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SERIES K: PROTECTION AGAINST INTERFERENCE

Surge protective component application guide – Fuses

Recommendation ITU-T K.140

ITU-T

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Surge protective component application guide – Fuses

Summary

Recommendation ITU-T K.140 describes the types, construction, operation and selection of fuses used in information and communication technology (ICT) and alternating current (AC) powering equipment ports. Series connected fuses and fusible components operate by the fusing of one or more of their elements which opens a connected circuit by breaking the current when it exceeds a given value for a sufficient time. Fuses and fusible components are intended to prevent potential hazards caused by overcurrents. The two main equipment application areas are AC mains ports and ICT ports where AC mains incursion is possible. This Recommendation considers fuse and fusible component types, the electrical stress levels pre- and post-operation and gives circuit examples.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
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Keywords

AC powering port, arcing, fuse, ICT ports, lightning surge, melting, overcurrent protection, I^2t.

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Table of Contents

Recommendation ITU-T K.140

Surge protective component application guide - Fuses

1 Scope

This Recommendation covers the types, construction, operation and selection of fuses used in information and communication technology (ICT) and alternating current (AC) powering equipment ports. Particular attention is paid to fuse operation under lightning surge conditions to quantify the I^2t and let-through current to the following electronic circuits.

Information is also provided on the overcurrent performance of fusible resistors, standard resistors and printed circuit board (PCB) traces.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

None.

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

3.1.1 arc voltage of a fuse [b-IEC 60269-1]: Instantaneous value of the voltage which appears across the terminals of a fuse during the arcing time.

3.1.2 arcing time of a fuse [b-IEC 60269-1]: Interval of time between the instant of the initiation of the arc in a fuse and the instant of final arc extinction in that fuse.

3.1.3 breaking capacity of a fuse [b-IEC 60269-1]: Value of prospective current that a fuse is capable of breaking at a stated voltage under prescribed conditions of use and behaviour.

3.1.4 conventional fusing current [b-IEC 60269-1]: Value of current specified as that which causes operation of the fuse-link within a specified time (conventional time).

3.1.5 conventional non-fusing current [b-IEC 60269-1]: Value of current specified as that which the fuse-link is capable of carrying for a specified time (conventional time) without melting.

3.1.6 current-limiting fuse-link [b-IEC 60269-1]: Fuse-link that during and by its operation in a specified current range, limits the current to a substantially lower value than the peak value of the prospective current.

3.1.7 fuse [b-IEC 60269-1]: Device that by the fusing of one or more of its specially designed and proportioned components opens the circuit in which it is inserted by breaking the current when this exceeds a given value for a sufficient time. The fuse comprises all the parts that form the complete device.

3.1.8 I^2t; Joule integral [b-IEC 60269-1]: Integral of the square of the current over a given time interval.

NOTE 1 – The pre-arcing I^2t is the I^2t integral extended over the pre-arcing time of the fuse.

NOTE 2 – The operating I^2t is the I^2t integral extended over the operating time of the fuse.

NOTE 3 – The energy, in joules, released in 1 Ω of resistance in a circuit protected by a fuse is equal to the value of the operating I^2t expressed in A^2s.

3.1.9 operating time; total clearing time [b-IEC 60269-1]: Sum of the pre-arcing time and the arcing time.

3.2 Terms defined in this Recommendation

None.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

AC Alternating Current

EMC Electromagnetic Compatibility

ICT Information and Communications Technology

PCB Printed Circuit Board

RMS Root Mean Square

5 Conventions

None.

6 Characteristics and ratings

6.1 General

There are numerous decisions to be made when selecting a fuse. One of the first is determining what type of current is being interrupted. Special fuses are required for breaking direct current (DC) sources as there isn't any polarity reversal to stop arcing as with AC sources. The electricity supply voltage value is another important factor in fuse selection. Where transients are expected, the fuse characteristic needs to have an I^2t value greater than the expected surge to be resistant to such events. The rated fuse current needs to be greater than the normal system current to avoid nuisance operation. A further item is that the fuse form factor needs to be appropriate for the application. This Recommendation only covers a few of these fuse selection factors. Fuses are a surprisingly complex subject and readers are encouraged to consult reference works, such as [b-Wright] and fuse manufacture resources.

6.2 Types and construction

Fuses are classified into the following three categories: high voltage, low voltage and miniature. The division between high and low voltage occurs at 1000 V AC, and miniature fuses by physical dimensions. Fuses are produced in the following basic forms: cartridge, semi-enclosed, liquid and expulsion. Cartridge fuses form the most common group and may be designed for high voltage, low voltage and miniature applications. Fuses for the protection of electronic equipment are selected from the miniature fuse category, of which there are many types ranging from a few mA to 10 A. Fuses have a tolerance which results in a minimum and maximum fusing current. The minimum fusing current must be greater than the normal system current at all times and the maximum fusing current must be below the following circuit maximum current capability. Miniature fuses are sub-divided into the following categories depending on breaking capacity and speed of operation: FF – super quick acting; F – quick acting; M – medium time lag; T – time lag and anti-surge; TT – super time lag.

Quick action fuselinks (category F) are constructed with a single wire element of uniform cross-section, which is made from a variety of materials such as silver, copper and its alloys, nickel and nickel-chromium. Low current rated fuselinks are constructed of high resistivity materials, in order to maximise the cross-sectional area. This is an important factor considering that a typical 50-mA fuse, made from nickel- chromium, will have an element diameter of only 0.013 mm. If constructed of silver or copper this diameter would be prohibitively small having very little tensile strength. Low current rated fuses restrict the maximum current due to high resistance, an example of this is a 50-mA fuse which has a typical resistance of 150 Ω.

Super quick-acting fuselinks (category FF) are similar to quick acting fuses but with the addition of a restriction in the element which increases the localised resistance by reducing the cross-sectional area and therefore enhancing the fusing performance by reducing the let-through current to the protected circuit. This type of fuse is used to protect very sensitive electronic components and equipment. However, they are difficult to produce and generally it is more cost effective to use a semiconductor device with a current rating just above the nominal circuit value.

Medium time-lag fuselinks (category M) utilise the "M" effect, which enhances the fusing performance by lowering the minimum fusing level. This is achieved by a silver element with a solder globule deposited centrally on the element. The solder acts on the silver element by diffusing at temperatures above the normal operating level, which reduces the melting point of the silver, by up to 60%, depending on the solder composition. Fuses using the "M" effect are susceptible to ambient temperature affects.

Time-lag fuselinks (category T) are usually constructed with a spirally wound element on an insulated former. The pitch of the turns is maintained within close limits to ensure consistent performance. The wire diameter is larger than the straight wire fuse types to be comparable in resistance due to the longer length. The increase in element mass results in lower temperature rise and consequently slower speed of operation. This type of fuse does not use the "M" effect and therefore is not prone to ambient temperature effects. It can be used in systems up to 70°C without any major degradation to the performance.

Super time-lag fuselinks (category TT) consist of a straight wire element soldered to a coil spring. For use in high ambient conditions the soldered joint must use high melting point solder, to prevent susceptibility to ambient temperatures greater than 50°C. Below 50°C, low melting point solders are used. The operating times depend on the following parameters to control the heat transfer process the specific heats, masses and physical dimensions of the element, spring and solder.

Telecommunication electronic circuit protection fuses are specifically designed and selected from the T and TT categories. They must employ anti-surge properties to withstand the secondary protection surge specifications, as well as being able to clear at low current levels, minimising the let-through current to the equipment.

6.3 Current-time characteristic

A typical set of current time characteristics are shown in Figure 1.

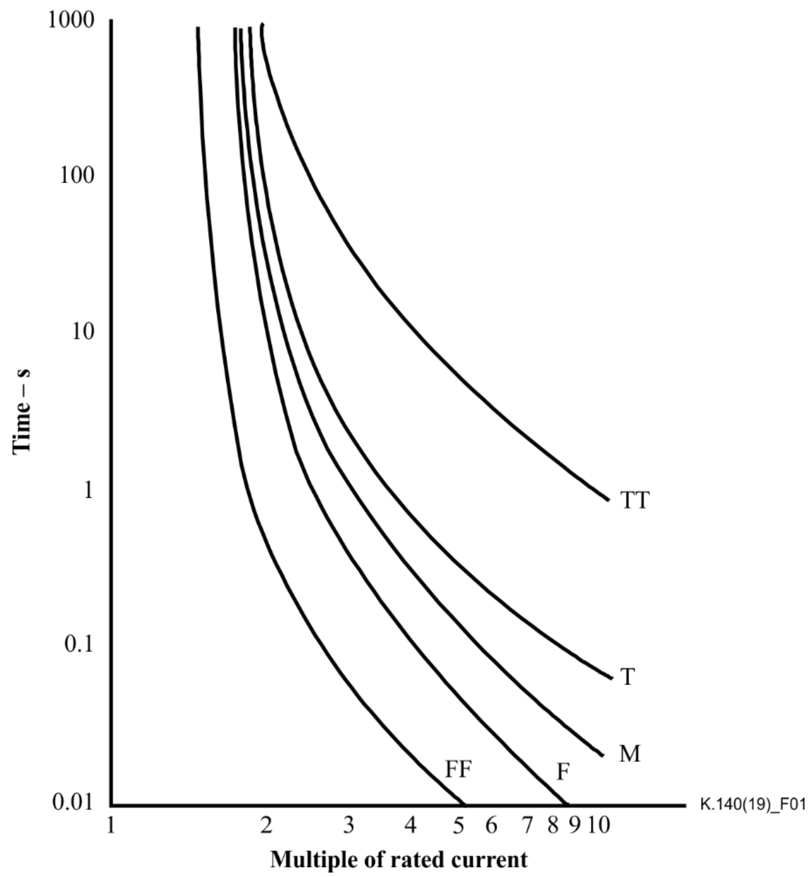

Figure 1 – Time/current characteristics for miniature fuses

The individual characteristics are designated by the operation speed at short time durations by the following codes:

– FF (Flink Flink) very fast operating;

– F (Flink) fast operating;

– M (Mitteltrage) medium operating;

– T (Trage) slow operating;

– TT (Trage Trage) very slow operating.

Often these codes are simplified to semiconductor (FF), fast blow (F) and slow blow (T). If transients have to be survived then a T type fuse is often selected. Some fuses include dual elements, which allows optimisation of long-term and short-term current capability.

6.4 Operating

Fuses, when conducting current levels above the minimum fusing level, will melt and then vaporise when sufficient time has elapsed; the resulting arc must then be extinguished to achieve a satisfactory interruption. The period prior to melting and vaporization is known as the pre-arcing period. The time from vaporisation until the arc is extinguished is called the arcing period, from which the element cannot return to its original state. The greater the current level exceeds the minimum fusing level, the shorter the time taken for the element to reach the melting point.

All fuses have resistance and therefore dissipate power. If the current level flowing is increased suddenly to a level just below the minimum fusing level, the power dissipated will increase, consequently the temperature of the element increases, however thermal equilibrium will be established. If the fuse is operated at or just above its minimum fusing level, thermal equilibrium will not be achieved and the element will melt. This is because the power available to cause temperature rise is equal to the input power (which is proportional to the square of the current) and the power dissipated by the fuselink. The latter quantity is limited by the melting point of the material.

The performance of fuses, to fault conditions, depends on the level of current above the minimum fusing level, which is itself a level somewhat above the nominal fuse current rating. The ratio of the minimum fusing level to the current rating is referred to as the fusing factor. Under the action of high current levels, the pre-arcing period is short, since as the heat transfer within the element is considered to be negligible, causing localized heating and thus rapid clearance. The rate of heat rise at any instant, in terms of the element's parameters, is considered to be:

$$d\theta/dt = \text{(Instantaneous Power)}/(\text{(Mass)(Specific Heat)})$$

The behaviour at current levels at or just above the minimum fusing level is somewhat different. In this case, the heat supplied to the element will dissipate not only in the element, but also in the surrounding atmosphere, end caps, connectors and connecting wires, which reduces the fusing efficiency. Therefore, pre-arcing times are considerable and under these conditions the system can be vulnerable if the current versus time performance of the fuse is not carefully matched to the system.

The arcing behaviour is extremely complex. The condition arises when liquefaction and vaporisation occur. Voltages build-up for short durations leads to ionization and the formation of arcs. The arc persists until the current is diminished to zero. At this point it is necessary to maintain arc extinction by ensuring a sufficiently large gap. The higher the fault current, the longer the arcing time the greater the let-through current to the system.

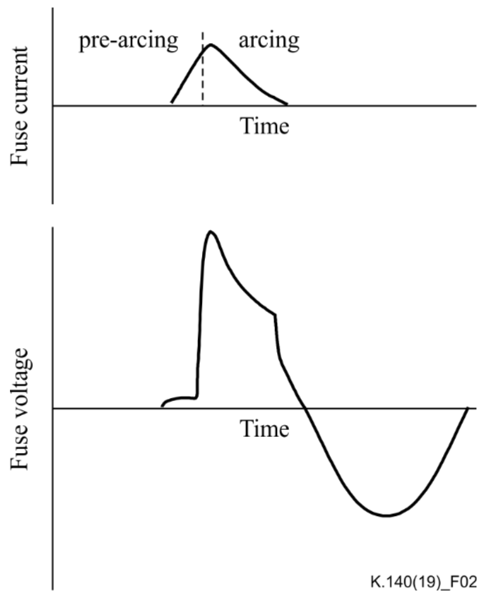

Figure 2 – Fuse pre-arcing (melting) and arcing periods under AC conditions

6.4.1 Operation under AC conditions

Under AC conditions two components of operating time periods can be easily identified; see Figure 2. In the pre-arcing (melting) period the fuse current is increasing and the fuse voltage is relatively low. In the arcing period, the fuse current is decreasing and the fuse arcing voltage is high.

Figure 3, shows the I RMS versus time performance of 50 mA and 100 mA, F and T type 20 mm glass miniature fuselinks. The characteristics demonstrate the operating performance of the two different categories for the same nominal current ratings.

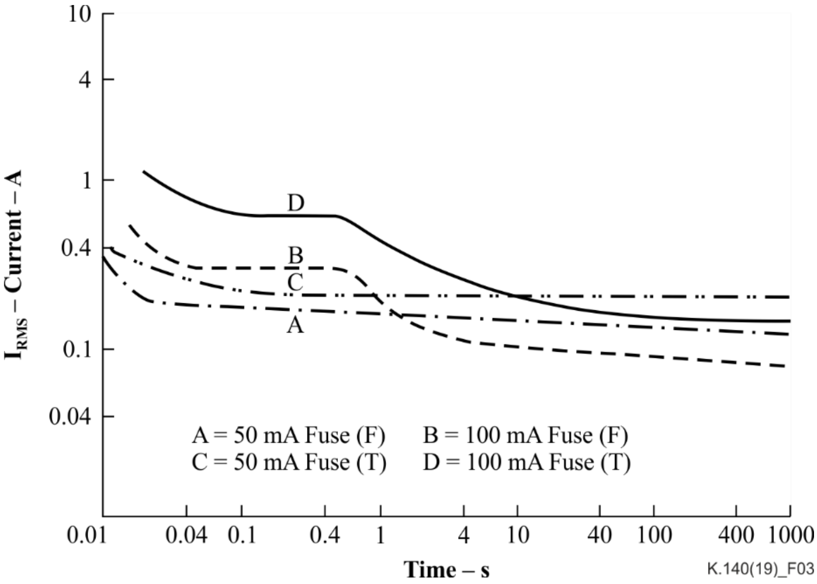

Figure 3 – F and T type fuses RMS current versus time

6.4.2 Operation under lightning conditions

Fuses are not usually designed to protect against lightning overvoltage conditions. This is easily understood when considering the increase in voltage across the fuse during the arcing period. To prevent nuisance blowing, fuses are required to pass multiple impulses of positive and negative polarity, at the surge levels used for equipment compliance. For impulse currents in excess of those levels, fuse operation may result. As shown next, the arc produced will be maintained until the current reduces to zero.

Due to test equipment limitations, it was not possible to ascertain the exact minimum fusing level of AC tested fuses A, B, C and D under surge conditions. However, all fuses did operate at 10 A, with a generator voltage of 400 V. These particular fuselinks are not suitable for line card protection. Figure 4 shows the operation of fuse D under surge conditions.

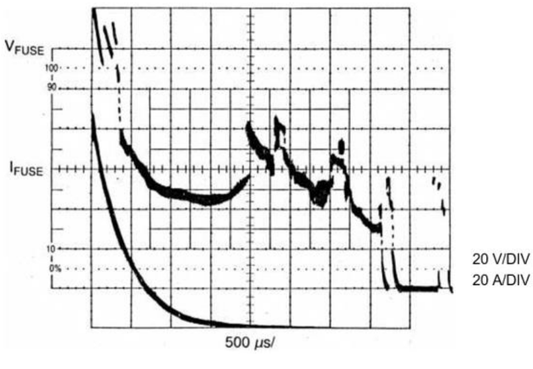

Figure 4 – 10/700 100 mA (T) fuse voltage and current waveforms

The important point here is that fuses do not protect against surges by truncating the current. Arcing allows the majority of the surge current to flow. There is some specialized current-limiting fuse-links that have a filling that quenches the arc earlier.

Figure 5 shows the non-melting voltage developed across a 1.25 A T fuse subjected to increasing impulse currents from three surge generators with different waveforms. Even through the fuse resistance is below 0.1 Ω, measurable voltages are developed across the fuse. The 10 Ω source impedance 10/1000 generator at 1000 V produces a peak current of about 100 A and the fuse voltage is about 9 V. A 1.2/50-8/20 combination wave generator with source impedances of 2 Ω and 12 Ω developed the following peak fuse voltages and currents of 18 V, 250 A and 7 V, 83 A.

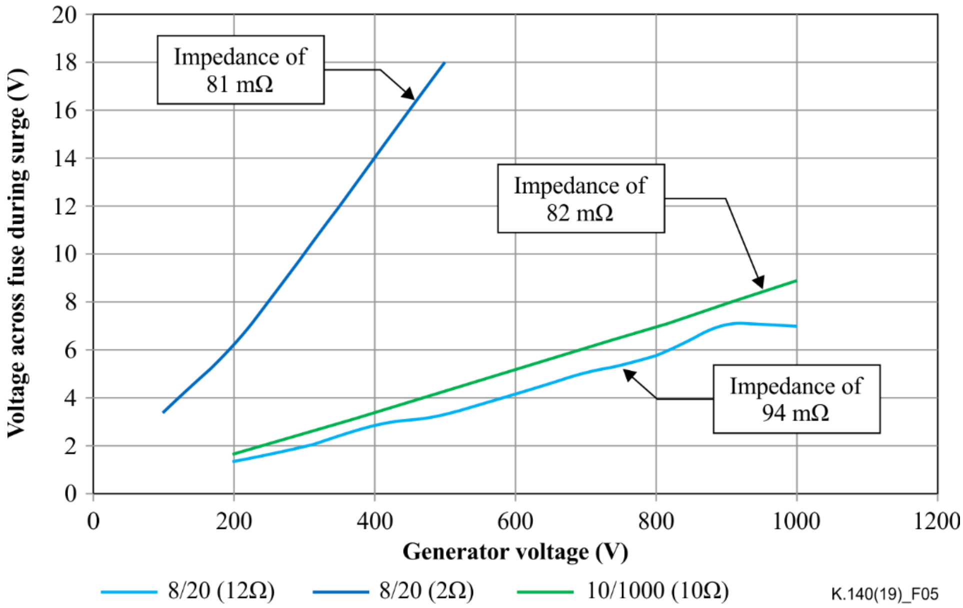

Figure 5 – 1.25 A (T) fuse non-operating voltage and current values for three different surge generators

Figure 6 shows the fuse operation with a 10/1000 generator production a peak current of 118 A. The fuse arcing mode starts at about 2.2 ms after the peak current. Arcing stops when the current reaches zero, which occurs when the generator source voltage and fuse arcing voltage are equal at 73 V.

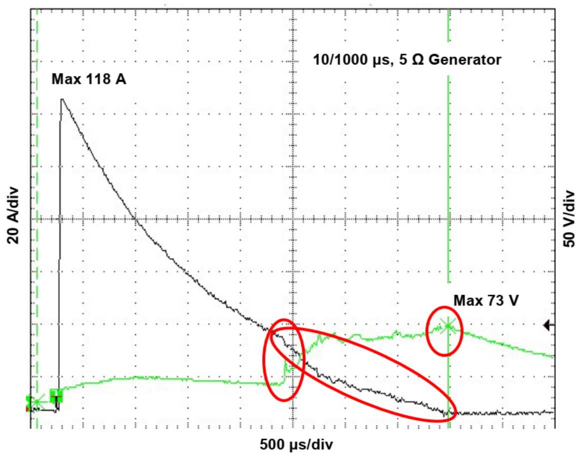

Figure 6 – 1.25 A (T) fuse operating voltage and current values for a 118 A, 10/1000 surge generator

Figure 7 is similar to Figure 6, with the peak current increased to 179 A. At this higher current, the fuse arc mode starts earlier at 0.75 ms. The arc voltage is higher too, with the arc current stopping when the generator source voltage and fuse arcing voltage are equal at 217 V.

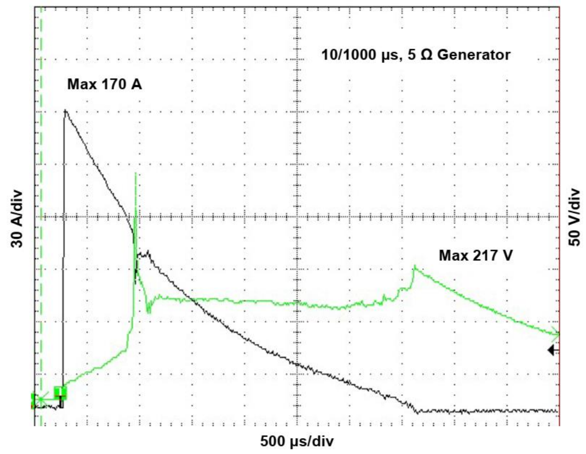

Figure 7 – 1.25 A (T) fuse operating voltage and current values for a 170 A, 10/1000 surge generator

7 Surge I^2t levels

7.1 ICT ports

The I^2t of a surge waveform with a rapid rise can be approximated to $I^2t = 0.721 \times I_{pk}^2 \times t_D$, where I_{pk} is the peak surge current and t_D is the current waveform decay time to $0.5 \times I_{pk}$. A fuse capable of withstanding a 100 A, 10/1000 current impulse would require an I^2t greater than $0.721 \times 100^2 \times 0.001 = 7.21\ A^2s$

For an 8/20 current wave form, the commonly used relationship is $I^2t = 12 \times 10^{-6} \times I_{pk}^2$. A fuse capable of withstanding a 1000 A, 8/20 impulse would require an I^2t greater than $12 \times 10^{-6} \times 1000^2 = 12\ A^2s$. This equation is derived for an 8/20 with zero undershoot. If there is undershoot, then the I^2t value will be greater. To allow for undershoot, the rapid rise equation could be used with t_D = 20 µs giving $I^2t = 15 \times 10^{-6} \times I_{pk}^2$.

Figure 8 shows the I^2t and rated current relationship for a popular North American 600 V AC pigtail fuse family. Normally a 1.25 A or greater rated fuse is used as its 15 A^2s rating will withstand a 100 A, 10/1000 surge (7.21 A^2s). At most current rating values, the I^2t value can be assumed to be proportional to the current rating squared. The best fit curve equation from 0.1 A to 5 A is $I^2t = 1800 \times i^2/(i^2 + 190)$, where i is the rated current.

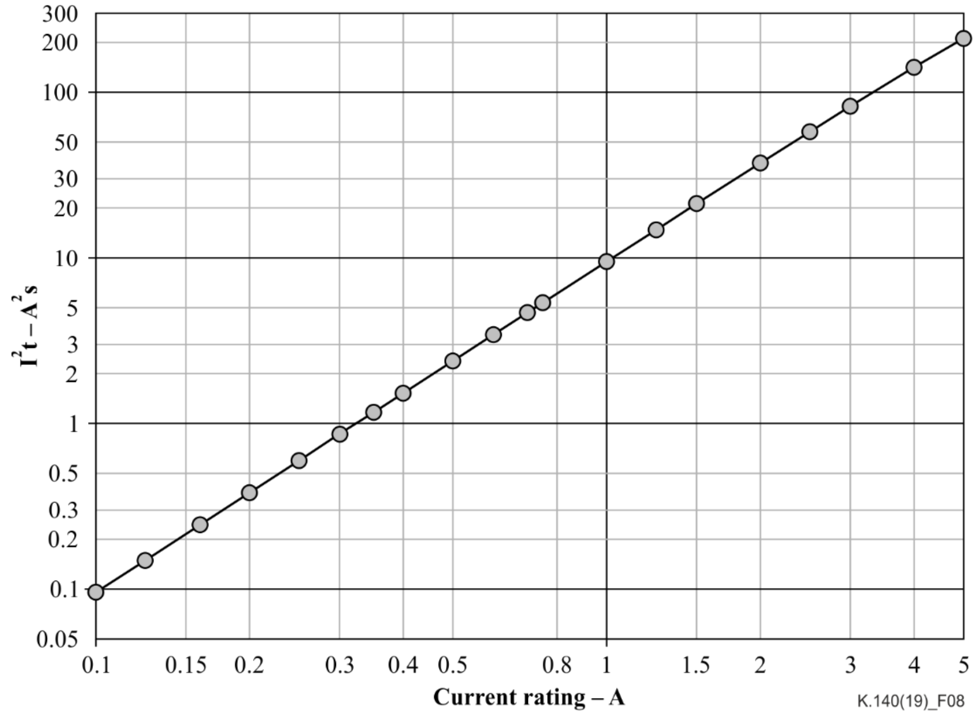

Figure 8 – Example fuse I^2t versus current rating

7.2 AC mains ports

The AC mains supply will often be subjected to transient voltages. These transients are classified in terms of overvoltage categories I through IV set by the equipment location in the AC distribution system and overvoltage levels set by the specific value of AC mains voltage. To test equipment resistibility with the appropriate transient voltage, a 1.2/50-8/20 generator is used. Using a 1.2/50-8/20 generator means that the transient prospective current and I^2t are also defined. All of these parameters are summarised in Table 1.

Table 1 – Mains transient table

AC mains voltage up to and including V RMS	**Mains transient**				
	Overvoltage Category				
	Values	**I**	**II**	**III**	**IV**
150	Peak voltage	0.8 kV	1.5 kV	2.5 kV	4 kV
	Prospective current	400 A	750 A	1250 A	2000 A
	Prospective I^2t	2.3 A^2s	8.1 A^2s	23 A^2s	58 A^2s
300	Peak voltage	1.5 kV	2.5 kV	4 kV	6 kV
	Prospective current	750 A	1250 A	2000 A	3000 A
	Prospective I^2t	8.1 A^2s	23 A^2s	58 A^2s	130 A^2s

Table 1 – Mains transient table

<table>
<tr><th rowspan="3">AC mains voltage up to and including
V RMS</th><th colspan="5">Mains transient</th></tr>
<tr><th colspan="5">Overvoltage Category</th></tr>
<tr><th>Values</th><th>I</th><th>II</th><th>III</th><th>IV</th></tr>
<tr><td colspan="2">Equipment and it's AC mains connection point</td><td>Equipment that will be connected to a special mains in which measures have been taken to reduce transients</td><td>Pluggable or permanently connected equipment that will be supplied from the building wiring</td><td>Equipment that will be an integral part of the building wiring</td><td>Equipment that will be connected to the point where the mains supply enters the building</td></tr>
<tr><td colspan="6">NOTE – This table is based on [b-IEC 62368-1] Tables 12 and I.1.</td></tr>
</table>

Table 1 provides an idea of the equipment fuse I^2t requirement for transients. Another consideration is the equipment current surge at AC power switch on. To model the switch-on transient; a power supply reservoir capacitor of 100 μF is assumed charged from an AC source impedance of 0.5 Ω to 20 Ω with switching occurring at the peak of the AC supply voltage; see Figure 9. For reference the I^2t equation used was $0.5\times(V_{pk}/R_S)$^$2\times R_S\times C$, where Vpk is the AC peak voltage, R_S is the AC source resistance and C is the power supply reservoir capacitor value. In practice, the actual I^2t will be lower than the equation estimates due to wiring and electromagnetic compatibility (EMC) filter inductance.

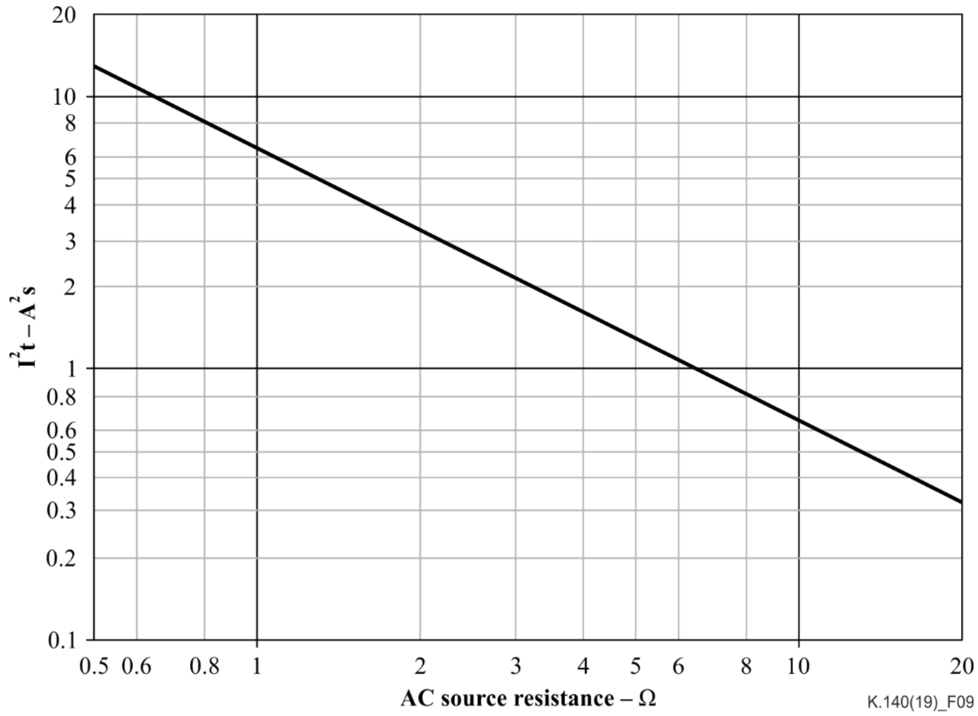

Figure 9 – Power supply initial charging I^2t versus AC source resistance

Comparing Table 1 and Figure 9, I^2t values show that in general the fuse I^2t requirement will be set by AC mains transients.

8 ICT port power fault current levels

The 1.25 A T fuse referenced in clause 7.1 has rated maximum clearing time of less than 1 h at 1.7 A and less than 20 s at 2.5 A. As the fuse isn't providing any overcurrent protection for these time periods the following circuitry may suffer excessive dissipation. If excessive dissipation occurs then some form of mitigation needs to be employed to avoid extensive damage to the port.

The normal approach is to divert the fuse let-through current via a switching element or a sacrificial element. Figure 10 shows thyristors, TH1 and TH2, which switch on when the circuit voltage exceeds the thyristor breakover voltage level. The thyristors are rated to withstand the various fuse let-through currents before the fuse operates. Figure 11 shows a diode bridge comprised of diodes D1 to D6, which feeds the fuse let-through current to the voltage limiting breakdown diode D7. The bridge diodes are rated to withstand the various fuse let-through currents before the fuse operates, but the breakdown diode is not. The excessive current through the breakdown diode causes it to fail short-circuit, thus protecting the rest of the circuit. The diode bridge arrangement lowers the circuit loading capacitance from the breakdown diode.

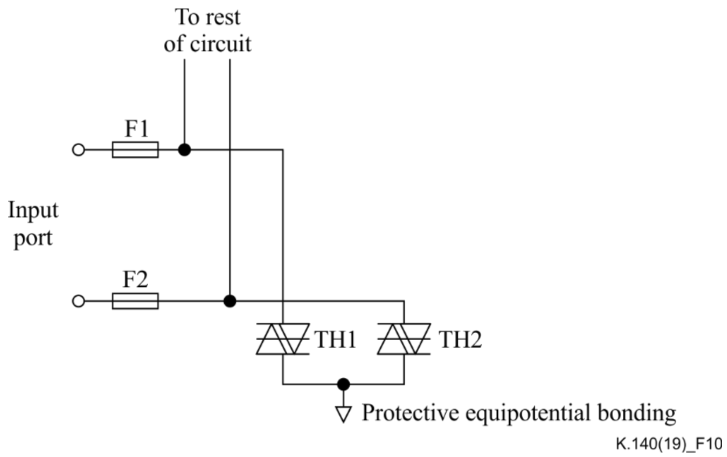

Figure 10 – Switching voltage limiter diverts fuse let-through current

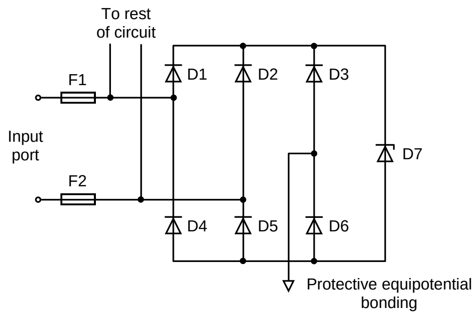

Figure 11 – Sacrificial breakdown voltage limiter diverts fuse let-through current

9 AC mains port continuous current level

The mains port fuse must not operate under normal conditions. The continuous current rating of the fuse should be at least the equipment maximum power demand divided by the lowest rated AC mains voltage multiplied by 1.25 (to allow for fuse derating at higher ambient temperatures). The fuse should then be selected to have the next higher current rating in the chosen fuse family.

It maybe that the I^2t requirement demands an even higher current rating.

Annex A

Fusible resistors

(This annex forms an integral part of this Recommendation.)

A.1 Fusible resistors

A.1.1 Construction

Flameproof metal film fusible resistors are constructed basically of a ceramic core onto which the metal film is plated or evaporated. The end caps are press fitted with the lead assembly butt welded. The nominal resistor value is produced by helixing the conductive film, using a laser process, and a small weakness is also notched into the film to enhance fusing performance. Figure A.1, shows the basic construction.

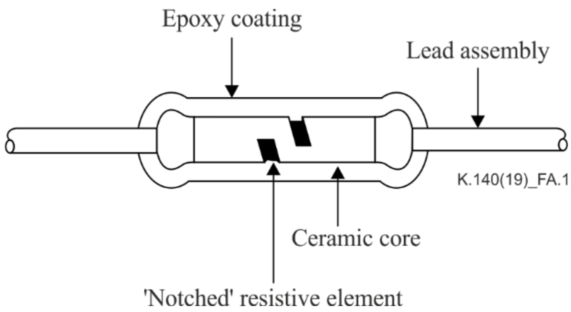

Figure A.1 – Fusible resistor construction

Unlike standard resistors, this type is designed to fuse in accordance with a pre-defined power/fusing time characteristic. In order to control the fusing process, heat is retained within the device by encasing the unit with an insulated coating, which also contains inert materials to suppress flames. Therefore, this type of resistor will not support combustion.

A.1.2 Lightning surge performance

The resistors have two beneficial characteristics. First, on fusing, no flame was produced, only a short flash and failure was limited to a small area, leaving the resistor intact. Second, the resistor maintained its ohmic value during consecutive lower level surges, while the open-circuit resistor was arced over with surge voltages greater than 700 V.

The resistors evaluated were not specifically designed for ICT protection, since the voltage withstand capability under surge, like the carbon film resistor is limited by the spacing of the spiralled film. However, there appears to be no reason why these devices could not be designed specifically for this type of application.

A.1.3 AC power performance

The current/time characteristic described in Figure A.2, shows the 10 Ω, 0.5 W fusible resistor to have a predictable and superior performance over the standard carbon composition and carbon film resistors. On fusing, the resistor produces a short flash but does not flame or combust, because of the inert materials in the coating. The enhanced performance of this type of resistor is its ability to retain heat, within the element, until the power dissipated exceeds a predefined level causing failure at the notched weakness in the film.

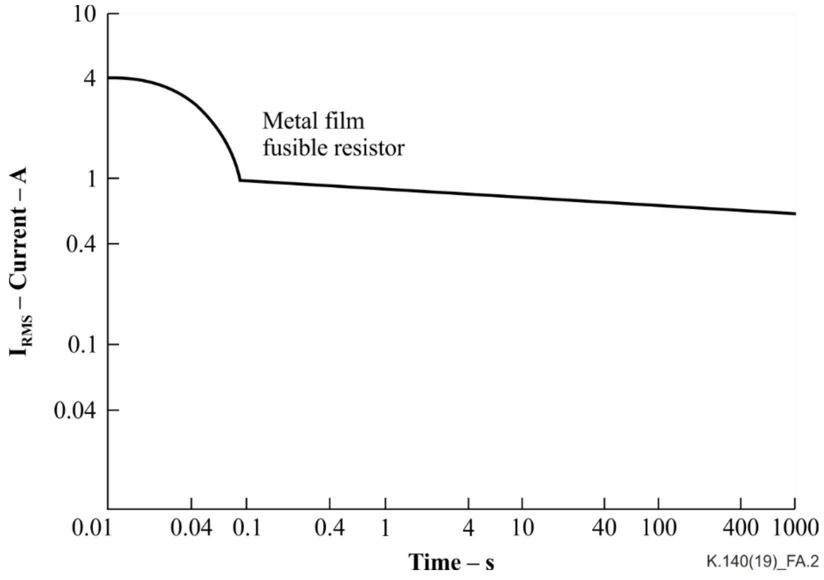

Figure A.2 – Fusible resistor AC performance

A.2 Pulse absorbing resistors

A.2.1 Construction

Pulse absorbing resistors have been specifically designed to provide circuit protection from high-energy pulses and AC power line contact. Under lightning impulse conditions, the resistor is required to pass certain specified levels, with only a small parametric change. Failure at higher levels, while permitted, is not specially engineered for line protection. However, under AC power pulse conditions, the requirements of the device are specifically engineered to withstand certain levels and fail others in a non-hazardous manner, depending on the nature of the pulses allowed to reach the resistor. The fusing characteristic is therefore pre-defined to withstand or to fuse depending upon the level of the applied fault. They are made with matched pairs of resistors for line balancing. Construction of the resistor on a flat ceramic substrate allows the protection resistors to be produced on one side and complex resistor networks on the other. Laser trimming is used for final adjustment of resistance values.

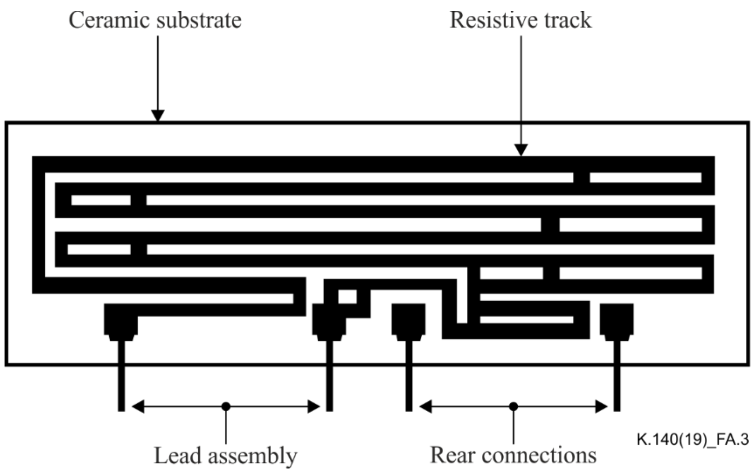

Figure A.3 – Pulse absorbing resistor construction

Under the influence of a high-energy pulse, the flat ceramic substrate will experience a massive thermal shock. This causes a rapid rise in surface temperature, with severe thermal gradients appearing throughout the substrate thickness, as well as on the surface, particularly between the resistor edges and the cooler substrate. To minimise temperature gradients and therefore maximise pulse power capability, areas not covered with resistive tracks are minimised. Also, the effect of thermal gradients between both surfaces is reduced by the selection of suitable substrate material, thickness for strength and good thermal conductivity. Internal stresses are reduced by having the resistors on both surfaces.

A.2.2 Lightning surge performance

Pulse absorbing resistors are application specific and therefore designed to pass certain test levels. Three types of units were analysed each with an ohmic value of 100 Ω but differing in physical size and track area, with type C also incorporating a thermal fuse. The thermal fuse is simply a link, usually of a solder alloy, which melts when substrate or ambient temperature is driven too high. It can only be considered to be a current fuse in the remotest sense. The time to operate being dependent on substrate working and ambient temperatures, means that these devices are slow acting which, typically, are engineered to open circuit in the range of 5 s to 100 s. All resistors evaluated passed their 10/700 surge ratings. Above the rated levels the resistors fractured but did not combust, which in many specifications is an allowable condition. The resistors ability to withstand high-energy transients is related to their thermal capacity and construction. The construction which is described above is designed to reduce stress levels due to thermal shock.

A.2.3 AC power line contact performance

As these resistors are specifically designed, their performance under AC power contact conditions is good and compares favourably with fuse operation, with the additional feature of incorporating the line balancing resistors as part of the protection. Specifications for systems using this type of device define gates (similar to fuses) which form "go, no-go" areas, through which the performance characteristic of the resistor must pass. Figure A.4, demonstrates three different resistor characteristics: A, B and C.

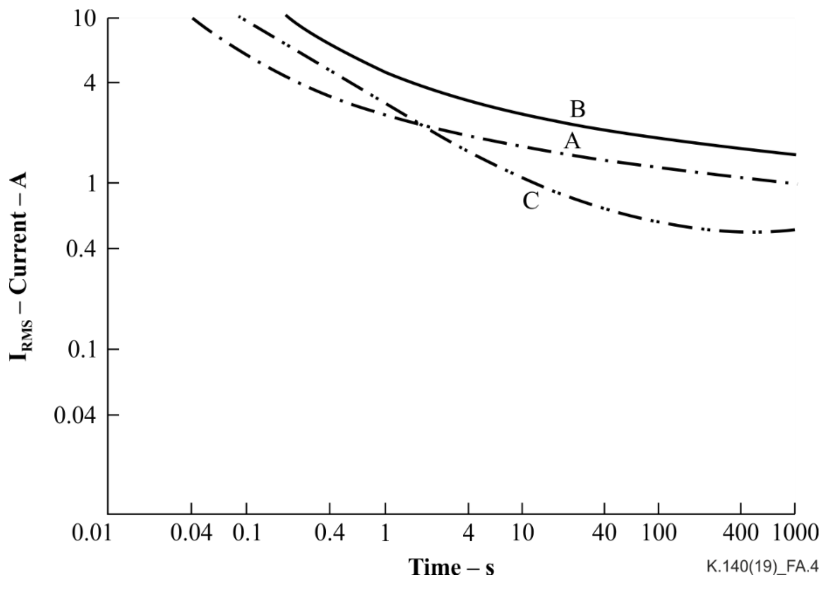

Figure A.4 – Pulse absorbing resistor AC performance

Appendix I

Resistive component overload performance

(This appendix does not form an integral part of this Recommendation.)

I.1 Carbon composition resistors

I.1.1 Construction

General purpose through-hole carbon composition resistors are basically constructed of a composite element formed into a solid cylinder or tubular section and cured at about 500°C, into which capless leads are deeply embedded, as shown in Figure I.1. Resistance values are determined by the composition elements. Due to predominance of surface mount technology, these resistors are mostly found in older equipment.

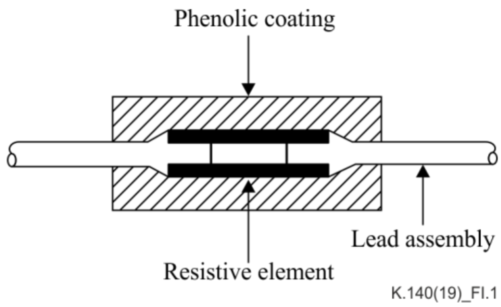

Figure I.1 – Carbon resistor construction

This type of resistor has low inductance due to the non-spiralled construction allowing good frequency performance. The embedded leads form a good heat sink which allows heat to be dissipated axially and permits reductions of element size, thereby allowing a thick phenolic coating to be compression moulded around the resistor. This type of construction provides a high voltage performance of 500 V rms working and a dielectric withstand of 1000 V rms.

I.1.2 Lightning surge performance

This type of resistor was found to perform well under surge conditions. A 100 Ω, 0.5 W, resistor was tested and passed the secondary surge level of 1.5 kV, 10/700. At levels greater than 3.5 kV, the resistor tested would crack axially, producing smoke. At levels greater than 4 kV, the resistor would explode. The ability of this type of resistor to withstand high-energy transients, can be attributed to the unit's thermal capacity and construction, as the lead assembly is separated by the carbon element length, unlike film resistors which are spirally wound.

I.1.3 AC power line performance

The performance of carbon 10 Ω, 0.5 W carbon composition resistors was found to be poor. With reference to Figure I.2, at current levels above 4 A, the device cracked and smoke was released as the element burned red-hot. At the failure point the resistor combusted producing a considerable flame. Lower current levels cause device cracking, release of smoke and the element burning red-hot for periods greater than 16 minutes, when the device fell apart. The reason for this failure mode can be attributed to the phenolic coating, which produces carbon when hot. Hence, a parallel path for current is formed with the conductive element and the resistor no longer functions in its original form. This type of resistor provides little protection for the system or the shunt protector. Under fault conditions they could prove catastrophic to any electronic equipment, by presenting a fire hazard.

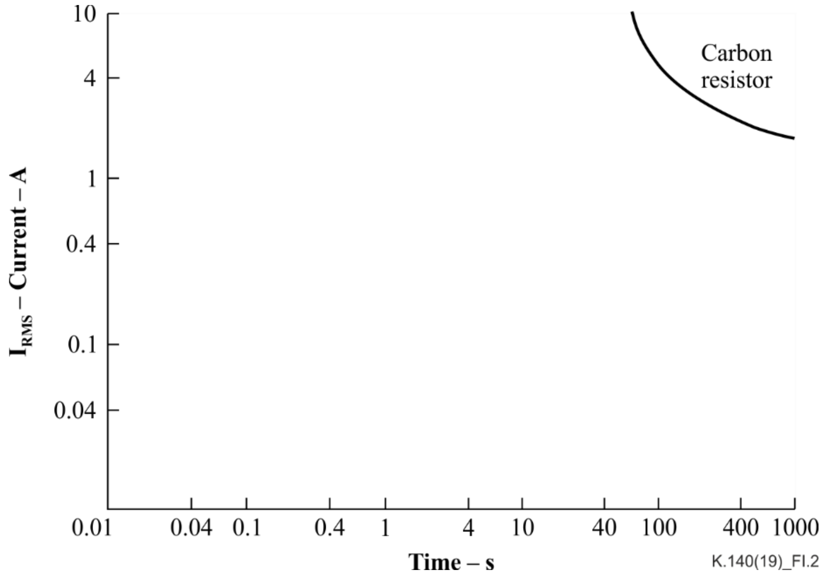

Figure I.2 – Carbon resistor AC performance

I.2 Carbon film resistors

I.2.1 Construction

This type of resistor is constructed by depositing pure carbon onto a ceramic core, by a process referred to as "cracking", which uses hydrocarbons to produce purer carbon in a furnace. The steel end caps are press fitted to the element with the electroplated copper lead assembly butt welded to the caps, as described in Figure I.3. The nominal resistance value is produced by helixing the carbon conductive layer and then using a laser for fine trimming. The element is then coated with epoxy for environmental protection.

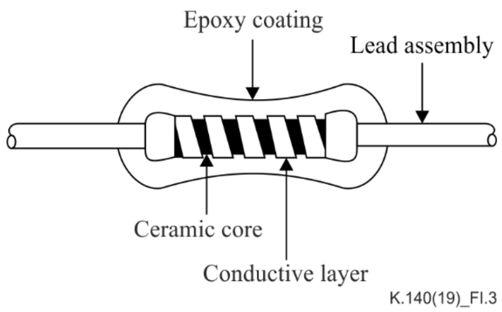

Figure I.3 – Carbon film resistor construction

I.2.2 Lightning surge performance

Performance to a 10/700 surge was poor. Devices cracked at a source voltage of 1.5 kV and open-circuit failures occurred repeatedly at 2 kV (400 V across the resistor). The failed resistor would crack cross-sectionally. This creates the danger in the application, that due to board insertion the resistor would be restrained into forming a poor contact, which could cause spurious operating conditions.

The limiting factor for this type of resistor is high voltage transients, due to the spacing between the spirals, unlike carbon composition resistors where the length of the resistive elements separates the leads. General carbon film resistors are limited to 250 V rms continuous working voltage.

I.2.3 AC power performance

At current levels above 2 A, the performance of the 10 Ω, 0.5 W resistor was slightly better than carbon composition resistors, in that failures occurred in less than 20 seconds, as shown in Figure I.4. Under these conditions the epoxy coating burns off rapidly followed by the conductive layer, resulting in an open-circuit condition. The resistors tested did not combust.

At lower current levels, a different situation occurs which is highly dangerous. As before the epoxy coating and conductive film burn off, but at a slower rate. This causes the ceramic core to heat and maintain conduction. The core then continues to burn white-hot for periods in excess of 16 minutes, until the core is burnt away. Under these conditions, it was found that the core of a 10 Ω, 0.5 W resistor dissipated about 45 W of power. This situation could prove catastrophic in any electronic equipment.

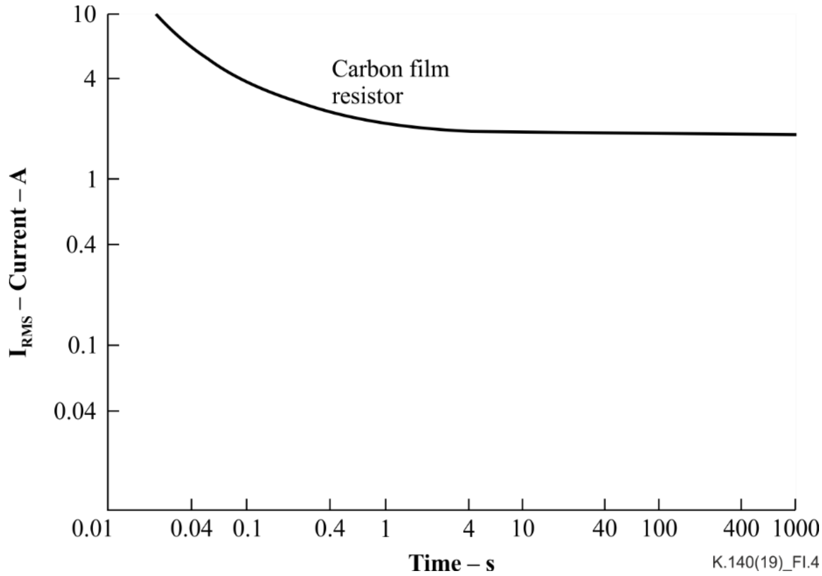

Figure I.4 – Carbon film AC performance

Appendix II

Printed Wiring I^2t

(This appendix does not form an integral part of this Recommendation.)

II.1 Melting current

II.1.1 General

It is important that the printed wiring traces on the printed circuit board carrying the surge current to the fuse do not melt before or during fuse operation. [b-Brooks] provides an equation for the adiabatic melting of copper as $I^2t = 8\times10^4\times(A)^2$ A^2s, where A is the wire cross-sectional in mm^2. This appendix applies this equation to printed wiring traces under adiabatic conditions since lightning surges are short-term events.

II.1.2 Copper clad board

The amount of copper cladding on a printed circuit board is often expressed as oz/ft^2. Cladding of 1 oz/ft^2 in metric terms is 305 g/m^2, which is a thickness of 35 µm or 0.035 mm. Thus, a cladding of n oz/ft^2 has a thickness of $n\times0.035$ mm. In this case, a trace width of w mm will have a cross-sectional area of $0.035\times w\times n$ mm^2. Inserting this into the melting equation gives $I^2t = 100\times(w\times n)^2$ A^2s.

II.1.3 Trace width, *w*

Rearranging the last equation for trace width gives $w = 0.1\times(I^2t)^{0.5}/n$ mm. If a fuse of I^2t of 20 A^2s is used one might choose a trace capability of three times that, 60 A^2s, on the basis that when the fuse operates it conducts a far larger value of I^2t due to the arcing period. Inserting this into the width equation for $n = 1$ gives $w = 0.1\times(60)^{0.5} = 0.77$ mm. A 1 mm trace width would result in an I^2t capability of 100 A^2s.

II.1.4 Accuracy

This analysis is for short-term lightning events and, being approximate, is likely to overestimate the trace I^2t capability. For a more accurate estimate, which takes into account the board microclimate temperature, references, such as [b-Brooks], should be consulted. Reliance on using trace fusing as the prime means of overcurrent protection is cautioned against because of variability and it may prove unacceptable for standards compliance.

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