability of PTCs to reset themselves after exposure to a fault current makes them ideal for use in circuits that are not easily accessible to a user or technician. Typical applications include port protection on personal computers (USB, Firewire, keyboard/mouse, and serial ports), peripherals (hard drives, video cards, and hubs), cell phones, battery packs, industrial controls, lighting ballasts, and motor controls.

6. Types

A variety of fuse types have been designed for printed circuit board mounting. This section deals with a brief overview, description, and application of these fuses. Three main types of fuses will be discussed:

- Through-hole PCB Fuses
- Surface-mounted PCB Fuses
- Resettable PCB Fuses

- 6.1 Through-Hole PCB Fuses

Through-hole devices form a strong bond between the device and the PCB, making them great for higher power, higher voltage, and applications where mechanical stresses must be endured. Despite these benefits, one disadvantage of through-hole devices is the extra space they occupy on a PCB, as compared to surface-mounted devices. Another disadvantage is the need to drill holes in the PCB, which are necessary to secure the devices in place, limiting PCB space and routing area for tracing signals. In the end, the use of through-hole devices such as fuses depends on the application. Here are some types of through-hole PCB fuses:

473 Series, PICO® II Slo-Blo® Fuse

A good example of a through-hole fuse is the axial-leaded PICO® II Slo-Blo® Fuse, which offers time-delay performance characteristics for enhanced inrush withstand capability for limiting long-term overloads and high short-circuit fault currents. It has an encapsulated epoxy-coated body with solder-coated copper wire leads (the RoHS-compliant version has pure tin-coated copper wire leads). It has a voltage rating of 125V AC/DC, a fusing current of 3A, and a breaking capacity of 50A AC/DC. It's used in a wide variety of electronic products, such as flat–panel display TVs, LCD monitors, lighting systems, and medical equipment.

Fuses that interrupt short-circuit fault currents greater than their interrupting current rating can in some circumstances unleash an explosive event. In a hazardous location, such as a coal mine, grain elevator, or other type of industrial facility that has combustible particles suspended in the air, all that's needed to create an explosive chain reaction is the spark to ignite the explosion. To ensure that fuses do not become the spark for an explosion in a hazardous location, specially-designed fuses are selected that can be safely employed in hazardous atmospheres, per ATEX or IEC Ex requirements.

PICO® 259-UL913 Series Intrinsically Safe Fuse (ATEX and IECEx)

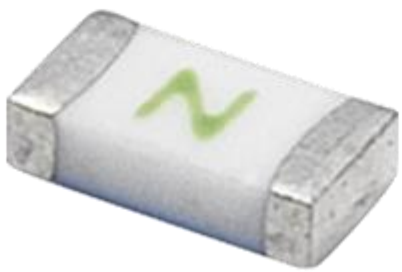
A good example of a fuse that is designed for use in a hazardous location is the 259-UL913 Series. The fuse is designed to limit the energy and temperature generated during its operation. Its hermetically sealed encapsulant is approved under the UL913 standard, meeting ATEX and IEC Ex requirements, and is certified for use within intrinsically safe apparatus for applications such as gas plants, petrochemical facilities, mines, and processing industries.

- 6.2 Surface-Mounted PCB Fuses

Surface-mounted devices have some advantages over through-hole mounted ones. Fewer holes are drilled on the PCB, and oftentimes fewer wires are needed, since the devices are soldered to the board and connected in place. As a result, PCBs with surface-mounted devices can enable higher component density and accommodate a smaller overall footprint. Finally, with no need to drill holes, surface-mounted devices lend themselves to automated assembly, which often is less expensive. Let's look at some common types of surface-mounted fuses.

467 Series Fast-Acting Surface Mount Fuse

The 467 Series Fast-Acting Fuse is a good example of a very compact, surface-mounted fuse for secondary protection in space-constrained applications such as cell phones, digital cameras, and DVD players. It is an ultra-small (0603 size) thin-film device with a low profile for height-sensitive applications and a flat top surface for pick-and-place operations. It is 100% lead-free, meets the requirements of the RoHS directive, and is compatible with lead-free solders and higher temperature profiles. It is constructed with an advanced high temperature substrate with terminations of nickel over copper, with a conformal element coating that's resistant to standard cleaning operations.



437 Series - High Temperature Fast-Acting Fuse

The 437 Series Fast Acting Ceramic Fuse is a good example of a fuse that has been designed specifically to provide overcurrent protection for circuits in ambient temperatures up to 150°C. It is constructed of an advanced ceramic body with silver/nickel/tin terminations and a lead-free glass element cover coating. It has high I^2t values to ensure high inrush current withstand capability, and it is suitable for both leaded and lead-free reflow/wave soldering. The 437 Series is frequently used in servers, printers, LDC displays, and data modems.

- 6.3 Resettable PCB Fuses

Overcurrent circuit protection can be accomplished with the use of either a traditional fuse or the more recently-developed resettable PTC fuse. Both devices function by reacting to the heat generated by the excessive current flow in the circuit. Here are a few common types of resettable fuses:

PolySwitch RXEF Series PPTC Resettable Fuse

The PolySwitch RXEF Series is a good example of a through-hole, PPTC Resettable Fuse that is often used in computer motherboards, USB hubs, gaming machines, battery packs, and more. They feature low hold currents (down to 50mA) and high voltage rating (up to 72V). They are compatible with high-volume electronics assembly. They are made of cured, flame retardant epoxy polymer that meets UL94 V-0 requirements and tin-plated nickel-copper alloy leads.

POLYFUSE LoRho Series PPTC Resettable Fuse

The LoRho Series is a good example of a surface mount PPTC device where ultra-low internal resistance, ultra-low voltage drop, and automatic resettable protection are desired for electronic products such as smartphones, HDTVs, hard-disk drives, USB peripherals and more. They allow a higher hold current device in a smaller factor and lower profile as compared to a standard PPTC. All devices are UL and TUV recognized and have a maximum fault current of 50A.

7. Standards

Fuse ratings and other performance criteria are evaluated under laboratory conditions and acceptance criteria, as defined in one or more of the various fuse standards. Here is a brief list of the standards relevant for fuses.

UL-Listed

A UL-Listed fuse meets all the requirements of the UL/CSA/ANCE 248-14 standard. The following are some of the requirements: UL ampere rating tests are conducted at 100%, 135%, and 200% of rated current. The fuse must carry 100% of its ampere rating and must stabilize at a temperature that does not exceed a 75°C rise. The fuse must open at 135% of rated current within one hour. It also must open at 200% of rated current within 2 minutes for 0-30 ampere ratings and 4 minutes for 35-60 ampere ratings. The interrupting rating of a UL-Listed fuse is 10,000 amperes AC minimum at 125 volts.

Recognized Under the Component Program of Underwriters Laboratories

The Recognized Components Program of UL is different from UL-Listing. UL will test a fuse to a specification requested by the manufacturer. The test points can be different from the UL-Listed requirements if the fuse has been designed for a specific application. Application approval is required by UL for fuses recognized under the Component Program.

CSA Certification

CSA Certification in Canada is equivalent to UL-Listing in the United States.

The Component Acceptance Program of CSA

The Component Acceptance Program of CSA is equivalent to the Recognition Program at UL.

METI Approval

METI-A approval in Japan is similar to UL Recognition in the United States.

METI-B has its own design standard and characteristics.

International Electrotechnical Commission(IEC)

The IEC organization is different from UL and CSA, since IEC only writes specifications and does not certify. UL and CSA write the specifications, and are responsible for testing and certification. Certification to IEC specifications are given by such organizations as SEMKO (Swedish Institute of Testing and Approvals of Electrical Equipment), BSI (British Standards Institute), and VDE (German Standard Institute), as well as UL and CSA.

IEC 60127-4 (Universal Modular Fuse-Links) covers both PCB through-hole and surface-mount fuses. This standard covers fuses rated 32, 63, 125, and 250 volts. This standard will be accepted by UL/CSA, making it the first global fuse standard.

MIL-PRF-15160 and MIL-PRF-23419

These specifications govern the construction and performance of fuses suitable primarily for military electronic applications.

Test Your Knowledge

Are you ready to demonstrate your fuse knowledge? **Then take a quick 15-question multiple choice quiz to see how much you've learned from this Circuit Protection 2 module.**

Take Quiz