

18

Resistors

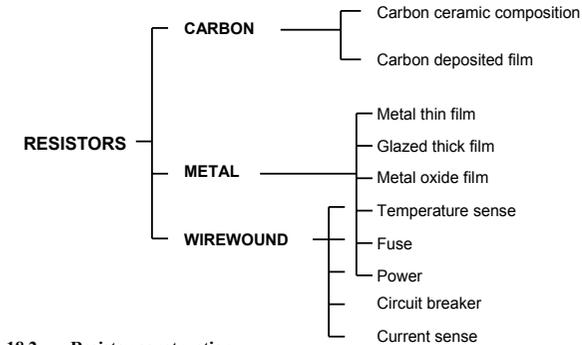
Power resistors ($\geq 1W$) are used extensively in power electronic circuits, either as a pure dissipative element, or to provide a current limiting path for charging/discharging currents. These energy transfer paths may be either inductive or non-inductive. Resistors are used for the following non-inductive resistance applications.

Series <i>R-C</i> circuit for diode, mosfet and thyristor snubbers	(6.1.2, 8.1, 8.3)
Series turn-on <i>L-R-D</i> snubbers	(6.1.2, 8.3.3)
<i>R-C-D</i> turn-off snubbers for GTO thyristors	
- inductance in <i>R</i> is allowable	(8.2)
Static voltage sharing for series connected capacitors and semiconductors	(10.1.1)
Static current sharing for parallel connected semiconductors	(10.1.2)
Resistor divider for proportional voltage sensing	(10.2.3)
Current sensing	(10.2.3)
Damping, clamping, and voltage dropping circuits	

The resistive element specification can be more than just fulfilling resistance and power dissipation requirements. For example, a current shunt resistor should be non-inductive in order to give good high frequency performance. Conversely, the resistor of the *R-C-D* turn-off snubber considered in 8.3 can be inductive thereby reducing the high initial peak current associated with an *R-C* discharge. An important resistor requirement is working voltage and the dielectric withstand voltage. High voltages (>200 V) are common in power circuits and the physical construction of a resistor places a limit to allowable voltage stress levels. Certain applications within the realm of power electronics may necessitate a power resistor with a low temperature coefficient of resistance (or even a negative temperature coefficient), a high operating temperature, a high pulse power ability or even a low thermoelectric voltage. Any one of these constraints would restrict the type of resistor applicable.

18.1 Resistor types

The tree below illustrates the main types of resistors used in electrical power applications. The three main resistor types are carbon film, metal film and wire wound. The main electrical and thermal properties of each resistor type are summarised in table 18.1. Typical values for power resistors are shown, which may vary significantly with physical size and resistance value.



18.2 Resistor construction

Almost all types of power resistors ($\geq 1W$) have a cylindrical high purity ceramic core, either rod or tube as shown in figure 18.1. The core has a high thermal conductivity, is impervious to moisture penetration, is chemically inert, and is capable of withstanding thermal shock. The resistive element is either a carbon film, a homogeneous metal-based film or a wound wire element around the ceramic body. For high accuracy and reliability, a computer-controlled helical groove is cut into the film types in order to trim the required ohmic resistance.

The terminations are usually nickel-plated steel, or occasionally brass, force fitted to each end of the cylindrical former in order to provide excellent electrical contact between the resistive layer and the end-cap. Tinned connecting wires of electrolytic copper or copper-clad iron are welded to the end-caps, thereby completing the terminations.

All fixed resistance resistor bodies are coated with a protective moisture-resistant, high dielectric field strength, and some times conformal coating, such that the wire terminations remain clear and clean.

The resistors are either colour coded by colour bands or provided with an identification stamp of alphanumeric data.

Table 18.1. The main characteristics of electrical power resistors

			carbon composition	carbon deposited film	metal thin film	glazed thick film		metal oxide film	power wire wound	fusible	circuit breaker	temperature sense	current sense
	R	Ω				LV	HV						
Resistance range	R	Ω	10-22M	1-10M	1-5M	1-2M	300k-1G	15-100k	1-1.5M	0.1-3.9k	0.27-82k	0.1-300	0.01-10
Watts @ 70°C	P_R	W	1	2	2.5	2	90	7	>300	2	6	2	9
Maximum temperature	T_h	°C	150	125	300	175	100	235	275	160	150	200	250
Working voltage	V_m	V	500	500	500	1k	100k	650	2.5k	160	500	700	\sqrt{PR}
Voltage coefficient	ϕ	$10^{-6}/V$	200	50	5	10	-	0.1	<1	-	-	-	-
Residual capacitance	C_R	pF	¼	½	-	-	½	½	-	-	-	-	-
Temperature coefficient	α	$10^{-6}/K$	-500 -1000	+50 -350	±350	±200	±150	±500	50	500	-80 +500	-3000 +5500	100
Thermal resistance	R_{θ}	K/W	80	27	90	35	13	26	0.3	50	14	0.55	20
Reliability	λ	$10^{-9}/hr$	1	10	1	-	-	3	300	-	-	-	-
Stability $\frac{\Delta R}{R}$ %	@ $P_R, T_s = 70^\circ C, @ 10^3$ hours		5	3	5	½	2	3	3	5	2 @ 150°C	0.1	3

18.2.1 Film resistor construction

Figure 18.1a shows a sectional view of a typical film resistor having a construction as previously described. The resistive film element is produced in one of four ways:

- cracked carbon film
- glaze of glass powder mixed with metals and metal compounds fired at 1000°C, giving a firmly bonded glass-like film on the core
- precisely controlled thin film of metal alloy (Cr/Ni or Au/Pt) evaporated, baked or vacuum sputtered on to the inert core and of thickness between $10^{-8}m$ and $10^{-7}m$
- metal oxide (SnO₂) resistive film deposited or sintered on to the core.

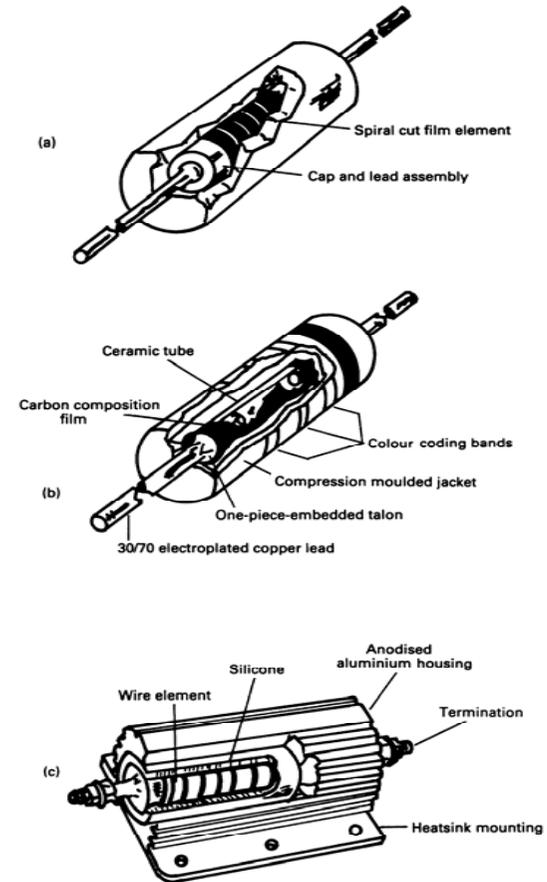


Figure 18.1. Power resistor construction: (a) metal glaze, thick film; (b) moulded carbon composition film; and (c) wire wound aluminium clad.

The film materials exhibits a wide range of resistivity, ρ , which extends from $40 \times 10^{-6} \Omega \text{ cm}$ for gold/platinum to in excess of $10^2 \Omega \text{ cm}$ for layers of thick film mixture. The thinnest possible film, for maximum resistance, is limited by the need for a cohesive conductive film on the ceramic substrate while the thickest film, for minimum resistance, is associated with the problem of adhesion of the resistance film to the substrate.

The helical groove shown in figure 18.1a, used to trim resistance, is shown clearly and is either laser or diamond cut. The residual inductance is significantly increased because of the formed winding which is a spiral around the core. Below 100Ω , a helical groove may not be used.

Resistive materials such as polymer and ruthenium oxide are used for high voltage and high resistance resistors up to 100 kV , $1 \text{ G}\Omega$ and 20 kV , $150 \text{ G}\Omega$ respectively.

18.2.2 Carbon composition film resistor construction

A sectional view of a moulded carbon composition film resistor is shown in figure 18.1b. The resistive carbon film is cured at 500°C and is unspiralled, and hence non-inductive with excellent high frequency characteristics. The resistance value is obtained by variation of film composition and thickness, which may be between $0.01 \mu\text{m}$ and $30 \mu\text{m}$. A component with a wide nominal value tolerance results since the film is not helically trimmed.

A special formed one-piece talon lead assembly is deeply imbedded into the substrate for good uniform heat dissipation. These terminations are capless.

The following example illustrates typical parameters and dimensions for carbon film resistors.

Example 18.1: Carbon film resistor

A 470Ω resistor is constructed from a film of carbon with a resistivity $3.5 \times 10^{-5} \Omega \text{ m}$, deposited on a non-conducting ceramic bar 3 mm diameter and 6 mm long. Calculate the thickness of film required, ignoring end connection effects.

Solution

Let thickness of the film be t metre, then
cross-sectional area $\approx \pi \times 3 \times 10^{-3} \times t \text{ (m}^2\text{)}$

Now $R = \rho l/\text{area}$, that is
 $470 \Omega = 3.5 \times 10^{-5} \times 6 \times 10^{-3} / \pi \times 3 \times 10^{-3} \times t$

$$t = 0.0474 \mu\text{m}$$



18.2.3 Wire-wound resistor construction

The sectional view of an aluminium-housed power wire-wound resistor, shown in figure 18.1c can dissipate up to 300 W with a suitable heatsink in air or up to 900 W when water-cooled.

The former is a high purity, high thermal conductivity ceramic, of either Steatite or Alumina tube, depending on size. The matching resistive element is iron-free, 80/20 nickel-chromium for high resistance values or copper-nickel alloy for low resistance.

These alloys result in a wire or tape which has a high tensile strength and low temperature coefficient. The tape or wire is evenly wound on to the tube former with an even tension throughout. This construction is inductive but gives a resistor which can withstand repeated heat cycling without damage.

The assembled and wound rod is encapsulated in a high temperature thermal conducting silicone moulding material and then clad in an extruded, hard, anodised aluminium housing, ensuring electrical stability and reliability.

Alternatives to the aluminium-clad resistor are to encapsulate the wound rod in a vitreous enamel or a fire-proof ceramic housing.

Power wire-wound resistors with a low temperature coefficient, of less than $\pm 20 \times 10^{-6} / \text{K}$, use a resistive element made of Constantan (Nickel and Copper) or Nichrome (Nickel and Chromium). Constantan is used for lower resistance, up to several kilo-ohm, while Nichrome is applicable up to several hundred kilo-ohm. The resistance ranges depend on the ceramic core dimensions, hence power rating. The element is wound under negligible mechanical tension, resulting in a reliable, low temperature coefficient resistor which at rated power can safely attain surface temperatures of over 350°C in a 70°C ambient. Because these resistors can be used at high temperatures, the thermally generated emf developed at the interface between the resistive element and the copper termination can be significant, particularly in the case of Constantan which produces $-40 \mu\text{V/K}$. Nichrome has a coefficient of only $+1 \mu\text{V/K}$.

Ayrton-Perry wound wire elements can be used for low inductance applications. The resistive element is effectively wound back on itself, such that the current direction in parallel conductors oppose. Either a bifilar winding or an opposing chamber winding is used. The net effect is that a minimal magnetic field is created, hence residual inductance is low. The maximum resistance is one-quarter that for a standard winding, while the limiting element voltage is reduced, by dividing by $\sqrt{2}$. The low inductance winding method is ineffective below 4.7Ω . This winding style also lowers the maximum permissible winding temperature, called *hot spot temperature*, T_h . The hot spot temperature is the resistor surface temperature at the centre of its length.

18.3 Electrical properties

An electrical equivalent circuit for a wirewound resistor is shown in figure 18.2. The ideal resistor is denoted by the rated resistance, R_R , and the lumped residual capacitance and residual inductance are denoted by C_r and L_r respectively. A film type

resistor is better modelled with the capacitance in parallel with the resistive component. The terminal resistance of a homogeneous element of length ℓ and area A is given by

$$R(v, f, T) = \rho(v, f, T) \frac{\ell}{A} = \frac{\ell}{\sigma A} \quad (\Omega) \quad (18.1)$$

where ρ is the resistivity of the resistive element and σ is the conductivity ($= 1/\rho$). The terminal resistance is a function of temperature, voltage, and frequency. Temperature dependence is due to the temperature dependence of resistivity α , typical values of which are shown in table 18.1. The temperature coefficient may vary with either or both temperature, as with carbon and metal film resistors, or resistance, as with thick film and noble metal film resistors. A reference for measurement is usually 25°C. Frequency dependence is due to a number of factors, depending on the type of resistive element and its resistance value. Typical factors are due to skin effects in the case of wire-wound resistors or residual capacitance in film types. Frequency dependent resistance, R_{ac} , for carbon composition film and metal glaze thick film resistors, is shown in figure 18.3.

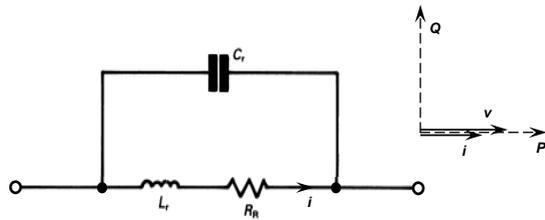


Figure 18.2. Equivalent model of a resistor.

A voltage dependence factor, which is called ϕ , is given in table 18.1 and is resistive element type dependent. For operation at low frequencies, resistance is given by

$$R(v, T) = R(0, 25^\circ\text{C})(1 + \phi v)(1 + \alpha T) \quad (\Omega) \quad (18.2)$$

Values for non-linearity coefficients ϕ and α are given in table 18.1.

Electrically, the terminal voltage and current are related by Ohm's law, namely

$$v = i \times R \quad (\text{V}) \quad (18.3)$$

where it is assumed that R is constant. This electrical relationship is shown in the phase diagram in figure 18.2. In practice when a pure sinusoidal current is passed through a resistor its terminal voltage may not be a pure sinusoid, and may contain harmonic components. This voltage distortion is termed nonlinearity and is the harmonic deviation in the behaviour of a fixed resistor from Ohm's law, equation (18.3). Another resistor imperfection is *current noise* which is produced by fluctuation of conductivity in the resistive element. The noise is proportional to current flow. Wire-wound resistors

generate negligible current noise. The resistance value itself can change: *long term drift* due to chemical-physical processes such as oxidation, recrystallisation corrosion, electrolysis, and diffusion, as may be appropriate to the particular resistive element. The power dissipated, P_d , in an ideal resistor, is specified by

$$P_d = vi = i^2 R = v^2 / R \quad (\text{W}) \quad (18.4)$$

where the power dissipated is limited by the power rating, P_R , of the resistor. In turn, the power limit also sets the maximum voltage that can be withstood safely.

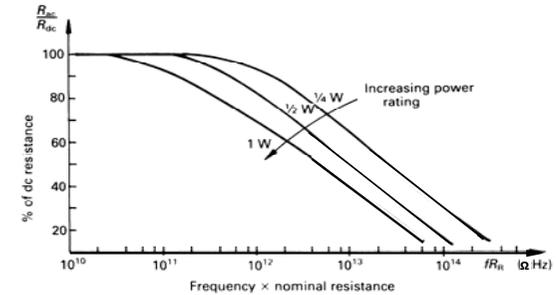
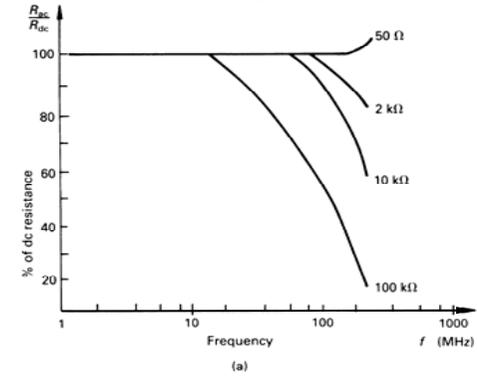


Figure 18.3. Resistor high frequency characteristics: (a) of a metal glaze thick film 3 W resistor and (b) moulded carbon composition film resistors.

18.3.1 Maximum working voltage

The maximum working voltage \hat{V} , either dc or ac rms, is the limiting element voltage that may be continuously applied to a resistor without flashover, subject to the maximum power rating P_R not being exceeded. A typical characteristic is shown in figure 18.4, which illustrates the allowable voltage bounds for a 10 W resistor range, having a limiting flashover voltage of 300 V rms.

At lower resistance, power dissipation capability limits the allowable element voltage, and above a certain resistance level, termed critical resistance, R_c , the maximum working voltage, \hat{V} , is the constraint. Maximum working voltage decreases with decreased air pressure, typically a 30 per cent reduction for low pressures.

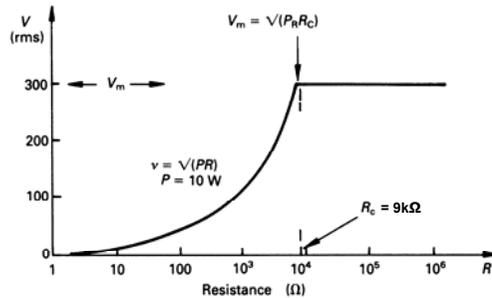


Figure 18.4. Resistor voltage limits for a given power rating.

18.3.2 Residual capacitance and residual inductance

Generally all resistors have residual inductance and shunt capacitance. Inductance increases with both resistance and power rating as shown by figure 18.5, while residual capacitance increases mainly with increased pulse rating. For example, a 2 W metal oxide film resistor (typical of film resistors) has $\frac{1}{2}$ pF residual capacitance and inductance varying from 16 nH to 200 nH. A $\frac{1}{4}$ W family member has 0.13 pF of capacitance and 3 to 9 nH of inductance.

Film resistors, with resistance above 1 k Ω , having a helical groove, tend to be dominated by interspiral capacitance effects at frequencies above 10 MHz, as seen in figure 18.3a. Non-inductive elements have low shunt capacitance, such as in the case of carbon composition, while wire-wound resistors can have microhenries of inductance. For

example from figure 18.5, a 25 W, 47 Ω , wire-wound resistor may have 6 μ H of inductance. Residual inductance increases with resistance and decreases with frequency.

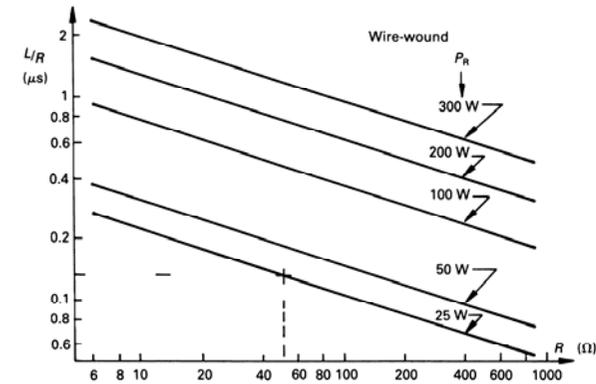


Figure 18.5. Resistor time constant versus resistance and power rating.

18.4 Thermal properties

The continuous power rating of a resistor, P_R , is based on three factors:

- Maximum surface temperature, in free air, over the usable ambient temperature range, typically from -55°C to well over 100°C .
- Stability of resistance when subjected to a dc cyclic load. Typical power dissipation is limited to give 5 per cent resistance change for 2000 hours continuous operation in a 70°C ambient air temperature.
- Proximity of other heat sources and the flow of cooling air.

The temperature rise of a resistor due to power dissipation is determined by the laws of conduction, convection, and radiation (see Chapter 5). The maximum body temperature, the hot spot temperature, occurs on the surface - at the middle of the resistor length. As previously considered, any temperature rise will cause a change in resistance, depending on a temperature coefficient; examples are given in table 18.1.

Within the nominal operating temperature range of a resistor, the hot spot temperature, T_h , is given by (equation 5.10)

$$T_h = T_a + R_{\theta_{sa}} P_d \quad (K) \quad (18.5)$$

The hot spot temperature is limited thus as the ambient temperature, T_a , increases the allowable power dissipated decreases, as shown in figure 18.6a for four different elements. These curves show that:

- No power can be dissipated when the ambient temperature reaches the hot spot temperature.
- No derating is necessary below 70°C.
- Some resistors, usually those with higher power ratings, can dissipate higher power at temperatures below 70°C.

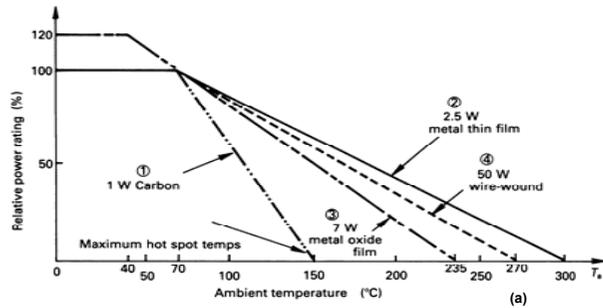
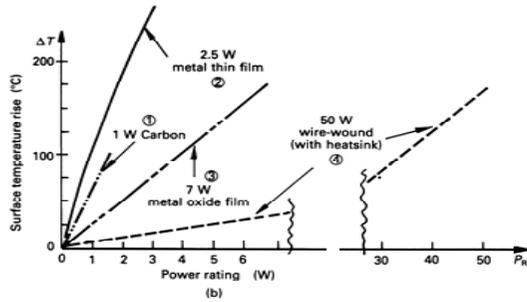


Figure 18.6. Power resistor thermal properties: (a) power derating with increased temperature and (b) surface temperature increase with increased power dissipation.

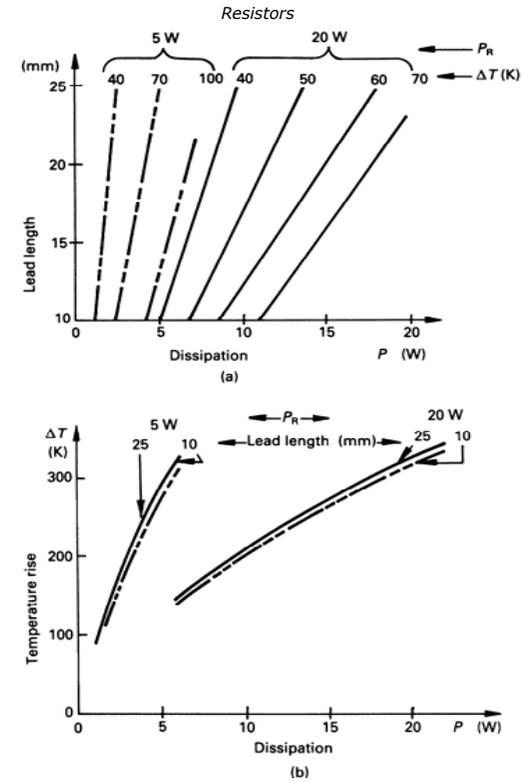


Figure 18.7. Wire-wound 5 W and 20 W resistor dissipation as a function of: (a) lead length and temperature rise at the end of the lead (soldering spot) and (b) temperature rise of the resistor body, for two lead lengths.

Figure 18.6b shows the resistor surface temperature rise above ambient, nominally 20°C, at different levels of power dissipation. The lead lengths can significantly affect the thermal dissipation properties of resistors and an increase in lead length

- decreases the end of the lead, or soldering spot temperature
- increases the body temperature.

These characteristics are shown for 5 W and 20 W 'cemented' wire-wound resistors in figure 18.7. Figure 18.7a shows how the soldering spot temperature is affected by lead length. Figure 18.7b, on the other hand, is based on the assumption that the soldering spot is represented by an infinite heatsink. Therefore the shorter the lead length, the lower the body temperature for a given power dissipation. It is important to limit the solder pad temperature in order to ensure the solder does not melt.

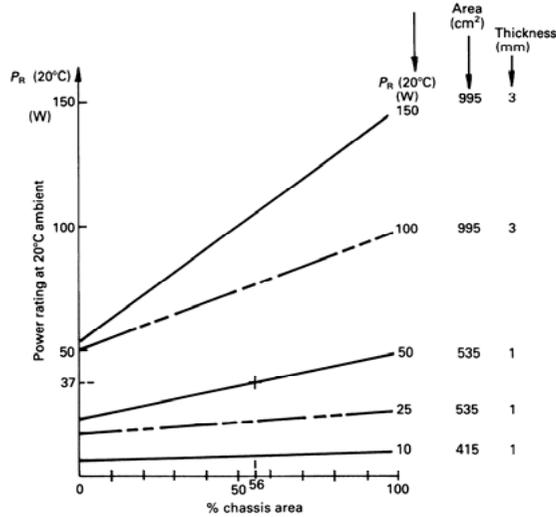


Figure 18.8. Power dissipation of resistors mounted on a smaller heat sink than specified, right.

18.4.1 Resistors with heatsinking

Aluminium clad resistors suitable for heatsink mounting, as shown in figure 18.1c, are derated with any decrease in the heatsink area from that at which the element is rated. Figure 18.8 shows the derating necessary for a range of heatsink-mounted resistors. For

a given heatsink area, further derating is necessary as the ambient temperature increases. Figure 18.6a, curve 4, describes the ambient temperature related power derating of the aluminium-clad resistors on the rated heatsink, characterised in figure 18.8. Figure 18.6a, curve 4, can be used to derate these resistors when operating in an ambient other than 20°C, with the rated heatsink area shown in figure 18.8. The same percentage derating is applicable to a heatsink area smaller than the nominal area.

Example 18.2: Derating of a resistor with a heatsink

What power can be dissipated by an aluminium-clad, wire-wound resistor, rated nominally at 50 W, in an ambient of 120°C with a heatsink reduced to 300 cm² and 1 mm thick?

Solution

The heatsink area has been reduced to 56 per cent, from 535 to 300 cm², hence from figure 18.8 the power rating below 70°C is reduced to 37.5 W.

From figure 18.6a, curve 4, at 120°C ambient, derating to 75 per cent of the relevant power rating is necessary. That is, 75 per cent of 37.5 W, 28.1 W, can be dissipated at an ambient of 120°C and with a heatsink area of 300 cm².

18.4.2 Short time or overloading ratings

Resistors with power ratings greater than a watt are designed to handle short-term overloads, either continuously for minutes, or repetitively in short bursts of a few seconds. Figure 18.9 can be used to determine allowable short-duration, repetitive pulses. It can be seen that high, short-duration power pulses of a few seconds can be handled if the repetition rate is low. As the pulse duration increases, the overload capability reduces rapidly, with minimal overload allowable with power pulses over a few minutes in duration.

For power pulses of less than 100 ms, the power is absorbed by the thermal capacity of the resistive element and little heat is lost to the surroundings. The temperature rise ΔT of the resistive element in this adiabatic condition is given by (equation 5.2)

$$\Delta T = \frac{W}{mc} \quad (K) \quad (18.6)$$

where c is the specific heat capacity of the resistive element (J/kg/K)

W is the energy in the pulse of time t_p , (J)

m is the mass of the resistive element (kg).

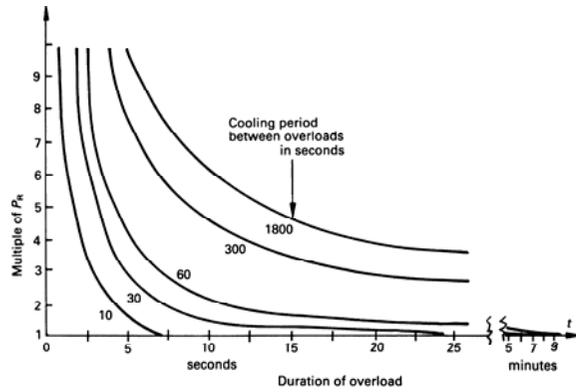


Figure 18.9. Permissible short time overload ratings for heavy-duty tape wound power resistors.

Example 18.3: Non-repetitive pulse rating

A 100 A rms, sine pulse with a period of 50 ms is conducted by a wire-wound resistor, constructed of 1 mm² cross-section Ni-Cr alloy (Nichrome). Calculate the temperature rise. Assume for Ni-Cr

- resistivity $\rho = 1 \times 10^{-6} \Omega \text{ m}$
- specific heat $c = 500 \text{ J/kg/K}$
- density $\gamma = 8000 \text{ kg/m}^3$

Solution

The mass m of the element of length ℓ and area A is given by

$$m = \gamma \ell A \quad (\text{kg})$$

Resistance R of the wire is given by

$$R = \rho \frac{\ell}{A} \quad (\Omega)$$

The pulse energy is given by

$$W = \int_0^{t_p} i^2 R dt = \int_0^{50\text{ms}} (\sqrt{2} \times 100 \sin(\omega t))^2 R dt = 500R \quad (\text{J})$$

Substitution for R yields

$$W = 500 \times \rho \frac{\ell}{A} \quad (\text{J})$$

The temperature rise ΔT from equation (18.6) is given by

$$\begin{aligned} \Delta T &= \frac{W}{mc} = 500 \times \frac{\rho \ell}{A} \times \frac{1}{c} \times \frac{1}{\gamma \ell A} \\ &= \frac{500 \rho}{\gamma c A^2} = \frac{500 \times 1 \times 10^{-6}}{8000 \times 500 \times 1 \times 10^{-12}} \\ &= 125\text{K} \end{aligned}$$



18.5 Repetitive pulsed power resistor behaviour

A resistor may be used in an application where the power pulse experienced at a repetition rate of kilohertz is well beyond its power rating, yet the average power dissipated may be within the rated power. The allowable square power pulse \hat{P} , of duration t_p and repetition time T , can be determined from figure 18.10a, which is typical for power film resistors, at a 70°C ambient. Within these bounds, any resistance change will be within the limits allowable at the continuous power rating. The pulse duration t_p , restricts the maximum allowable pulse voltage \hat{V} , impressed across a film resistor, as shown in figure 18.10b.

Example 18.4: Pulsed power resistor design

A 1 k Ω -10 nF, R-C snubber is used across a MOSFET which applies 340 V dc across a load at a switching frequency of 250 Hz. Determine the power resistor requirements.

Solution

The average power dissipated in the resistor is:

$$\bar{P} = CV^2 f = (10 \times 10^{-9}) \times 340^2 \times 250 = 0.29 \text{ W}$$

Figure 18.10 is applicable to a 2.5 W metal film resistor, when subjected to rectangular power pulses. The peak power \hat{P} occurs at switching at the beginning of an R-C charging or discharging cycle.

$$\hat{P} = V_s^2 / R = (340\text{V})^2 / 1000\Omega = 116 \text{ W}$$

where V_s , 340 V, is the maximum voltage experienced across the resistor. The 2.5W element has a power rating greater than the average to be dissipated, 0.29W. Assuming exponential pulses, then

$$t_p = \frac{1}{2} \tau = \frac{1}{2} CR = \frac{1}{2} \times 10 \times 10^{-9} \times 10^3 = 5\mu\text{s}$$

The average pulse repetition time, T , is 2 ms, therefore $T/t_p = 400$. From Figure 18.10, the peak allowable power is 150 W while the limiting voltage is 500 V. Both the experienced voltage, 340 V, and power, 116 W, are below the allowable limits. The proposed 2.5 W, 1 kΩ, metal thin film power resistor is suitable.

Furthermore from figure 18.6, curves 2, with an average power dissipation of 0.29 W, that is 11.6 per cent of P_R , the maximum allowable ambient temperature is 213°C, while the hot spot temperature is 40°C above ambient for an ambient below 70°C. In terms of average power dissipated, this resistive element is lightly stressed. On the other hand, the transient stress is relatively high.

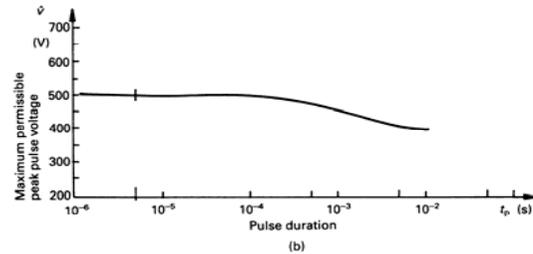
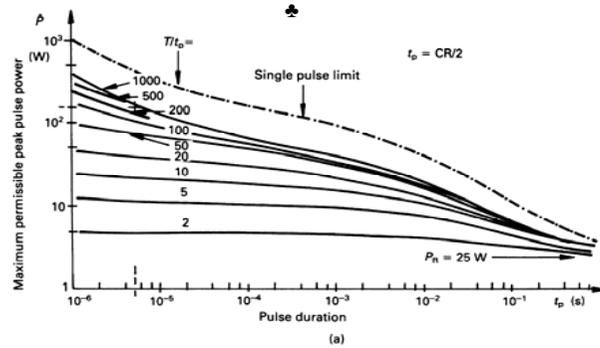


Figure 18.10. Pulsed capabilities of a power metal film resistor, 2.5 W: (a) maximum permissible peak pulse power versus pulse duration and (b) maximum permissible peak pulse voltage versus pulse duration.

18.5.1 Empirical pulse power

An empirical formula for the maximum pulse power may be given in the case of a metal film resistor. Typically, for a 1 W @ 70°C, 700 V rated, 60 K/W, metal film resistor

$$\hat{P} \leq \sqrt{\frac{15}{t_p}} \quad (W) \quad (18.7)$$

where $1 \mu s \leq t_p \leq 100 \text{ ms}$, such that the average dissipation is less than the rated dissipation.

Using $t_p = 5 \mu s$ from example 18.2 in equation (18.7) indicates that this 1 W resistor is suitable for the application considered in example 18.4. In fact a $\frac{1}{2}$ W, 600 V rated resistor can fulfil the snubber function when using a quoted $\hat{P} = \sqrt{5/t_p}$.

18.6 Stability and endurance

The resistance stability of a resistor is dependent on power dissipation, ambient temperature, and resistance value. An endurance test gives the worst-case variation in resistance value or stability. It is the percentage resistance change at rated power and hot spot temperature after a specified time. An endurance specification is of the form:

1000 hours at recommended maximum dissipation P_R , which will limit the hot spot temperature to 375°C: ΔR better than 5 per cent of R

The time, percentage change in R , and temperature are varied with resistor type and size.

At power levels below rated dissipation, better stability than that for the endurance test is attainable, for the same duration. The stability period can be extended by the following empirical formula

$$\left| \frac{\Delta R}{R} \right| \approx X^{\log_{10} \frac{t}{t_1}} \times \left| \frac{\Delta R}{R} \right|_{t_1} \quad (18.8)$$

which is valid for $10^{-3} \leq t \leq 10^5$ hours. The base χ depends on the resistor type and is between 1.1 and 5.

Performance monograms as shown in figure 18.11 are provided to enable a given resistor to be used at dissipation levels which will result in the stability required for that application. The first quadrant in figure 18.11 satisfies the thermal equation (18.5), while the third quadrant satisfies equation (18.7), with $\chi = 3.17$. The following example illustrates many of the features of the stability performance monogram of figure 18.11.

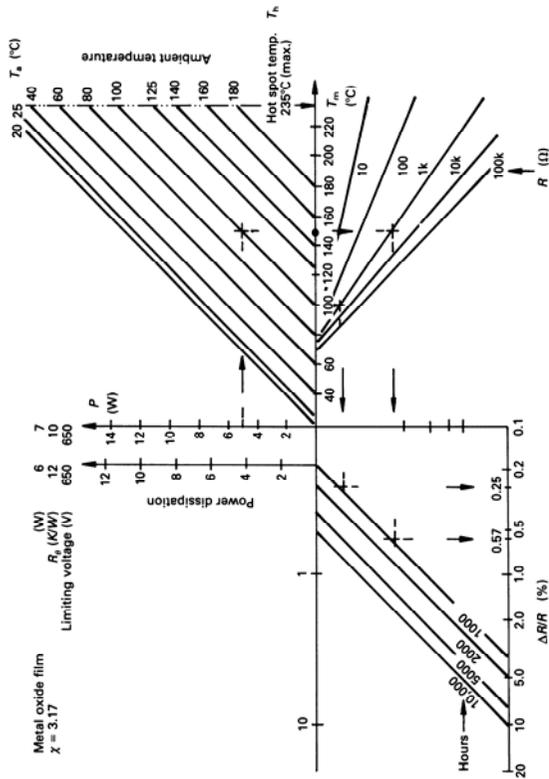


Figure 18.11. Performance nomogram for power resistors, showing the relationship between power dissipation, ambient temperature, hot spot temperature and maximum resistance drift in time.

Example 18.5: Power resistor stability

A 1 kΩ, 7 W, power metal oxide film resistor dissipates 5 W. If the maximum ambient is 100°C, use the monograph in figure 18.11 to find

- i. the stability at 100°C while in circuit for 1000 hours but in a standby mode, that is, $P = 0$ W
- ii. the hot spot temperature when dissipating 5 W
- iii. the maximum expected resistance drift after 10^3 and 10^5 hours.

Solution

- i. The resistance change given from the monogram for $P = 0$ W at a 100°C ambient is indicative of the shelf-life stability of the resistor when stored in an 100°C ambient. The stability is determined by performing the following operations. Find the intersection of $P = 0$ and the diagonal for $T_a = 100^\circ\text{C}$. Then project perpendicularly to the 1 kΩ diagonal. The intersection is projected horizontally to the 1000 hour diagonal. This intersection is projected perpendicularly to the stability axis.
- ii. The 5 W load line is shown in figure 18.11. A hot spot temperature, T_m , of 150°C is predicted ($100^\circ\text{C} + 5 \text{ W} \times 10^\circ\text{C/W}$).
- iii. With a 1 kΩ resistor after 1000 hours, a $\Delta R/R$ of 0.57 per cent is predicted, as shown on figure 18.11. There is a 95 per cent probability that the actual change will be less than 5.7 Ω.

The monogram does not show stability lines beyond 10,000 hours. Equation (18.8), with $\chi = 3.17$, can be used to predict stability at 100,000 hours

$$\frac{\Delta R}{R} \Big|_{10^5} \approx 3.17^{\log_{10} \frac{10^5}{10^3}} \times 0.57\% = 18.25\%$$

After 100,000 hours, it is 95 per cent probable that the actual resistance change of the 1 kΩ resistor will be less than 182.5 Ω.

18.7 Special function power resistors

Film and wire-wound resistors are available which have properties allowing them to perform the following functions

- fusing
- circuit breaking
- temperature sensing
- current sensing.

18.7.1 Fusible resistors

Resistors up to 2 W are available which fuse when subjected to an overload current. The resistive element fused is generally metal alloy film, although only wire-wound elements are suitable at low resistance levels. The power load and interruption time characteristic shown in figure 18.12a shows that rated power can be dissipated indefinitely, while as the power increases significantly above the rated dissipation, the interruption time decreases rapidly. Interruption generally means that the nominal resistance has increased at least 10 times. Irreversible resistance changes can be caused by overloads which raise the change in hot spot temperature beyond 150°C, for the elements illustrated by figure 18.12b. The nature of the resistive element makes it unsuitable for repetitive power pulse applications. Typical fusible resistors are summarised in table 18.2.

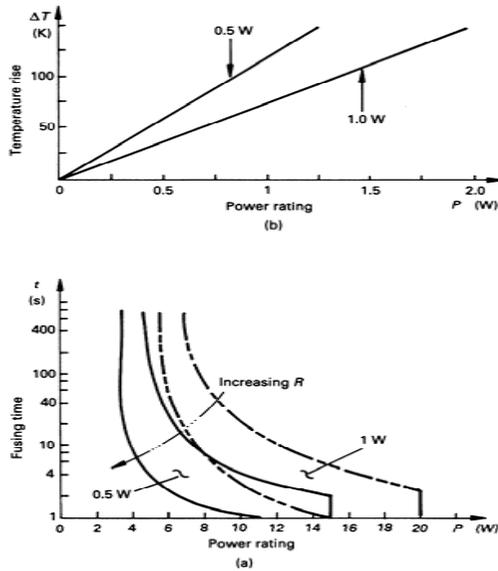


Figure 18.12. Fusible resistor characteristics:
 (a) time to interruption ($10 \times R_R$) as a function of overload power and
 (b) temperature rise above ambient as a function of power dissipated.

Table 18.2: Fusible resistor characteristics

parameter		condition	units	Metal alloy film	Wire wound
Power	P_R	@ 70°C	W	0.25 - 4.5	1 - 2
Resistance range	R		Ω	0.22 - 10k	0.1 - 1k
Tolerance			%	2	5
Temperature coefficient (resistance dependent)	α		/K	± 500	-400 to + 1000
Stability		@ P_R $T_a=70^\circ\text{C}$ 1000 hours	%	2	10
Working voltage	V_m		V	$\sqrt{P_R R}$	$\sqrt{P_R R}$

18.7.2 Circuit breaker resistors

The construction of two types of wire-wound circuit breaker resistors is shown in figure 18.13. Under overload conditions the solder joint melts, producing an open circuit. After fusing, the solder joint can be resoldered with normal 60/40, Sn/Pb solder.

The joint melts at a specified temperature, and to ensure reliable operation the solder joint should not normally exceed 150°C. This allowable temperature rise is shown in figure 18.14a, while the circuit breaking time and load characteristics for both constructions are shown in figure 18.14b. This characteristic is similar to that of fusible resistors. A typical power range is 1 to 6 W at 70°C, with a resistance range of 75 m Ω to 82 k Ω and temperature coefficient of -80 to $+500 \times 10^{-6}/\text{K}$ depending on the resistance values. The maximum continuous rms working voltage tends to be limited by the power, P_R , according to $\sqrt{P_R R}$.

18.7.3 Temperature-sensing resistors

The temperature dependence of a resistive element can be exploited to measure temperature indirectly. Unlike normal resistors, temperature-sensing resistors require a large temperature coefficient to increase resistance variation with temperature. Both metal film and wire-wound temperature sensing elements are available with a temperature coefficient of over $+5000 \times 10^{-6}/\text{K}$ with 1 per cent linearity over the typical operating range of -55°C to 175°C . The high temperature sensitivity gives a 57 per cent increase in resistance between 25°C and 125°C .

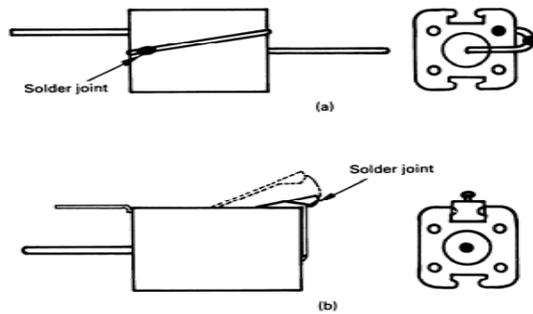


Figure 18.13. Two circuit breaker resistors construction: (a) type 1 and (b) type 2.

The low power elements, up to ¼W @ 70°C, tend to be metal oxide, with a typical resistance range at 25°C of 10 Ω to 10 kΩ. A conformal encapsulation is used to minimise thermal resistance, hence ensuring an extremely fast response. For example, a 1/20 W temperature sensing resistor can have a thermal time constant to a step temperature, in still air, of 3.7 s. This time constant increases to 31 s for a ¼ W rated resistor.

At powers commencing at 1 W, wire-wound elements are employed which utilise positive temperature coefficient alloy resistance wire. The nominal resistance range is lower than the film types; typically from 0.1 Ω to 300 Ω at 25°C. Response is slower than film types, and can be improved if oil immersed.

Glazed thick film temperature sensing resistors can be used to provide a negative temperature coefficient, $-3000 \times 10^{-6}/K$ at 25°C. Power is limited to ¼ W with a dissipation constant of up to 8.1 mW/K at 25°C in still air. Low thermal time constants of only 2.9 s are possible with 1/20 W elements. The allowable working voltage for all types is power limited.

18.7.4 Current-sense resistors

The resistive element consists of a flat metal band, with spot-welded terminals, and a ceramic encapsulation. The flat-band construction results in a non-inductive resistor of both high stability and overload capacity. Low current third and fourth terminal voltage sensing leads may be incorporated; alternatively a mΩ/cm correction factor for lead length is given.

Power ratings of up to 20 W at 70°C and 20 A maximum, with a resistance range of 10

mΩ to 10 Ω are available. At these low resistance levels, the maximum continuous working voltage is power limited. The resistance temperature coefficient is typical of a wire-wound resistor, 100 to 600 × 10⁻⁶/K depending on the resistance level.

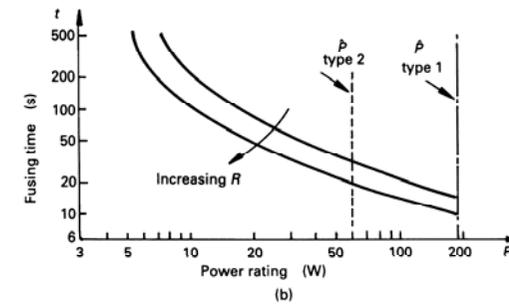
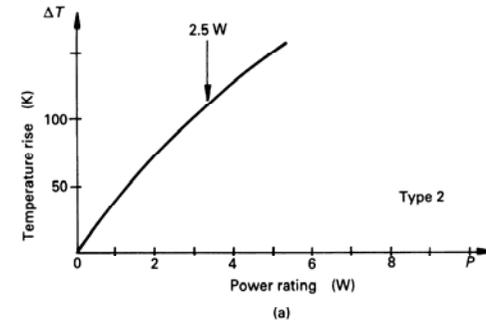


Figure 18.14. Circuit breaker characteristics: (a) solder joint temperature rise versus power dissipated for resistor type 2 and (b) fusing times versus load for resistor types 1 and 2.

Reading list

Philips, Book 3, Part 1c, Fixed Resistors, 1985.

Philips, Book 3, Part 1f, Varistors, Thermistors and Sensors, 1986.

Siemens, Components, 1986.

Siemens, NCT Thermistors, Data Book, 1986/87.

Problems

18.1. The resistance of a temperature dependent negative temperature coefficient resistor is given by

$$R(T) = Ae^{\frac{B}{T}}$$

where $B = 3300$ K and $R = 10 \Omega$ at 25°C . The resistive element has a thermal resistance to ambient of 45.5 K/W. Assume the maximum resistor temperature is 1000°C and absolute zero is -273°C .

(1) Calculate the temperature coefficient at 25°C .

[-0.037 or -3.7 per cent/K]

(2) When the non-linear resistor is dissipating power, what is the maximum attainable terminal voltage? At what temperature and current does this voltage occur at? Assume the ambient temperature is 25°C .

[58.3°C , 3.29Ω , 0.73 W, 1.55 V, 0.47 A]

(3) The non-linear resistance dependence on temperature can be 'linearised' by the parallel connection of a resistor. The resultant characteristic has an inflexion point, which is set at the mid-point of the required temperature operating range. Calculate the required parallel connected resistor if the mid-temperature point of operation is 58.3°C .

[2.2Ω , 1 W]

(4) What series resistor must be added such that the maximum voltage condition occurs at 5 V across the series plus parallel combination?

[3.45Ω , 6 W]

18.2. Derive a series of general formulae for the parts of problem 18.1.

$$\left[\alpha = -B/T^2; \hat{T} = \frac{1}{2}B(1 - \sqrt{1 - 4T_a/B}); R_p = R_m \left(\frac{B - 2T_m}{B + 2T_m} \right) \right]$$

18.3. Resistors coming off the production line are selected according to value and allocated to one of 12 bins for each decade.

Find the nominal centre value for each bin to give a range with equal ratios, and compare with the 'E12' series (1, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2, 10).

Find the maximum percentage difference between the nominal value and the E12 value.

Show that the 12-step series corresponds to a ± 10 per cent tolerance for practical resistors.

[4.5 per cent between 3.16 and 3.3]