Fuses for the protection of electronic equipment

The construction, characteristics and design considerations of fuses

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A "simple" fuse is the most widely used, and often the most overlooked and underestimated protection component in a circuit. Although the mechanical construction of a fuse is relatively straightforward, its operation is complex. As a result, much research and development has taken place to keep up with new technologies and devices.

This article describes how modern fuses, when chosen correctly and properly installed, provide cheap, accurate and reliable protection which in many respects is superior to other switching devices.

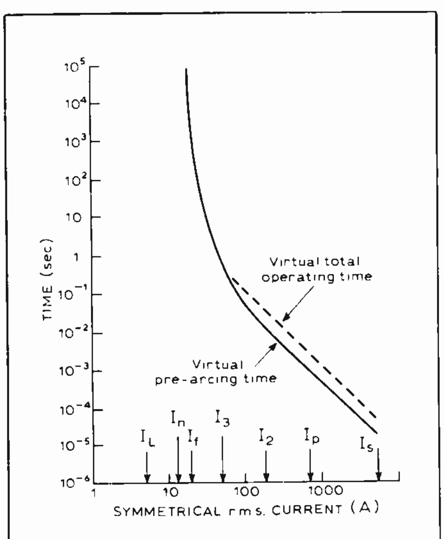
A FUSE, according to the IEC, is a switching device that by fusion of one or more of its specially designed and proportioned components opens the circuit in which it is inserted and breaks the current when it exceeds a given value for a sufficient time. The fuse comprises all the parts that form the complete switching device.

Fuses are the most common protective device and are used at rated currents up to above 2000A and in circuits operating at up to 132kV. Physically, a fuse is of simple construction but its operation is complex. The late H. W. Baxter of the ERA was one of the leading authorities and the results of some of his classic research over the period 1930 to 1950 has been published.

A fuse is one of a chain of components in a circuit, all of which rise in temperature with the passage of current. Under heavy overload or short circuit conditions there is no time for the heat to escape and the temperature of the fuse element rises rapidly to the melting point of the element. At small values of over-current a single break occurs in the element which gradually lengthens until arc extinction. At high values of fault current a large number of breaks occur almost simultaneously. With wire elements there may be 40 or more arcs per inch and the arc voltage may reach several hundred volts per inch particularly when there is a high inductance in the circuit. This high arc voltage quickly forces the current down to zero before the first peak of the fault current. Excess voltage, even a transient type, is however objectionable particularly to semiconductors, and upper limits are prescribed in many specifications. For a.c. circuits, part 1 of BS88 specifies maximum arc voltages of 1000V and 2000V with circuits rated up to 60V, and 61 to 300V respectively. Lower arc voltages can be obtained with fuses specially designed for semiconductor protection.

In a modern cartridge fuse the element is totally enclosed. For high current ratings and for specially designed semiconductor fuses the cartridge is usually filled with powered quartz, of controlled grain size, which is free from moisture and organic impurities. With this type of fuse, fire risk and damage is greatly reduced because of its ability to limit the current and thus reduce the let-through energy. Cartridge fuses are non-deteriorating and retain their characteristics almost indefinitely. The filler plays an important part in fuse operation because it cools and condenses the hot metal and vapour produced by arcing, and it also reduces the pressure on the cartridge wall. In addition, it is capable of extracting a large amount of energy from the circuit. This energy vitrifies part of the quartz which forms a fulgurite. As the fulgurite and remaining filler cools its resistance quickly increases and it is able to withstand full working voltage indefinitely. The size of the quartz particles is important because arcs are drawn into the interstices between the particles. But, because there are other conflicting requirements the choice of particle size is a compromise.

Fig. 1. *Typical t/I characteristic for a 13A plug top fuse to BS1362. Assumed values for I_p and I_L are 740A and 6A respectively.*



All fuses have an inverse t/I characteristic of the general shape shown in Fig.1. Current I_n is the rating of the fuse link, I_f is the minimum fusing current and I_L is the full load current of the equipment which should not be greater than I_n. Values I_2 and I_3 are higher currents used for descriptive purposes. The prospective current at the fuse position is denoted by I_p, and is the current that would flow if the fuse were replaced by a solid link of negligible impedance. The maximum current which the fuse is subjected, I_s, in the manufacturers certification tests must be greater than I_p. The current range 0 to I_n is the working zone and the complete fuse should carry any current in this range without overheating. The current range I_n to I_f is the non-operating zone and the ratio I_f/I_n is the fusing factor. This depends on the design of the fuse, and varies from about 1.2 with some designs of powder filled fuse, to as much as 2 with some semi-enclosed rewireable fuses. Any value of current above I_f causes operation of the fuse although it may take an hour or more with a current only slightly above I_f. A small current increase in the range I_f to I_3 results in a considerable increase in operating speed whereas a small increase in current above I_3 has only a small effect. With 3 pin plug top fuse links to BS:1362, I_s is 6000A which is well above any likely value of I_p. The value of I_p may be approximately determined by connecting a load at this position and measuring the supply voltage before and after application of the load. The accuracy is improved by using a heavy load. Current rating I_n of a fuse in the mains supply should be at least equal to the value of I_L, and must also be sufficient to cater for surges. However, it should not be too large because with lower values of I_n there is a better chance of clearing earth faults. The prospective earth fault current I_E on the 240V mains is $I_E = 240/Z_e$ where Z_e is the phase earth loop impedance at the fuse position. To meet the IEE wiring regulations I_E must exceed $3I_n$ when $I_f/I_n > 1.5$, and I_E must exceed $2.4I_n$ when $I_f/I_n < 1.5$. A low value of Z_e is therefore necessary with high current rated fuses. In urban areas with cable sheath earthing, Z_e is likely to be less than 1Ω and I_E greater than $240A^2$. Difficulties in obtaining a sufficiently low value of Z_e are more likely to arise with overhead services particularly in areas of high soil resistivity. The Electric Supply Authority can often render assistance both in testing and in obtaining a good earth.

Tests at various currents between I_f and I_s are made in order to plot the t/I characteristic. In the range I_n to I_3 these may be made at a reduced voltage. Fig.2 shows a typical current in a fuse during a high current test in which the melting of the fuse element prevents the current reaching the maximum value. The graphical method of determining virtual pre-arcing time is superimposed in Fig.2. and shows that:

$$I^2_p\, t_{vp} = i^2 dt$$
$$t_{vp} = i^2 dt / I^2_p$$

where I^2_p is the prospective current, t_{vp} is the virtual pre-arcing time, and i is the instantaneous value of current during the pre-arcing period. The virtual arcing time may be determined in a similar manner and can be added to the virtual pre-arcing time to give the virtual total operating time. The virtual pre-arcing time is drawn to show the mean value of the test results and the virtual arcing time is taken as the maximum value of the test results. Fig.1 shows that the arcing time is only significant at high fault currents.

The only current known to the user apart from the load current is the prospective current, I_p. The user needs to know a time value as shown in Fig.2 so that it can be multiplied by I^2_p to obtain the heating effect of the current. Equipment can then be selected and designed to withstand this with a safety margin. Manufacturers usually present this as a characteristic with I^2t in A^2s as the ordinate and I_n as the abscissa. Fig.3 shows total operating I^2t and pre-arcing I^2t for each value of I_n.

It is fortunate that fuses have an inverse time/current characteristic as this enables suitably chosen fuses to operate satisfactorily when in series. It is not practicable to examine or replace every fuse that has experienced a through fault, but discrimination can be achieved if the total energy let through by the minor fuse, total I^2t, is less than the pre-arcing energy I^2t_{vp} of the major fuse. In general, discrimination is achieved if the current rating of the major fuse is twice that of the minor fuse although a lower ratio is often possible when I_p is relatively low. Difficulties arise when different types of protective equipment are involved. Discrimination cannot always be achieved when rewireable fuses or miniature circuit breakers are in series with cartridge fuses. In Fig.4 the 45A rewireable fuse discriminates with the 80A cartridge fuse up to about 500A. With fault currents above 500A the cartridge fuse operates first.

Two fuses are sometimes used in the mains supply to apparatus with the erroneous belief that this is twice as good as one fuse. If the fuses are of the same type and current rating, the fuse in the neutral lead may operate first. In this condition the apparatus remains at a dangerous potential above earth. A single fuse should be used in the live lead. Sometimes the earthed chassis of equipment is accidentally or deliberately connected to the neutral. This is most undesirable for a number of reasons. Such a connection encourages part of any short circuit current to flow through the metal work to earth. This fault current may originate from other apparatus in the same premises or even from apparatus in adjacent premises. If the local earth and sub-station earth have low resistances, very high currents can flow without any effect on the fuse in the apparatus. Secondly, the neutral is used to carry unbalanced currents from other phases of the supply network and usually differs from earth by a continuously varying potential of up to several volts. The corresponding current will therefore fluctuate and cause hum and other difficulties particularly when the parallel earth paths have a low resistance. Thirdly, and even more important, the danger that arises in the event of a broken neutral. Although this is a very rare occurrence, if the break occurs between the apparatus in question and the sub-station, considerable load currents from apparatus in all premises beyond the break can flow to earth through this connection. Again,

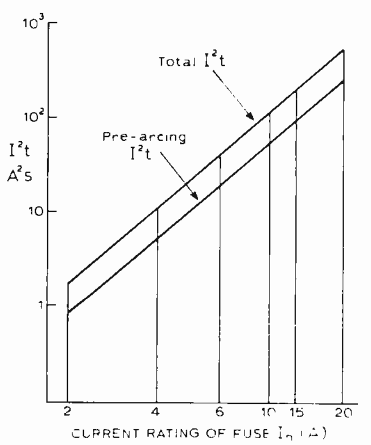


Fig. 3. *Typical I^2t values for a family of fuses.*

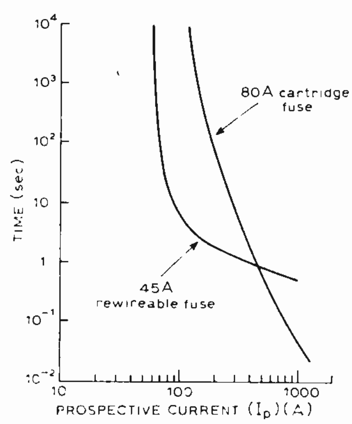


Fig. 4. *T/I characteristic of cartridge and rewirable fuses.*

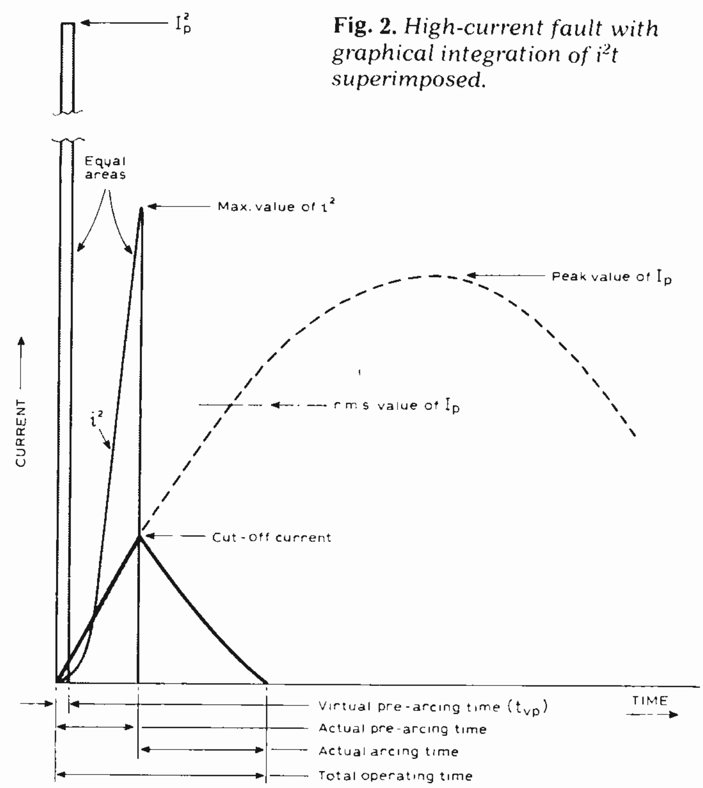


Fig. 2. *High-current fault with graphical integration of i^2t superimposed.*

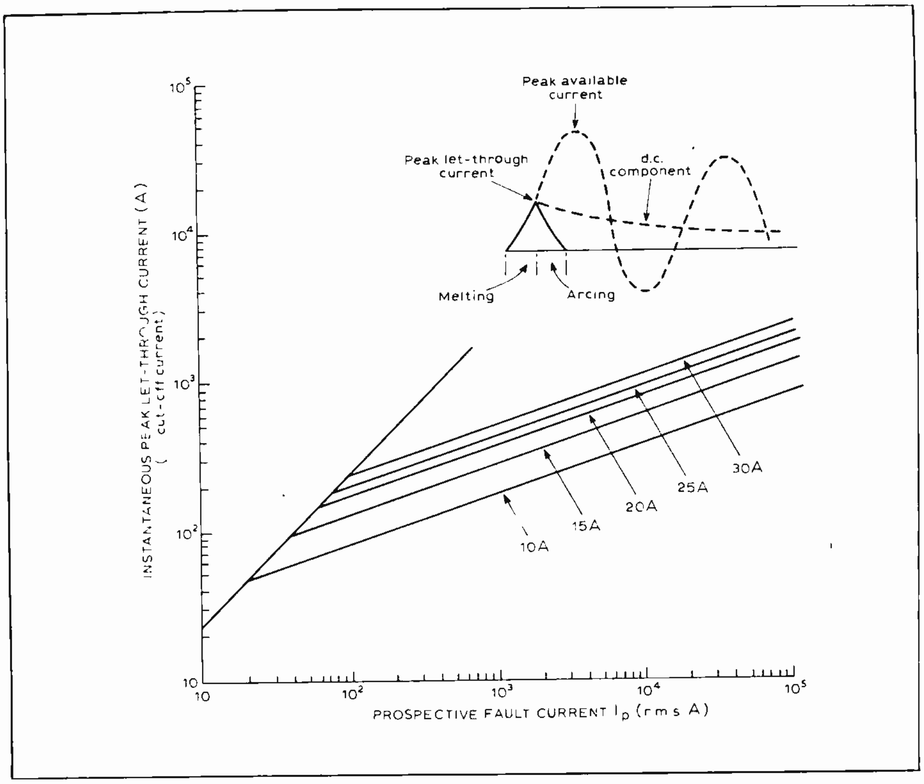


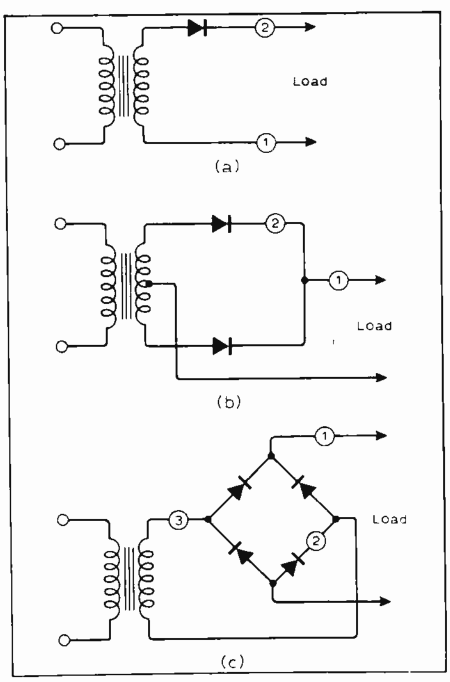
Fig. 5. *Cut-off characteristics for a family of 250V semi-conductor fuses.*

the fuse on the apparatus is completely unaffected. Furthermore, even if the local earth has a fairly low resistance, the metalwork of the apparatus may rise to a dangerous potential.

Cut-off characteristics are usually presented on equal decade logarithmic paper, and an example for a family of semiconductor fuses is shown in Fig.5. The 45° line is the transition point and is the asymmetrical fault current which is the limit of cut-off. There is no precise value but it is usually considered to be about 2.4 times the r.m.s. symmetrical fault current for circuits of less than 1000V. Cut-off currents for the individual fuses correspond to a slope of 1 in 3 because at currents greater than the transition value the cut-off current is proportional to $3\sqrt{I_p}$. In Fig. 5 all of the fuses exhibit cut-off at I_p values above $10I_n$. At very high values of I_p the cut-off current is quite small, particularly with fuses of lower current ratings.

Temperature rise is the difference between the actual temperature at the fuse position and the ambient temperature. Under a steady current the temperature rise of a fuse will increase until a steady condition is reached when the heat dissipated is equal to the heat input, I^2Rt Joules where R is the resistance of the fuse. At currents up to I_n the temperature rise is approximately proportional to I^2 but usually increases at a greater rate for currents above I_n. Small overloads can therefore result in a large increase in temperature. A fuse may either gain heat or loose heat to the connecting cables. A considerable proportion of the total heat can be due to the resistance of the terminations and contacts. Some specifications give maximum permitted temperatures of fuses and the components parts. For example, BS 88:1975 Part I for cartridge fuses up to 1000V a.c. and 1500V d.c.

Fig. 6. *Half-wave rectifier with a single diode (a). The d.c. load current (1) is 1A, the r.m.s. diode current with a resistive load (2) is 1.57A. Full-wave rectifier using two diodes (b). The d.c. load current (1) is 1A, the r.m.s. diode current (2) with a resistive load is 0.785A, and with an inductive load is 0.707A. If only one fuse is used in the centre tap lead there is no protection for an undamaged diode. Full-wave rectifier (c). The d.c. load current (1) is 1A, the r.m.s. load current (2) for a resistive load is 0.785A, and for an inductive load is 0.707A. The r.m.s. current in the transformer secondary (3) for a resistive load is 1.11A, and for an inductive load is 1A.*



gives a temperature rise limit of 65°C for bolted tin plated contacts and terminals. Some specifications do not give temperature rise limits but, specify either maximum permitted power loss or maximum resistance. For a particular fuse and a given current rating, the ratio of steady state power loss at current rating/cold power loss, is mainly constant. Because the ratio of temperature rise at rated current/stable condition hot power loss, is also reasonably constant this amounts to specifying the maximum temperature. Power loss in a fuse increases with the increased current rating. With a 32mA fuse it is about 1/3W while at the other extreme a 1250A fuse may lose 100W. Because a fuse is a temperature sensitive device it may have to be derated in ambient temperatures above 40°C. Alternatively, it may be uprated if subjected to artificial cooling.

Potential drop across fuses with low current ratings may exceed the voltage of the equipment being protected. At the rated current a 32mA low breaking capacity fuse to BS:4265 has a maximum potential drop of 10V. Corresponding values for 1A and 6.3A fuses are 1V and 0.2V. These high values at low current ratings are due to the very fine wire used for the elements.

Some of the factors affecting the correct choice of fuse current rating have already been mentioned. With semiconductors, however, it is also necessary to distinguish between r.m.s. and average values. Current ratings of fuses are invariably given in r.m.s. values whereas average values are given for diodes and thyristors. A comparison of these currents for half-wave and full-wave single phase rectifiers assuming that i_{peak} is 1.0A shows tifiers, assuming that i_{peak} is 1.0A, shows that,

	I_{peak}	$I_{r.m.s.}$	$I_{average}$
half-wave rectification	1.0	0.50	0.318
full-wave rectification	1.0	0.707	0.637

When semiconductor rectifiers are used it is also necessary to take account of the fuse position in the circuit. The three most commonly used single phase rectifier circuits are show in Fig. 6 with currents at various positions assuming that the d.c. load current is 1A. Values for other currents will be in proportion. It should be noted that the published average current for some diodes may have to be derated to 0.81_{av} for battery or capacitive loads. With large installations several diodes may be used in parallel and a multi-phase arrangement can be used. It may then be desirable to connect a fuse in series with each diode in addition to main fuses. Ideally, the t/I characteristic of the fuse should be below that of the semiconductor by a safe margin. Semiconductor manufacturers obtain their I^2t values in less than 10ms by using a half sine wave at higher frequencies. These I^2t values can be compared with the I^2t/I_p characteristics of the fuse if the operating times are

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superimposed. This extra information can be obtained from the fuse manufacturer. With large and expensive installations it is also necessary to take into account the effects of overload, either cyclic of non-repetitive, and the possibility of heavy currents from capacitors.

For small equipment such as radio receivers and amplifiers, miniature fuses are used. A most popular type for many years was the 1¼ × ¼in to BS:2950. These can be obtained with current ratings from 50mA up to 25A. The corresponding voltage rating is reduced from 1000V. for the lowest currents to 32V at the highest currents. The fuses are colour coded and are available in quick blowing types with a maximum voltage of 250V. Recently, the 20 × 5.2mm fuse to BS:4265 and IEC 127 has been more extensively used with current ratings from 32mA to 6.3A. With miniature quick acting fuses the element is a very fine wire and tends to have relatively high arc voltages on operation. This depends on the resistance and reactance in the circuit and the instant when the fault occurs. A number of tests made on 200mA fuses with random point-of-wave switching on a 240V circuit showed that in one case a peak arcing voltage of 350V occurred. A diode in this circuit would therefore require a maximum repetitive peak reverse voltage of 400V.

Fuses to BS:4265 can be obtained with a wide range of operating speeds which are marked on the fuse link; FF is very quick acting, F is quick acting, M is medium time lag, T is time lag, and TT is long time lag. Various methods are used to meet the range of speeds, including the use of different materials such as silver, copper, nickel-chrome alloy or the use of two metals. Anti-surge fuses are available which withstand surges of $10I_n$ for up to 20ms. In this type the element often consists of two parts, one of which is a small spring soldered to a thin wire. Eutectic solder may be used to connect the element to the end cap and a low melting point alloy may be used for the junction.

The M effect, first described by Metacalf, is often used with medium time lag fuses. In a very precise machine operation, a small blob of solder about 2½ times the diameter of the element wire is placed on the element. The melting point of the alloy is very much lower than the wire and results in a longer operating time and a lower fusing factor.

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