16

Capacitors

Selection of the correct type of capacitor is important in all applications. Just satisfying capacitances and voltage requirements is usually insufficient. In previous chapters, capacitors have been used to perform the following functions:

- turn-off snubbering (8.3.1)
- *dv/dt* snubbering (8.1)
- (RFI filtering (10.2.4, 14.7)
- transient voltage sharing of series connected devices (10.1.1)
- switched-mode power supply output filtering and dc blocking (15)
- dc rail splitting for multilevel converters (14.4)
- power *L-C* filters

as well as

- ac power factor correction and compensation
- dc rail decoupling
- voltage multipliers
- motors for single phase supplies
- cascaded multilevel inverters for VAr compensation

which is just to name a few uses of capacitors in electrical power applications. In each application, the capacitor is subjected to stresses, such as high temperature, *dv/dt* or high ripple current, which must be taken into account in the design and selection process. To make the correct capacitor selection it is necessary to consider various capacitor types, their construction, features, and uses.

Two broad capacitor types are found extensively in power electronic circuits, namely:

- liquid and solid (wet and dry) electrolyte, oxide dielectric capacitors, for example an aluminium electrolytic capacitor
- plastic film dielectric capacitors, for example a polyester capacitor.

The first capacitor group has a metal oxide dielectric which offers large capacitance for a small volume. The second capacitor group, which uses a thin plastic film as a dielectric, offers high ac electrical stress properties.

Ceramic and mica dielectric capacitors are also considered. Ceramic capacitors are used extensively in high power, high frequency switched mode power supplies where they offer small size, low cost, and good performance. The voltage and capacitance ranges for the four main types of dielectric capacitors are shown in figure 16.1.

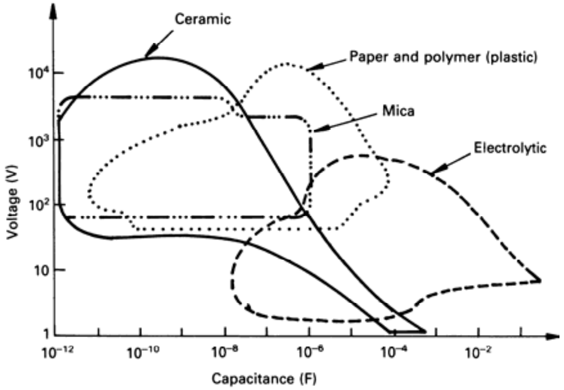


Figure 16.1. *Voltage/capacitance boundaries for the principal types of capacitors.*

16.1 Capacitor general properties

The following general principles, properties, and features are common to all capacitor dielectric types.

16.1.1 Capacitance

The primary function of a capacitor is to store electrical energy in the form of a charge. The amount of electrical charge, Q, is given by

$$Q = CV \quad \text{(C)} \tag{16.1}$$

while the stored energy is given by

$$E = ½QV = ½CV^2 \quad \text{(J)} \tag{16.2}$$

The value of capacitance, C, is directly proportional to surface area, A, and inversely proportional to the thickness of the dielectric layer, W; that is

$$C = \varepsilon_r \varepsilon_o \frac{A}{W} \quad \text{(F)} \tag{16.3}$$

The dielectric constants ε_r or alternatively K for materials in common usage, are summarised in table 16.1.

Table 16.1. Dielectric constants for common dielectric materials.

Dielectric material	*Relative dielectric constant* ε_r
Vacuum	1
Air (1 atmosphere)	1.00059
Polystyrene	2.5
Polypropylene	2.5
Polycarbonate	2.8
Polyethylene-terephthalate	3
Impregnated paper	2 - 6
Mica	6.5 - 8.7
Al_20_3	7
Glass	4 - 9.5
Ta_20_3	10 - 25
Ceramic	20 -12,000

16.1.2 Equivalent circuit

The impedance of a capacitor can be modelled by the capacitor equivalent circuit shown in figure 16.2. In series with the ideal capacitor, C_R, termed *rated capacitance,* is an *equivalent series resistor* R_s (ESR) and *equivalent series inductor* L_s (ESL). R_s is determined by lead and junction resistances, while L_s is the inductance of the electrodes due to the construction and the supply lines. The value of L_s is usually given for a specific package and capacitor type, and is generally neglected at lower frequencies, below the self-resonant frequency, which is given by

$$\omega_r = \frac{1}{\sqrt{L_s C_R}} \quad \text{(rad/s)} \tag{16.4}$$

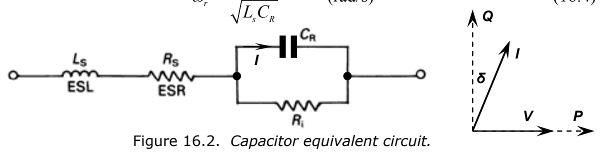


Figure 16.2. *Capacitor equivalent circuit.*

The electrical impedance Z of a capacitor, neglecting R_i the insulation resistance which is usually large, is

$$Z = R_s + jX \quad (\Omega) \tag{16.5}$$

Since the ESL is neglected, at lower frequencies, since ωL is small

$$Z = R_s - \frac{j}{\omega\, C_R} \quad (\Omega) \tag{16.6}$$

and

$$\tan\delta = \omega\, C_R R_s = \frac{R_s}{X_c} = \frac{1}{Q} = \frac{\text{real power}}{\text{reactive power}} \tag{16.7}$$

where δ is the loss angle and tan δ is termed the *dissipation factor,* which is the inverse of the circuit quality factor, Q. The angle δ is that necessary to make the capacitor current lead the terminal voltage by 90°, figure 15.2, as for the ideal capacitor.
If the insulating or dielectric dc resistance, R_i *(=* $\rho_i \ell/A$*),* is included, then

$$\tan\delta = \frac{1}{\omega C_R R_i} + \omega C_R R_s \tag{16.8}$$

and at low frequency

$$\tan\delta_\ell = \frac{1}{\omega C_R R_i} \tag{16.9}$$

while at high frequency

$$\tan\delta_u \approx \omega C_R R_s \tag{16.10}$$

Both R_s and X_c are dependent on temperature and frequency as shown in figure 16.3. Figure 16.3a shows that the rated capacitance illustrated has a positive temperature coefficient, the value of which also depends on capacitance and rated voltage. Also shown is the negative temperature dependence of equivalent series resistance ESR. Figure 16.3b shows that C_R and ESR both decrease with frequency.
Since C_R and ESR are temperature and frequency dependent, and are related to tan δ and Z, then tan δ and Z are frequency and temperature dependent as illustrated in figures 16.3c and 16.3d. Figure 16.3c shows the typical characteristics of the impedance of an oxide dielectric capacitor versus frequency, at different temperatures. At low frequencies the negative slope of Z is due to the dominance of the capacitive reactance, $Z \approx X_c = 1/\omega C_R$, whereas the horizontal region, termed the resonance region, is where Z is represented by the ohmic resistance R_s, that is $Z \approx R_s$. At higher frequencies the inductive reactance begins to dominate, whence Z $\approx \omega L_s$ and tan $\delta = R_s / \omega_s L$.
Figure 16.3d shows how the dissipation factor, tan δ, increases approximately proportionally with frequency to a high value at resonance, as would be expected from equation (16.9). At lower frequencies tan δ may be considered as having a linear frequency dependence, according to tan δ = tan $\delta_o + kf$.
The service life of a capacitor occurs when its parameters fall outside the specification limit, termed *degradation.* Such parameters are usually the capacitance, dissipation factor, impedance, and leakage current. The service life is specified under specific operating conditions such as voltage, ambient temperature, and current, and will increase

- the lower the ambient temperature, T_a
- the lower the ripple current or voltage, I_r
- the lower the operating voltage in proportion to the rated voltage, V_{op}/V_R
- the higher the ac load frequency, f.

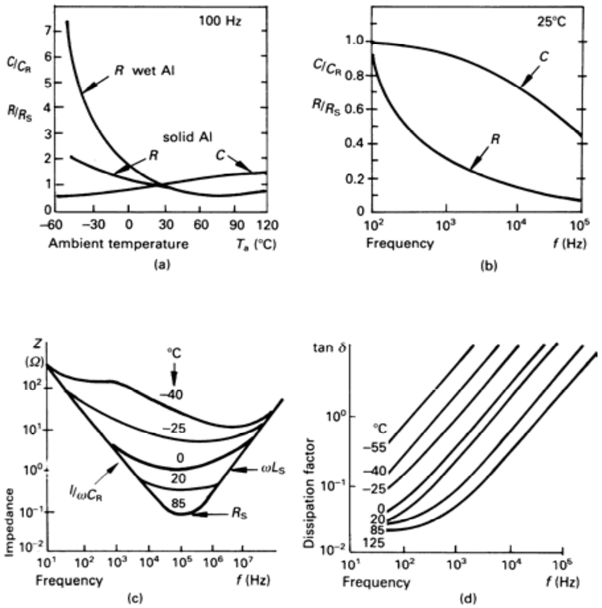


Figure 16.3. *Variation of capacitor equivalent circuit parameters with frequency and temperature for a high voltage (47 μF, 350 V) metal oxide liquid dielectric: (a) R_s and C_R as a function of temperature; (b) R_s and C_R as a function of frequency; (c) impedance Z as a function of frequency and temperature; and (d) tan δ as a function of frequency and temperature.*

16.1.3 Lifetime and failure rate

Other factors may be relevant to specific dielectrics.

Lifetime is the period until a given failure rate is reached. The failure rate, λ, is the ratio of the number of failures to the service life expected. It is usually indicated in failures per 10^9 component hours and is an indicator of equipment reliability.

If, in a large number N of identical components, percentage ΔN fail in time Δt, then the failure rated λ, averaged over Δt is expressed as

$$\lambda = \frac{\Delta N}{N \times \Delta t} \quad (/\text{h}) \qquad (16.11)$$

If the sample N is large, then the failure rate in time can be represented by a continuous 'bathtub'-shaped curve as shown in figure 16.4, such that

$$\lambda = \frac{1}{N}\frac{dN}{dt} \quad (/\text{h}) \qquad (16.12)$$

This figure shows the three distinct failure periods, and the usual service life is specified according to the failure λ_o, which is constant.

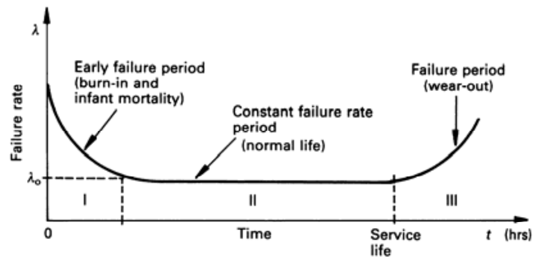


Figure 16.4. *The bathtub curve showing variation of failure rate with operating hours.*

In the case of voltage, current, and other stresses including temperature, which differ from those under which λ_o is specified, *conversion* or *acceleration factors* are used to calculate the new failure rate.

Typical conversion factors are given in table 16.2 for ambient temperature T_a, and operating voltage V_{op}, in relation to rated voltage V_R. Alternatively conversion graphs are also used or the Arrhenius' law

$$\lambda = \lambda_o \left(\frac{V_{op}}{V_R}\right)^n e^{-E\left(\frac{1}{KT} - \frac{1}{KT_o}\right)} \qquad (16.13)$$

Table 16.2. Stress conversion factors for an aluminium electrolytic capacitor

$\frac{V_{op}}{V_R}$%	Conversion factor	Temperature T_a (°C)	Conversion factor
100	1	≤40	1
75	0.4	55	2
50	0.2	70	5
25	0.06	T_{jmax}	10
10	0.04		
(a)		(b)	

Example 16.1: ***Failure rate***

A component has a failure rate $\lambda_o = 2 \times 10^9$/h, commonly termed 2 fit (failures in time) using 10^9/h as reference.
With reference to table 16.2, what is the failure rate if

i. the ambient temperature, T_a, is increased to 55°C
ii. the operating voltage is halved
iii. i. and ii. occur simultaneously?

Solution

Assume λ_o applies to conditions at $T_a \le 40$°C and V_R.

i. If the ambient temperature is increased from 40°C to 55°C, then using a conversion factor of 2 from table 16.2b

$$\begin{aligned}\lambda_{55} &= 2\times\lambda_o\\ &= 4 \quad \text{fit}\end{aligned}$$

that is, the failure rate has doubled, from 2 fit to 4 fit.

ii. Similarly, by halving the operating voltage, a conversion factor of 0.2 is employed from table 16.2a. The new failure rate is

$$\begin{aligned}\lambda_{\frac{1}{2}V} &= 0.2\times\lambda_o\\ &= 0.4 \quad \text{fit}\end{aligned}$$

that is, the failure rate has decreased by a factor of 5, from 2 fit to 0.4 fit.

iii. If simultaneously both the ambient temperature is increased to 55°C and the operating voltage is halved, then

$$\begin{aligned}\lambda_{55\frac{1}{2}V} &= 2\times 0.2\times\lambda_o\\ &= 0.8 \quad \text{fit}\end{aligned}$$

The conversion factors are cumulative and the failure rate decreases from 2 fit to 0.8 failures in time.

♣

If the number of units surviving decreases exponential with time, then the probability of failure after a service time t is given by

$$F(t) = 1 - e^{-\lambda t} \qquad (16.14)$$

Equipment failure rate can be calculated by summing the failure rates of the individual components, that is

$$\lambda_{total} = \lambda_1 + \lambda_2 ..... + \lambda_n \qquad (16.15)$$

If the failure rate is to be constant, then the instantaneous failure rate of the number of faults per unit time divided by the number of non-failure components must yield a constant

$$\frac{1}{1-F(t)}\frac{dF(t)}{dt} = \lambda \qquad (16.16)$$

For n components in a system the probability of system survival is

$$\begin{aligned}1-F(t) &= (1-F_1(t))\times(1-F_2(t))\times....(1-F_n(t)) = e^{-\lambda_1 t}\times e^{-\lambda_2 t}\times.....e^{-\lambda_n t}\\ &= n\lambda\end{aligned} \qquad (16.17)$$

if, since the units are identical, $\lambda_1 = \lambda_2 = ... = \lambda_n$.
The *meantime between failure* (*mtbf*) is given by

$$mtbf = \frac{1}{\lambda_{total}} = \int_0^\infty 1-F(t)\,dt = \int_0^\infty e^{-\lambda t}\,dt = \frac{1}{\lambda} \qquad (16.18)$$

The service operating life τ for a specified probability of failure is therefore given by

$$\tau = \frac{1}{\lambda}\,\ell n\frac{1}{1-F} \qquad (16.19)$$

Example 16.2: ***Capacitor reliability***

A capacitor has a failure rate λ of 200 x 10^{-9} failure/hour, 200 fit. Calculate

i. the probability of the component being serviceable after one year
ii. the service life if the probability of failure is chosen to be 1% or 0.1%
iii. the mean time between failure
iv. the mean time between failure for 10 parallel connected capacitors
v. the probability of survival for 1 year and of failure for units, if 1000 units each have 10 parallel connected capacitors.

Solution

i. The probability of the capacitor being serviceable after 8760 h (1 yr) is given by

$$1-F(1yr)=e^{-\lambda t}$$

$$=e^{-200\times10^{9}\times8760}=0.998 \quad (99.8\%)$$

ii. Component lifetime is given by

$$\tau=\frac{1}{\lambda}\ell n\frac{1}{1-F}$$

$$\tau(1\%)=\frac{10^{9}}{200}\ell n\frac{1}{1-0.01}=50{,}000\text{ h}=5.7\text{ years}$$

$$\tau(0.1\%)=\frac{10^{9}}{200}\ell n\frac{1}{1-0.001}=5{,}000\text{ h}=0.57\text{ years}$$

iii. The mean time between failure, given by equation (16.18) is

$$mtbf = 1/\lambda=\frac{10^{9}}{200}=5\text{ x }10^{6}\text{ h}=570\text{ years}$$

iv. The failure rate for 10 capacitors is 10λ = 2000 fit and the mtbf is

$$\frac{1}{10\lambda}=\frac{10^{9}}{2000}=57\text{ years}$$

v. For 1000 units, each with a failure rate of 10λ, the probability of one unit surviving 1 year is

$$1 - F(1\text{ yr}) = e^{-10\text{ x }200\text{ x }10^{-9}\text{ x }8760}=98.2\text{ per cent}$$

The probable number of first year failures with 1000 units is

$$F(1\text{ yr}) = 1 - e^{-200\text{ x }10^{-9}\text{ x }8760}=0.002\text{ pu}=2\text{ units}$$

♣

The reliability concepts considered are applicable to all electronic components and have been used to illustrate capacitor reliability.

16.1.4 Self-healing

One failure mode of a capacitor is voltage breakdown in a defective area of the dielectric. As a result of the applied voltage, the defective area experiences an abnormally high electric field which may cause failure by arcing. Oxide capacitors using an electrolyte and plastic film dielectric capacitors exhibit self-healing properties, which in the case of plastic film dielectrics allow the capacitor to remain functional after voltage breakdown.

In the case of a defect in the dielectric oxide layer of an electrolytic capacitor, the maximum field strength is reached first in the defective region. This is effectively the process which occurs during the formation of the oxide layer, which results in the formation of new oxide, thereby repairing the defect. The reforming process is relatively slow compared with the healing time for non-polarised capacitors.
By contrast, the high electric field at the defect in a plastic film capacitor causes an arc which evaporates the metallisation in the breakdown region, thereby isolating the faulty dielectric within a few microseconds.

16.1.5 Temperature range

The operating temperature upper and lower limits are either dictated by expected service life or the allowable variation limits on the nominal capacitance. Most capacitors can be used outside their nominal temperature limits, but at reduced lifetime, hence with reduced reliability. The extremes -55°C to 125°C are common, but obviously electrolytic capacitors must be restricted to a smaller range if the electrolyte is not either to freeze or to boil.

16.2 Liquid and solid, metal oxide dielectric capacitors

The oxides of metals such as aluminium and tantalum are capable of blocking current flow in one direction and conducting in the other. Operation of metal oxide dielectric capacitors is based on the so-called *valve effect* of these two metals.

16.2.1 Construction

The capacitor dielectric layer consists of aluminium oxide Al_20_3 or tantalum oxide Tn_20_3 which is formed by an electrochemical oxidising process of aluminium foil or sintered tantalum powder. These starting metals form the capacitor anode. The oxide layer withstands high electric field strengths, typically 8 x 10^8 V/m for Al_20_3 which represents 1.25 nm per volt, and are excellent insulators (hence result in a high capacitor loss factor). This field strength is maintained during the oxidising process, so that the oxide thickness is dependent and practically proportional to the *forming voltage* V_F. To avoid changing the oxide thickness during normal use, the component *operated rated voltage* V_R should always be lower than the forming voltage, as shown in figure 16.5. The difference V_F - V_R is the *over-oxidisation voltage* and substantially determines the capacitor operational reliability. For general-purpose electrolytic capacitors, the value of V_R / V_F is about 0.8, while solid capacitors are rated at 0.25.

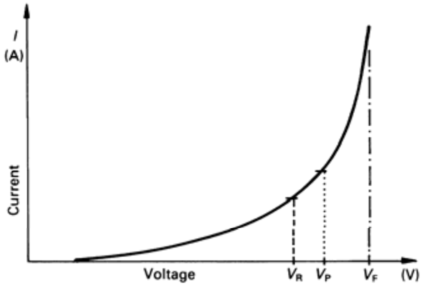


Figure 16.5. *Current dependence on voltage of Al electrolytic capacitors.*

The oxide dielectric constant ε_r is approximately 10 for Al_20_3 and 25 for Ta_20_3, while in comparison paper-based dielectrics have a value of approximately 5. An oxide thickness of W = 0.7 μm is sufficient for high voltage capacitors (≥ 160 V) as compared with minimum practical paper dielectric thickness of about 6 μm. The metal oxide type capacitors potentially offer high capacitance per unit volume. To further improve the capacitance per unit volume, before oxidation, the aluminium anode surface area is enlarged 10-300 times by electrochemical deep etching processes. In the case of tantalum capacitors, the sintered tantalum structure results in the same increase of area effect.

The capacitor is formed by the placement of the cathode on to the oxide layer. In the case of the electrolytic capacitor, a highly conductive organic acid electrolytic (based on dimethylacetamide) which is impregnated into porous paper forms the capacitor cathode. The electrolyte largely determines the ESR hence it must have a low resistivity over a wide temperature range. It must also have a breakdown voltage well above the capacitor rated voltage at maximum operating temperature. For long life, electrolytes with a water content must be avoided. Teflon spacers are sometimes used rather than paper. In the case of solid capacitors, a high conductive cathode is formed by a solid semiconductor metal oxide, such as manganese dioxide. The electrical contact to the cathode is a layer of etched aluminium, which has a thin oxide layer. In solid oxide capacitors, the manganese dioxide is dipped into graphite which is coated with silver epoxy for soldering.

The four possibilities are shown in figure 16.6. A porous paper or glass fibre is used as a space keeping agent in order to avoid short circuits and direct mechanical contact.

Long strips of the cross-sections are wound into cylindrical bodies and encased as shown in figure 16.6. Operation at high voltages causes oxide growth and the production of hydrogen. Any gas pressure relief valve should be orientated upwards.

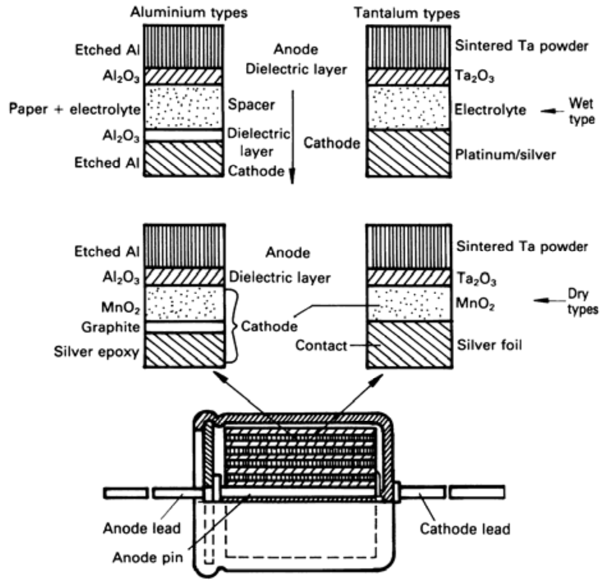


Figure 16.6. *Construction of metal oxide capacitors.*

16.2.2 Voltage ratings

Basic electrolyte (electrolytic) capacitors are suitable only for unipolar voltages, where the anode is positive with respect to the cathode. In the case of the aluminium electrolytic capacitor, the cathode connection metal does have a thin air-oxide layer which corresponds to an anodically generated layer with a blocking voltage capability of about 2 V. Above this voltage level, an electrolytic generated dielectric oxide film would be formed on the cathode foil. The effect is to decrease the capacitance and cause high internal heating and gas formation, which can lead to failure.

Solid, oxide capacitors are in principle capable of supporting bipolar voltage since the cathode is a semiconductor, manganese oxide. In practice, impurities such as moisture restrict the reverse voltage limits to 5-15 per cent of V_F. The usable reverse voltage decreases with increased ambient temperature.

The rated voltage V_R may be exceeded under specified intermittent conditions, resulting in a maximum or peak voltage limit V_P, as shown in figure 16.5, where

for $V_R \le 315V$ $\quad V_P = 1.15\ V_R$

for $V_R > 315V$ $\quad V_P = 1.1\ V_R$

Both V_R and V_P, are derated with increasing temperature.

16.2.3 Leakage current

When a dc voltage is applied to capacitors, a low current, $I_{\ell k}$ called the *leakage current,* flows through every capacitor, as implied by the presence of R_i in the equivalent circuit model in figure 16.2. With oxide dielectric capacitors, this current is high at first and decreases with working time to a final value, as shown in figure 16.7.

A low final leakage current is the criterion of a well designed dielectric, thus leakage current can be considered as a measure for the quality of the capacitor. The current is a result of the oxidising activity within the capacitor. The leakage current depends on both dc voltage and ambient temperature, as shown in figure 16.8. The purity of the anode metal, hence oxide dielectric determines the leakage current.

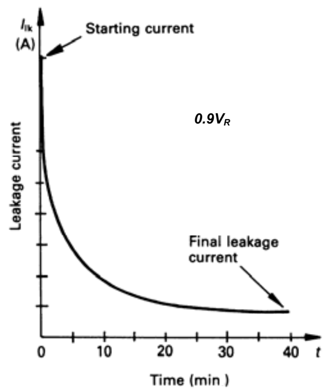


Figure 16.7. *Leakage current variation with working time for a liquid aluminium oxide capacitor.*

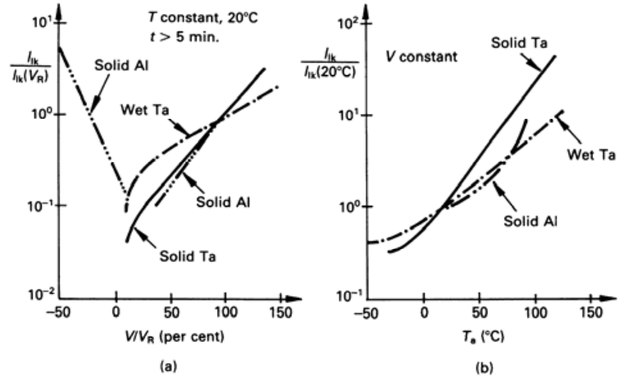


Figure 16.8. *Typical leakage current of oxide capacitors versus: (a) voltage and (b) temperature.*

Liquid, oxide capacitors have the lower leakage currents at rated voltage since when a voltage is applied; anions in the electrolyte maintain the dielectric electrochemical forming process. The $Mn0_2$ in solid oxide capacitors has lower reforming capabilities.

From figure 16.8 it will be seen that leakage increases with both temperature and voltage. The increase in leakage current with temperature is lower in liquid capacitors than in the solid because, once again, the electrolyte can provide anions for the dielectric reforming process.

For an aluminium electrolyte capacitor at 85°C, an expected lifetime of 2000 hours is achieved by selecting $V_R / V_F = 0.8$. However, V_F is inversely proportional to absolute temperature so for the same leakage current at 125°C, the ratio of V_R / V_F must be decreased to

$$\frac{V_R}{V_F} = 0.8 \times \frac{273 + 85}{273 + 125} = 0.7$$

For higher temperature operation, a higher forming voltage is required. But since $V_F \times C_R$ is constant for any dielectric/electrode combination, C_R is decreased.

When connecting electrolytic capacitors in series, parallel sharing resistors are necessary to compensate for leakage current variation between the capacitors. The design of the sharing network is as for the steady-state voltage sharing for semiconductors presented in 10.1.1. Additionally, the resistors provide a discharge path for the stored energy at power-off. When parallel connecting capacitors, highest reliability is gained if identically rated capacitors (voltage and capacitance) are used.

16.2.4 Ripple current

The maximum superimposed alternating current, or ripple current $\hat{I}_r$ is the maximum rms value of the alternating current with which a capacitor is loaded, which produces a temperature difference of 10 K between the core and ambient. Ripple current results in power being dissipated in the ESR, according to

$$P_d = \hat{I}_r^2 R_s \qquad \text{(W)} \qquad (16.20)$$

which results in an internal temperature rise until equilibrium with the ambient occurs.

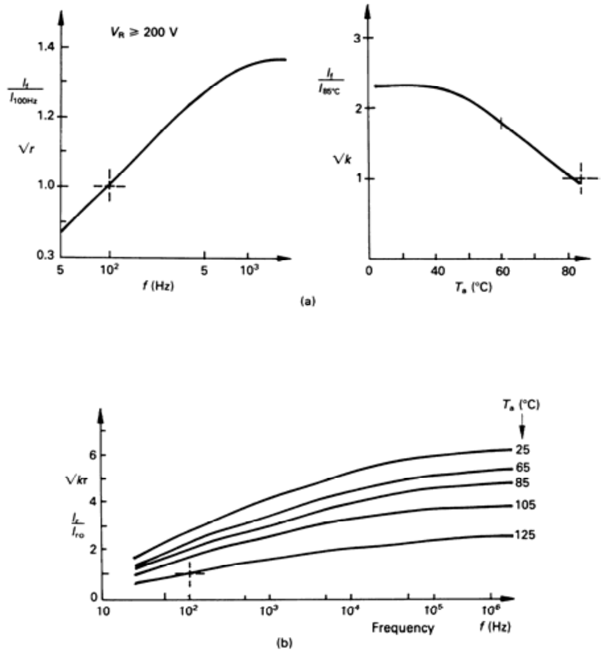


Figure 16.9. *Frequency and temperature ripple current conversion multipliers for: (a) liquid and (b) solid $A1_2 0_3$ capacitors.*

The maximum power dissipation $\hat{P}_d$ is dependent on the thermal dissipation properties of the capacitor, and from equation (5.4)

$$\hat{P}_d = h\,A\,\Delta T \qquad \text{(W)} \qquad (16.21)$$

where h = heat transfer coefficient (W/m^{2}K)
A = capacitor outer surface area (m^2)
ΔT = temperature difference between capacitor surface, T_s, and ambient, T_a (K)

Thus the maximum ripple current is given by

$$\hat{I}_r = \sqrt{\frac{\hat{P}_d}{R_s}} = \sqrt{\frac{hA\Delta\hat{T}}{R_s}} \qquad \text{(A)} \qquad (16.22)$$

The ESR, R_s, is both temperature and frequency dependent, hence rated ripple current I_{ro}, is specified at a given temperature and frequency, and at rated voltage V_R. Due to the square root in equation (16.22), conversion to other operating conditions is performed with the frequency multiplier $\sqrt{r}$ and temperature multiplier $\sqrt{k}$, such that

$$I_r = \sqrt{k}\,\sqrt{r}\,I_{ro} = \sqrt{k\,r}\;I_{ro} \qquad \text{(A)} \qquad (16.23)$$

Typical multiplier characteristics for aluminium oxide capacitors are shown in figure 16.9. It will be seen from figure 16.9a that electrolytic capacitors are rated at 85°C, while as seen in figure 16.9b solid types are characterised at 125°C. For each type, a reference frequency of 100 Hz is used. Electrolytic capacitors usually have a thermal time constant of minutes, which can be exploited to allow intermittent overloads.

Example 16.3: ***Capacitor ripple current rating***

A 1000 μF, 385 V liquid, aluminium oxide capacitor has an rms ripple current rating I_{ro} of 3.7 A at 100 Hz and 85°C.
Use figure 16.9a to calculate the allowable ripple current at

i. 60°C and 1 kHz
ii. lowest stress conditions.

Solution

i. Using equation (16.23)

$$I_r = \sqrt{k}\,\sqrt{r}\,I_{ro} = \sqrt{k\,r}\;I_{ro} \qquad \text{(A)}$$

where from figure 16.9a at 60°C, $\sqrt{k}$ = 1.85
at 1 kHz, $\sqrt{r}$ = 1.33

whence $\hat{I}_r$ = 1.33 × 1.85 × 3.7A
= 9.1 A

ii. This capacitor experiences lowest stressing at temperatures below 40°C, where $\sqrt{k}$ =2.25 and at frequencies in excess of 2 kHz when $\sqrt{r}$ = 1.37. Under these conditions the ripple current rating is

$$\hat{I}_r = 2.25 \times 1.37 \times 3.7\text{A}$$
$$= 11.4\text{A}$$

♣

Non-sinusoidal ripple currents have to be analysed such that the individual frequency components satisfy

$$\hat{I}_r^2 \geq \sum_n \frac{I_n^2}{r_n} \tag{16.24}$$

where $\hat{I}_r$ is for the appropriate rated ambient and reference frequency as indicated in figure 16.9.

Liquid tantalum capacitors have a ripple current rating which is determined by the physical dimensions, independent of temperature over a wide range, and independent of frequency above 50 Hz.

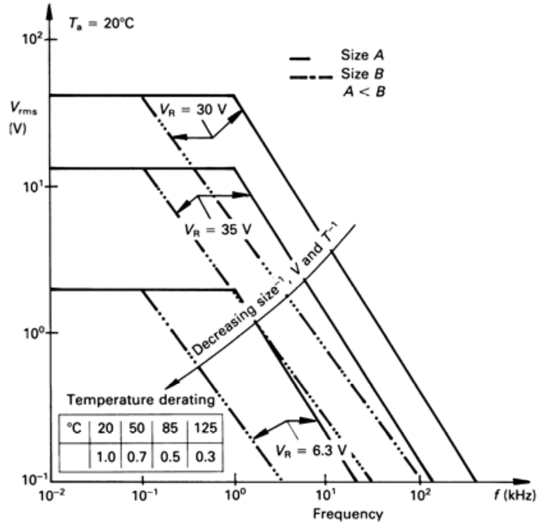


Figure 16.10. *Rms voltage limits of solid tantalum capacitors for different physical dimensions, temperature, voltage rating, and frequency.*

Ripple current ratings may not be specifically given for some capacitor types, for example solid tantalum capacitors. In this case an indirect approach is used. In satisfying ac voltage limitations as illustrated in figure 16.10, and any series resistance requirement, allowable ripple currents can be specified for a given temperature.

16.2.5 Service lifetime and reliability

16.2.5i - Liquid, oxide capacitors

As considered in 16.1.3, the reliability and lifetime of a capacitor can be significantly improved by decreasing the thermal and electrical stresses it experiences. Stress reduction is of extreme importance in the case of liquid aluminium oxide capacitors since it is probably the least reliable commonly used component.

The reliability and service lifetime of an aluminium oxide electrolytic capacitor are dominated by its ripple current, operating temperature, and operating voltage. Figure 16.11 in conjunction with figure 16.9a can be used to determine service life.

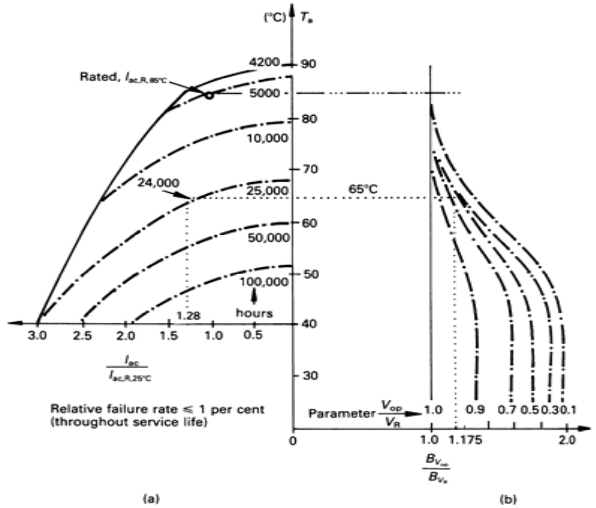


Figure 16.11. *Service life for an aluminium oxide liquid capacitor. Temperature dependence of lifetime variation with: (a) ripple current and (b) operating voltage.*

Example 16.4: Al_2O_3 *capacitor service life*

A 1000 μF, 385 V dc aluminium oxide liquid capacitor with a ripple current rating I_{ro} of 2.9 A at 100 Hz and 85°C ambient is used at 5 A, 4 kHz, in a 65°C ambient and on a 240 V dc rail. What is the expected service lifetime of the capacitor?

Solution

From figure 16.9a at 4 kHz, √r =1.35, whence

$$\frac{I_o}{I_{ro}} \times \frac{1}{\sqrt{r}} = \frac{5\text{A}}{2.9\text{A}} \times \frac{1}{1.35} = 1.28$$

From figure 16.11a, the coordinates 1.28 and 65°C correspond to a 24,000 hour lifetime with less than 1 per cent failures. Since a 385 V dc rated capacitor is used on a 240 V dc rail, that is, a ratio 0.64, an increase in service lifetime of 17½ per cent can be expected, according to figure 16.11b. That is, a service lifetime of 28,000 hours or greater than 3½ years is expected with a relative failure rate of less than 1 per cent.
Generally, between 40 and 85°C aluminium electrolytic capacitor lifetime doubles for every 10°C decrease in ambient temperature. A service lifetime of 7 years could be obtained by decreasing the ambient temperature from 65°C to 55°C.

♣

With aluminium electrolytic capacitors, degradation failures are mostly due to factors such as

- aggressiveness of the acidic electrolyte
- diffusion of the electrolyte
- material impurities.

16.2.5ii - Solid, oxide capacitors

The failure rate of solid aluminium and tantalum capacitors is determined by the occurrence of open and short circuits as a result of dielectric oxide layer breakdown or field crystallisation. In general, for a given oxide operating at rated conditions, liquid capacitors have a shorter lifetime than the corresponding solid type. Solid aluminium capacitors are more reliable than solid tantalum types and failure is usually the degradation of leakage current rather than a short circuit.
In comparison with liquid, electrolytic capacitors, solid types, and, in particular, tantalum type capacitors, have a number of desirable characteristics:

- higher capacitance per unit/volume due to the higher permittivity of Ta_2O_3 and the intrinsically high effective area per unit volume due to the sintered construction
- changes in parameters (*C*, tan *δ*) are less because the specific resistance of MnO_2 and hence temperature coefficient, is lower than that of liquid electrolytes
- electrolyte is stable, does not evaporate or corrode.

The failure rate of all capacitors can be improved by decreasing the stress factors such as temperature and operating voltage. But reliability of solid tantalum capacitors can be increased by placing a series resistor (low inductance) in the circuit. The improvement is illustrated by the following design example, which compares the lifetime of both liquid and solid tantalum capacitors based on the conversion curves in figure 16.12.

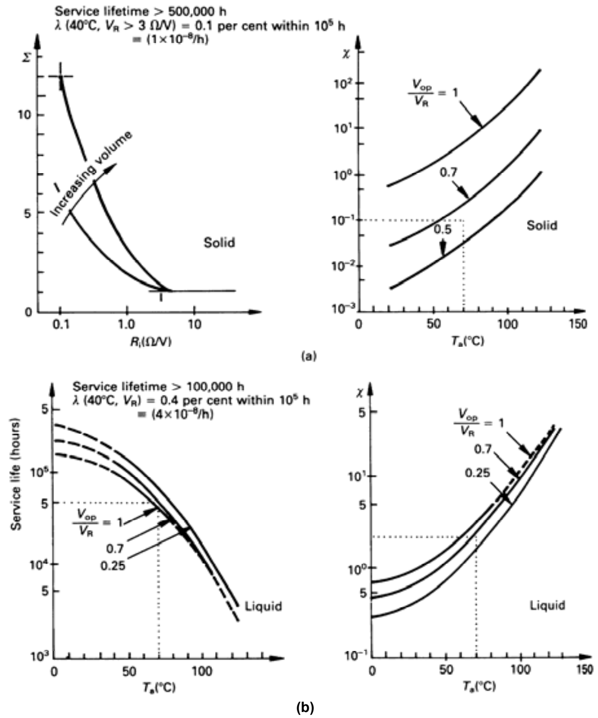


Figure 16.12. *Stress conversion factors for:*
(a) solid tantalum capacitors and (b) liquid tantalum capacitors.

Example 16.5: ***Lifetime of tantalum capacitors***

A 22 μF tantalum capacitor is required to operate under the following conditions:
ambient temperature T_a, 70°C
operating voltage V_{op}, 15 V
circuit resistance i. 1 Ω
ii. 100 Ω

Calculate the expected lifetime for solid and liquid tantalum capacitors.

Solution

Capacitor used C_R = 22 μF
V_R = 25 V
For each capacitor type (solid or liquid) the voltage stress factor is
$V_{op}/V_R = 0.60$
For the solid tantalum, the circuit resistance factor is given by
i. $R_i^{'} = 1\ \Omega/15\ \text{V} = 0.07\ \Omega/\text{V}$ which is < 0.1 Ω/V
ii. $R_i^{'} = 100\ \Omega/15\ \text{V} = 6.6\ \Omega/\text{V}$ which is > 3 Ω/V
Based on figure 16.12, the capacitor lifetime calculation is summarised below.

		Liquid tantalum	*Solid tantalum*	
R	Ω	1 and 100	1	100
R_i	Ω	n/a	0.1	3
Σ R_i		(1)	12	1
X at V_{op}/V_R=0.6 and 70°C		2.2	0.10	0.10
λ_o	/h	4×10^{-8}	1×10^{-8}	1×10^{-8}
λ $= \lambda_o\times\Sigma$	/h	$2.2\times4\times10^{-8}$ 8.8×10^{-8}	$12\times0.1\times10^{-8}$ 1.2×10^{-8}	$1\times0.1\times10^{-8}$ 0.1×10^{-8}
fit		88	12	1
τ (% failures) within $\lambda\Delta t$	h	45,000 (0.4%)	83,000 (0.1%)	100,000 (0.1%)

♣

16.3 Plastic film dielectric capacitors

Plastic (polymer) dielectric type capacitors are non-polarised capacitors and in general offer high *dv/dt* and pulse rating capability compared with oxide type capacitors.
The most common dielectric plastics used are:
polye***t***hylene-terephthalate (polyester or PEPT) T
poly***c***arbonate C

poly***p***ropylene P
poly***s***tyrene S
polyphenylene sulph***i***de I

The letter shown after each type is the symbol generally used to designate the film type. The symbol K is used to designate plastic, which is *Kunststoff* in German.
Two basic types of plastic film dielectric capacitors are common. The first type involves *metallisation* deposited on to the plastic and the metal forms the electrodes. Typically such a capacitor would be termed MKP, that is metallised - M, plastic - K, polypropylene - P. A foil capacitor, the second type, results when metal foil is used for the electrode. Typically such a capacitor would be termed KS, that is plastic - K, polystyrene - S. The plastic type is generally designated by the fifth letter of the plastic name, that is the letter after poly, with two exceptions.

16.3.1 Construction

16.3.1i - *Metallised plastic film dielectric capacitors*

The dielectric of these capacitors consists of plastic film on to which metal layers of approximately 0.02-0.1 μm are vacuum deposited. A margin of non-coated film is left as shown in figure 16.13a. The metallised films are either wound in a rolled cylinder or flattened to form a stacked block construction. In this construction, the metallised films are displaced so that one extends out at one end of the roll and the next layer extends out the other end as shown in figure 16.13a. This displaced layer construction is termed *extended metallisation* and facilitates electrical contact with the electrodes. A hot metal spray technique, called s*chooping,* is used for making electrical contact to the extended edges of the metallised plastic winding. This large disk area contact method ensures good ohmic contact, hence low loss and low impedance capacitor characteristics result.
The most common metallised plastic film capacitors are those employing polyester, MKT and polypropylene, MKP.
Polyester has a higher dielectric constant than polypropylene, and because of its stronger physical characteristics it is available in thinner gauges than is polypropylene. Very high capacitance values result in the smallest possible space. But polypropylene has a higher dielectric strength and lower dielectric losses, hence is favoured at higher ac voltages.

16.3.1ii - *Foil and plastic film capacitors*

Foil capacitors normally use a plastic film dielectric which is a flexible bi-axially aligned electro-insulator, such as polyester. Aluminium foils and/or tin foils are used as the electrodes. The thin strips are wound to form the capacitor as shown in figure 16.13b. An *extended foil* technique similar to the extended metallisation method is used to enable contact to be made to the extended foil electrodes.

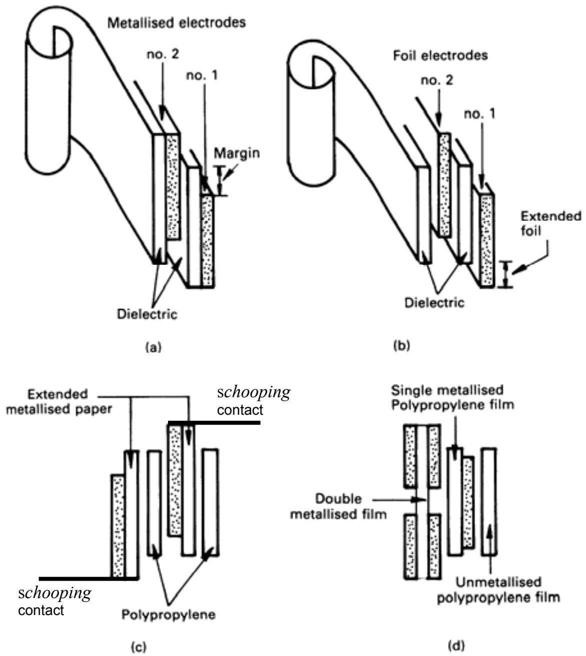


Figure 16.13. *Plastic capacitor constructions: (a) extended single metallisation; (b) extended foil; (c) mixed dielectric; and (d) mixed dielectric, double metallisation.*

***16.3.1iii** - Mixed dielectric capacitors*

To further improve the electrical stress capabilities of a capacitor, combinations of different dielectrics are commonly used. Such capacitors use combinations of metallised plastics, metallised paper, discrete foils and dielectrics, and oil impregnation.

Figure 16.13c shows the layers of a mixed dielectric paper and polypropylene capacitor. A thin gauge of polypropylene dielectric is combined with textured

metallised paper electrodes. The coarse porous nature of the paper allows for improved fluid impregnation of the dielectric material, which counters the occurrence of gas air bubbles in the dielectric. This construction has the electrical advantages of high dielectric strength, low losses, and a self-healing mechanism, all at high voltages.

Two plastic dielectrics can be combined, as shown in figure 16.13d, to form a *mixed layer* capacitor. It involves a double metallised polyethyleneterephthalate film and polypropylene films. These dielectric combinations give low inductance, high dielectric strength, and low losses with high ac voltage capability.

16.3.2 Insulation

The insulation characteristics of a capacitor are indicated either as a resistance value R_i as shown in Figure 16.2 or as a time constant, $\tau = R_i\, C_R$. The resistance comprises the insulation resistance of the dielectric (layer to layer) and the insulation resistance between layer and case. This later resistance is determined by the quality of the case insulating material and by the length of the surface leakage paths.

Both the time constant and resistance are dependent on voltage and temperature, as is shown in figure 16.14. These characteristics illustrate that extremely high insulation resistance values can be obtained.

16.3.3 Electrical characteristics

***16.3.3i** - Temperature dependence*

The capacitance of plastic film capacitors changes with both temperature and frequency, as shown in figure 16.15. The dependence is strongly dependent on the dielectric film although some foil types are virtually independent of frequency. Table 16.3 summarises capacitance temperature dependence for a wide range of dielectrics. The temperature coefficient is measured in parts per million per degree Kelvin, ppm/K. The temperature dependence of dissipation factor is shown in figure 16.21a.

***16.3.3ii** - Dissipation factor and impedance*

Figure 16.16a shows the typical frequency dependent characteristics of the dissipation factor for a range of plastic dielectric capacitor types. It is important to note that polyester types have 50-100 times the losses of polypropylene capacitors. A low loss characteristic is important in power pulse applications where capacitor package heat dissipation may be a limiting factor.

Generally, tan δ rises with increased frequency and increased capacitance. Tan δ is dominated by dielectric losses and the contact resistance of the leads. The extended foil/metallisation and schooping contact methods provide not only a low and constant ohmic contact, but because of the large contact area, result in a low self-inductance. The resonant frequency of such capacitors, because of their self-inductance and their capacitance, is high as shown by the minimum impedance in figure 16.16b. Minimum impedance decreases with increased capacitance and each capacitor in the range, here 1.5 nF to 4.7 μF, has its own Y-shaped impedance curve. The self-resonant frequency decreases with increased capacitance. In figure 16.16b, the full impedance curves for maximum and minimum capacitance only have been shown.

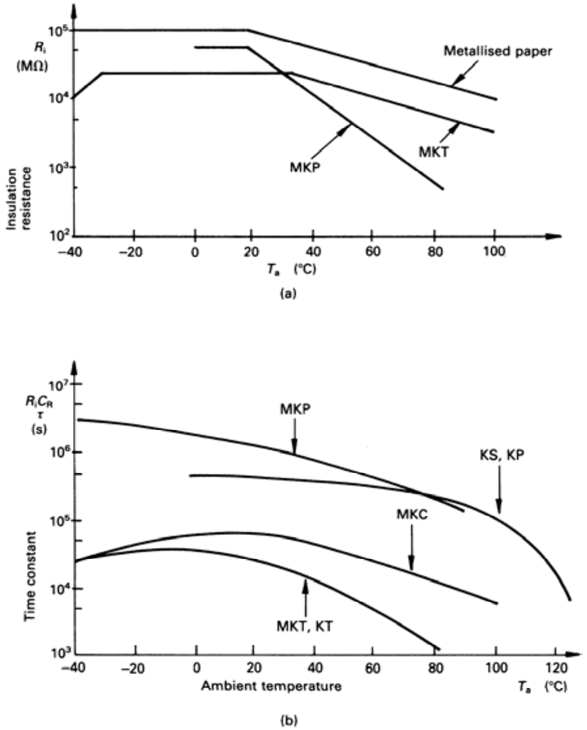


Figure 16.14. *Plastic dielectric insulation resistance temperature dependence characteristics:(a) resistance R_i and (b) time constant τ.*

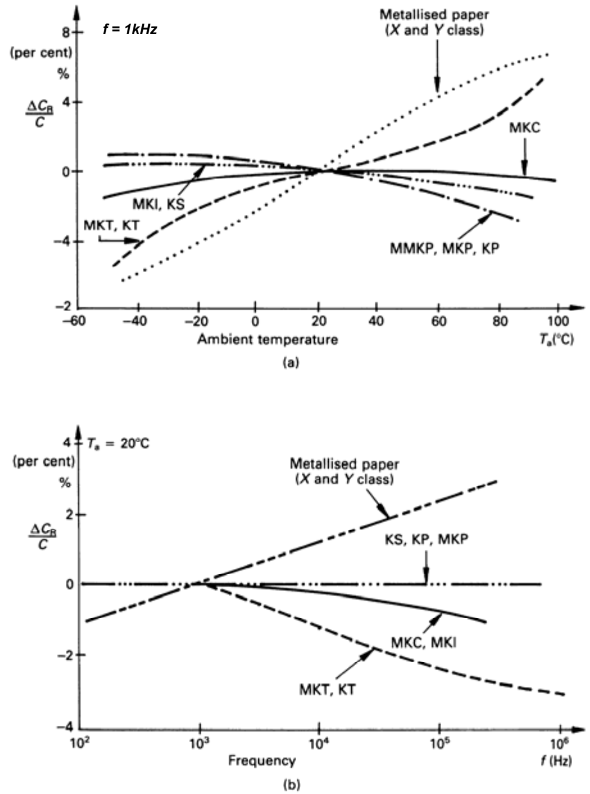


Figure 16.15. *Plastic film dielectric capacitance variation with: (a) ambient temperature and (b) frequency.*

Table 16.3. Capacitor temperature coefficient for various dielectric materials

Dielectric type	*Temperature coefficient (ppm/K)*		
	metallised	*other*	*film/foil*
Polypropylene	-170		-120
Polyester	400		400 (non-linear)
Polycarbonate	150		-50 to -150
Polystyrene			-125
Paper	300		300
Mica		100	
Ceramic		+ 1000 to -1000	(non-linear)
Aluminium		1500	
Tantalum (solid and liquid)		+200 to +1000	

16.3.3iii - *Voltage derating*

The ac and dc voltages which may be applied continuously to a capacitor vary with ambient temperature and also frequency in the case of ac voltage rating. Typical characteristics showing frequency and temperature dependence are shown in figure 16.17 for plastic dielectric capacitor types. It will be seen that the ac voltage rating is significantly less than the dc voltage rating, while both voltage ratings are derated above 85°C and at higher frequencies. In all situations, the sum of the dc voltage and peak value of superimposed ac voltage must not exceed the rated dc voltage.

An alternative approach for calculating the maximum ac voltage, allowable V_{ac}, for a capacitor is based on the power dissipation limits, *P*, of the package.

If we neglect R_i and ESL in the capacitor equivalent circuit shown in figure 16.2, then

$$P = \frac{V_{R_s}^2}{R_s} = I^2 R_s \qquad \text{(W)} \qquad (16.25)$$

and

$$V_{R_s}^2 = \frac{R_s^2}{R_s^2 + \dfrac{1}{\omega^2 C_R^2}} V_{ac}^2 \qquad (16.26)$$

Since from equation (16.10) for plastic dielectric capacitors

$$\tan\delta = \omega C_R R_s$$

then equation (16.25) can be written as

$$P = \left(R_s C_R\right) \omega^2 C_R V_{ac}^2 \qquad \text{(W)} \qquad (16.27)$$

or alternatively

$$P = \tan\delta \;\; \omega C_R V_{ac}^2 \qquad \text{(W)} \qquad (16.28)$$

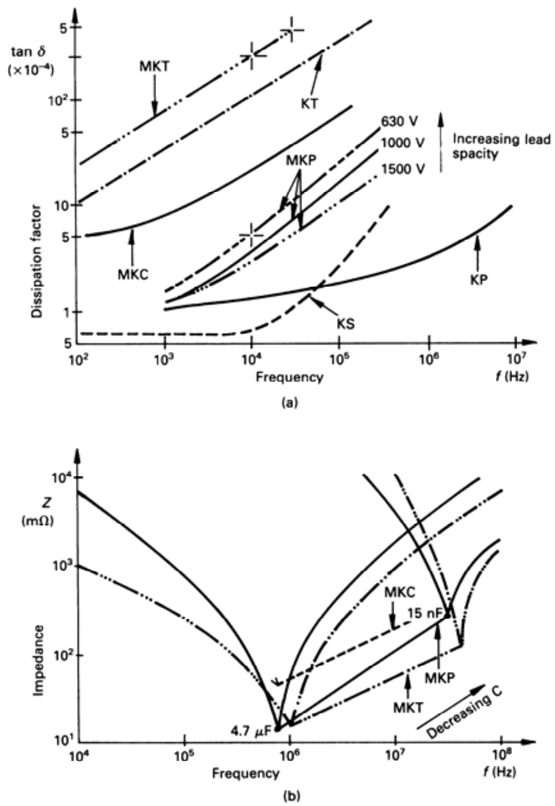


Figure 16.16. *Frequency characteristics for plastic dielectric capacitors: (a) maximum dissipation factor, tan δ and (b) typical impedance characteristics, Z, for metallised plastic dielectric capacitors.*

The value of tan δ for equation (16.28) is available from figure 16.16a or, alternatively, the value of R_sC_R for equation (16.27) is available from figure 16.18.
The maximum permissible power dissipation, $\widehat{P}$ which depends on the package dimensions and ambient temperature, is given in figure 16.19. Thus when the power dissipation, for a given ac voltage, has been calculated, figure 16.19 can be used to specify the minimum size (dimensions) capacitor capable of dissipating that power.
The following example illustrates the design approach outlined.

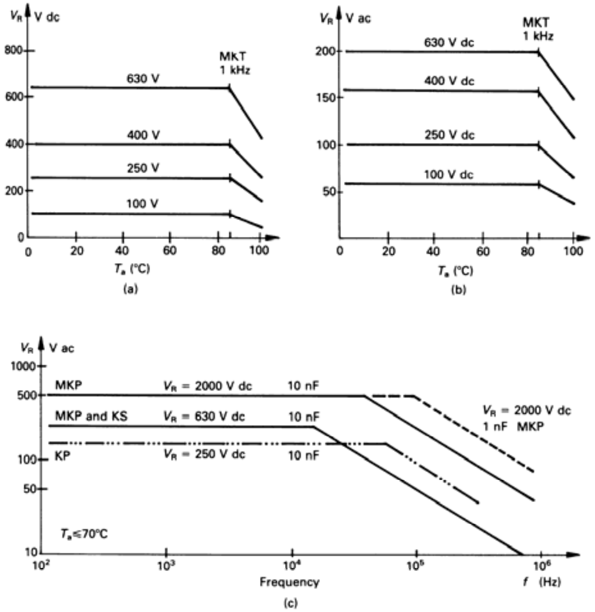


Figure 16.17. *Plastic dielectric capacitor, voltage derating characteristics: (a) dc voltage derating with ambient temperature; (b) ac voltage derating with temperature; and (c) ac voltage derating with frequency.*

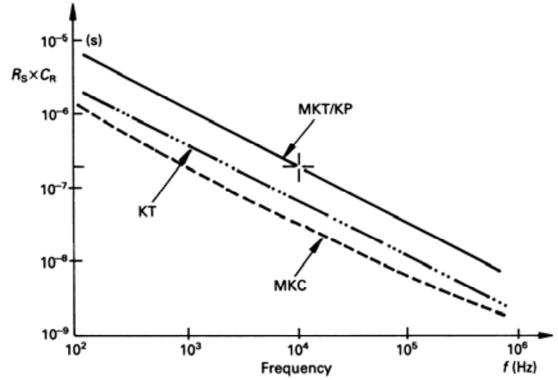


Figure 16.18. *Maximum product of series resistance, R_s, and rated capacitance, C_R, as a function of frequency.*

Example 16.6: ***Power dissipation limits - ac voltage***

A 0.1 μF plastic capacitor is used in a 100 V ac, 10 kHz and 50°C ambient application. Select suitable metallised polypropylene and polyester capacitors for this application.

Solution

i. Metallised polyester capacitor (MKT)
From equation (16.27)

$$P = (R_sC_R)\,\omega^2 C_R V_{ac}^2 \qquad \text{(W)}$$

From figure 16.18, $R_sC_R = 2 \times 10^{-7}$ at 10 kHz. Thus

$$P = (2\times10^{-7}) \times (2\pi\times10^{4})^2 \times (0.1\times10^{-6}) \times (100)^2$$
$$= 780 \text{ mW}$$

From figure 16.19, at 50°C a MKT capacitor of dimensions 11×20×31 (mm) can dissipate 930 mW. The applicable capacitor must have an ac voltage rating in excess of 100 V ac. From figure 16.17b, it can be seen that a 0.1 μF, 400 V dc MKT capacitor is necessary, given that the dimension constraints are met.

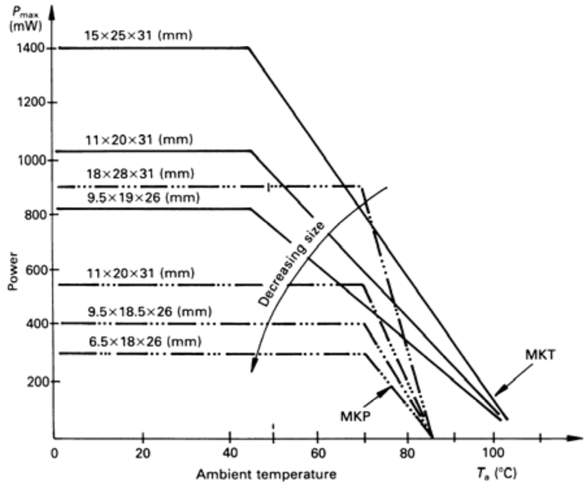


Figure 16.19. *Maximum power dissipation for metallised plastic capacitors as a function of ambient temperature and capacitor dimensions.*

ii. Metallised polypropylene capacitor (MKP)

From equation (16.28)

$$P = \tan\delta \;\; \omega C_R V_{ac}^2 \qquad \text{(W)}$$

From figure 16.16a, tan $\delta = 4.0 \times 10^{-4}$ at 10 kHz, for a 600 V dc type. Thus

$$P = (4.0\times10^{-4}) \times (2\pi\times10^{4}) \times (0.1\times10^{-6}) \times 100^2$$

$$= 25.6 \text{ mW}$$

From figure 16.19, at 50°C, the smallest volume MKP capacitor, of dimensions 6.5×15×26 mm, can dissipate 300 mW. From figure 16.17c it can be seen that a 0.1 µF, 630 V dc (250 V ac) MKP capacitor is necessary.

From figure 16.17c it can be seen that a 250 V dc 0.1 µF polypropylene foil capacitor (KS) is capable of 160 V ac at 10 kHz. Figure 16.16a shows the dissipation factor of KP type capacitors to be under half that of the metallised equivalent. That is, the expected losses are only

$$P = (1.4\times10^{-4}) \times (2\pi\times10^{4}) \times (0.1\times10^{-6}) \times 100^2$$

$$= 9 \text{ mW}$$

♣

16.3.3iv - Pulse dV_R/dt rating

Related to the ac voltage rating and power handling capabilities of a capacitor is the rated pulse slope dV_R/dt, which from $i = C_R\, dv/dt$ is specified by

$$R = \frac{V_R}{C_R\, dV/dt_{max}} = \frac{V_R}{\hat{I}} \tag{16.29}$$

where R is the minimum series resistance including the ESR. Generally for a given C_R, *dv/dt* capability increases with rated voltage V_R, and decreases as the distance between the metallised electrode contacts increases. If the capacitor operating voltage V_{op} is decreased below V_R, at which voltage, *dv/dt* capability is specified, *dv/dt* capability increases according to

$$\frac{dV_{op}}{dt} = \frac{dV_R}{dt} \times \frac{V_R}{V_{op}} \qquad \text{(V/s)} \tag{16.30}$$

The *dv/dt* capability depends on both the dielectric type and layer construction. Generally polystyrene (KS) and polyester (KT) foil type capacitors are not applicable to high *dv/dt* applications. Metallised polycarbonate capacitors offer slightly better *dv/dt* properties than those of metallised polyester. Metallised paper capacitors can withstand very high levels of *dv/dt,* 30-50 times higher than those for metallised polyester. Capacitors using polypropylene, or even better a mixed dielectric involving polypropylene, offer extremely high *dv/dt* capability. With the construction shown in figure 16.13d, a 1 µF metallised polypropylene capacitor with V_R of 2000 V dc and 1000 V ac, a 2500 V/µs capability is attainable. Practically the *dv/dt* limit may be restricted by the external connections. Such ratings are obtainable with polypropylene because of its extremely low losses, tan δ, as indicated in figure 16.16a. Under such high *dv/dt* stresses, it is important to ensure that the power dissipated does not exceed the package limit.

16.3.4 Non-sinusoidal repetitive voltages

Capacitors used for repetitive transient suppression, and for turn-off snubbers on GTO thyristors and diodes, experience high-magnitude short-duration voltage and current pulses which are not sinusoidal. High *dv/dt* capacitors based on metallised polypropylene are used, which are limited by their internal power losses, hence temperature rise and package power dissipation limit.

A restrictive graphical design approach for capacitor selection with sinusoidal, sawtooth, and trapezoidal pulse trains is shown in figure 16.20. The design approach is illustrated by the following example.

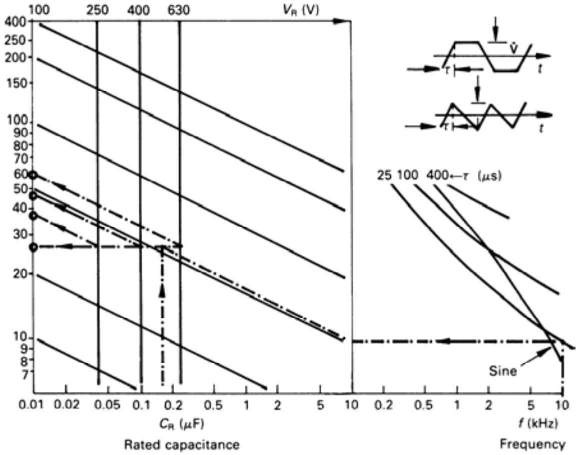


Figure 16.20. *Metallised polyester capacitor selection graph for sinusoidal and non-sinusoidal voltages.*

Example 16.7: ***Capacitor non-sinusoidal voltage rating***

A 0.15 µF MKT capacitor is used to generate a 10 kHz maximum and 25 µs risetime minimum, sawtooth ac voltage waveform. What voltage rated capacitor is applicable if the output voltage maximum is 100 V p-p?

Solution

Worst-case conditions are at maximum frequency, 10 kHz, and minimum risetime, 25 µs.
With reference to figure 16.20, use

f = 10 kHz (repetition frequency)
τ = 25 µs (risetime)
C = 0.15 µF (capacitance)

According to the dashed line in figure 16.20, starting from f = 10 kHz, yields

V_R = 100 V dc gives maximum peak voltage of 27 V
V_R = 250 V dc gives maximum peak voltage of 38 V
V_R = 400 V dc gives maximum peak voltage of 47 V
V_R = 630 V dc gives maximum peak voltage of 59 V

The peak to peak requirement is 100 V, hence only a 630 V dc 0.1 µF MKT capacitor can fulfil the specification.

♣

An alternative approach to specify the voltage limits for non-sinusoidal repetitive voltages is to sum the power contribution due to each voltage harmonic. The total power due to all harmonics must not exceed the capacitor package power limits.
The non-sinusoidal voltage v can be expressed in the form

$$v = \sum_{\forall i} V_i \sin\left(i\omega t + \phi_i\right) \qquad (16.31)$$

where V_i is the magnitude of the *ith* voltage harmonic, which has an rms value of

$$v_i = \frac{V_i}{\sqrt{2}}$$

From equations (16.10) and (16.27), assuming capacitance is frequency independent

$$P_i = \left(R_s C_R\right)_i \omega_i^2 C_{R_i} v_i^2 \qquad (16.32)$$

or

$$P_i = \tan\delta_i \; \omega_i C_{R_i} v_i^2 \qquad (16.33)$$

The total power dissipated is the sum of the powers associated with each frequency. The near-linear frequency dependence of tan δ and $R_S C_R$, as shown in figures 16.16a and 16.18, may be utilised to simplify the calculation procedure. Assuming the rated capacitance is independent of frequency may be a valid and helpful simplification, while the temperature dependence of C_R initially could be accounted for by using a value at 10 K above ambient.

Example 16.8: ***Capacitor power rating for non-sinusoidal voltages***

The applied voltage across a 1 µF MKP capacitor, at 40°C ambient is √2 100 sin(2π × $10^4 t$) + √2 Y sin(2π× 3 x $10^4 t$)
What is the maximum allowable voltage *Y?*

Solution

From equation (16.33), the total power is given by

$$P_i = \tan\delta_1 \; \omega_1 C_{R_1} v_1^2 + \tan\delta_3 \; \omega_3 C_{R_3} v_3^2$$

From figure 16.15b we may assume that capacitance is independent of frequency for polypropylene types. From figure 16.15a, at 50°C, rated capacitance has reduced by only 1 per cent - thus temperature effects on C_R may be neglected.
From figure 16.16, for a 600 V MKT capacitor

tan δ_1 at 10 kHz (ω_1) = 2.5 × 10^{-4}
tan δ_3 at 30 kHz (ω_3) = 4.2 × 10^{-4}

From figure 16.19b it can be seen that 880 mW can be dissipated in the largest package at 50°C. Total power is given by

$$0.88\text{W} = 2.5\times10^{-4} \times 2\pi\times10^{4} \times 1\times10^{-6} \times 100^{2} + 4.2\times10^{-4} \times 6\pi\times10^{4} \times 1\times10^{-6} \times Y^{2} \quad (\text{W})$$

Solving for Y, Y = 30.2 V rms.

♣

The key properties of plastic type non-polarised capacitors are summarised in table 16.4. The excellent dielectric properties of the polypropylene lead to metallised polypropylene capacitors being extensively used in power applications.

Table 16.4. Properties of non-polarised plastic type capacitors

dielectric type	ε_r	$\tan\delta$	λ_o	*dv/dt*	self-healing
polypropylene	low	low	good	high	good
polyester	medium	high	poor	medium	good
polystyrene	low	low	good	high	poor
polycarbonate	low	medium	good	medium	good
mixed dielectric	medium	medium	good	medium	good
paper	high	high	very good	high	very good

16.4 Emi suppression capacitors

Non-polarised capacitors are used in rfi filters for electrical appliances and equipment, as was introduced in 10.2.4. The capacitors used between line and neutral are termed class X while those used to earth are termed class Y.

16.4.1 Class X *capacitors*

X capacitors are suitable for use in situations where failure of the capacitor would not lead to danger of electric shock. X capacitors are divided into two subclasses according to the ac power line voltage applied.

- The Xl subclass must support a peak voltage in excess of 1.2 kV in service, while
- X2 capacitors have peak service voltage capabilities of less than 1.2 kV.

In order to obtain the peak voltage requirement of Xl capacitors, a construction comprising impregnated paper dielectric and metal foil electrodes is essential. The common capacitance range is 10 nF to 0.2 µF.

The lower peak voltage requirement of X2 capacitors allows the use of a metallised plastic dielectric, of which polyester and polypropylene are common. Impregnated paper dielectrics may also be employed. Advantageously, metallised plastic film suppression capacitors yield high *dv/dt* capability with low associated losses, tan δ, as

shown in figure 16.16a. These films also offer good insulation properties as shown in figure 16.14. Variation of capacitance with frequency and temperature is shown in figure 16.15, while percentage variation of losses, tan δ, with frequency and temperature is shown in figure 16.21. The typical capacitance range of X2 capacitors is from 10 nF to l µF, rated for 250 V ac application.

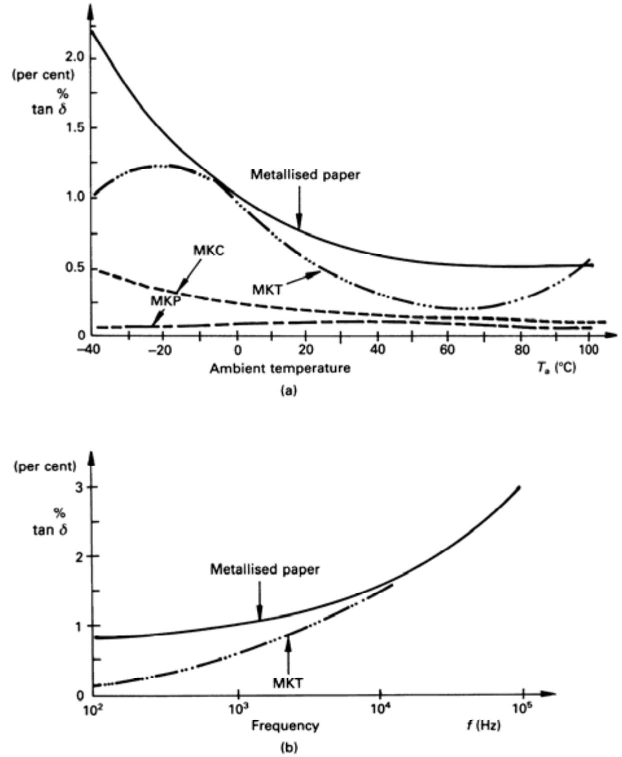


Figure 16.21. *RFI capacitance variation with: (a) ambient free-air temperature and (b) frequency.*

16.4.2 Class Y capacitors

Class Y capacitors are suitable for use in situations where failure of the capacitor could lead to danger of electric shock. These capacitors have high electrical and mechanical safety margins so as to increase reliability and prevent short circuit. They are limited in capacitance so as to restrict any ac current flowing through the capacitor, hence decreasing the stored energy to a non-dangerous level.

An impregnated paper dielectric with metal foil electrodes is a common construction and values between 2.5 nF and 35 nF are extensively used. Capacitance as low as 0.5 nF is not uncommon.

A Y-class capacitor for 250 V ac application can typically withstand over 2500 V dc for 2s, layer to layer. On an ac supply, 425 V ac ($\sqrt{3}\, V_R$) for 1000 hours is a common continuous ac voltage test.

If *dv/dt* capability is required, polypropylene film dielectric Y-class capacitors are available, but offer lower withstand voltage capability than paper types. Generally paper dielectric capacitors offer superior insulation resistance properties, as shown in figure 16.14a.

Metallised paper capacitors are also preferred to metallised plastic types because they have better self-healing characteristics. Breakdown in metallised plastic film dielectrics causes a reduction of the insulation resistance because of a higher carbon deposit in the breakdown channel than results with paper dielectrics.

16.4.3 Feed-through capacitors

Feed-through or four-terminal capacitors are capacitors in which the operating current flows through or across the electrodes. High frequency rfi is attenuated by the capacitors and the main power is transmitted unaffected. That is they suppress emi penetration into or from shielded equipment via the signal or power path.

Figures 16.22a and b show three terminal feed-through capacitors while figure 16.22c is a four-terminal capacitor. A three-terminal coaxial feed-through, wound capacitor cross-section is shown in figure 16.22d. The feed-through rod is the central current-carrying conductor: the outer case performs the function of an electrode plate and connector to produce an RF seal between the capacitor case and shielding wall.

These capacitors are effective from audio frequencies up to and above the SW and VHF band (>300 MHz). Current ratings from signal levels to 1600 A dc, 1200 A ac are available, in classes Xl and X2, rated at 240 V ac, 440 V ac and 600 V dc. Class Y feed-through capacitors rated at 25 A and 440 V ac, 600 V dc are available.

Important note: *This section on emi-suppression capacitors does not imply those requirements necessary to conform with governmental safety and design standards.*

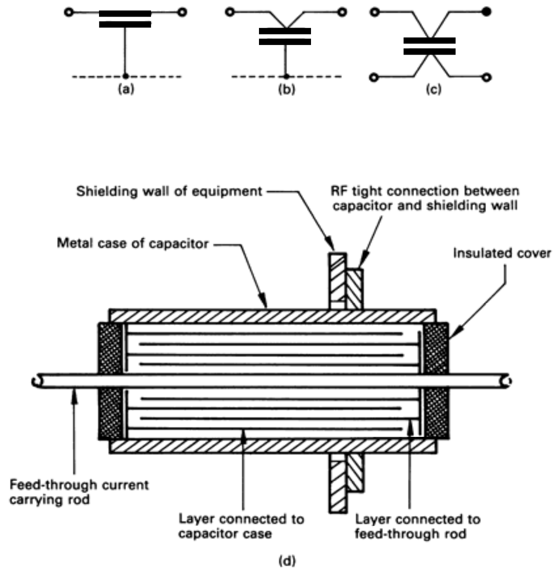


Figure 16.22. *Feed-through capacitors for RFI attenuation: (a), (b) three user terminals; (c) four terminals; and (d) coaxial feed-through capacitor construction.*

16.5 Ceramic dielectric capacitors

Ceramic capacitors as a group have in common an oxide ceramic dielectric. The dielectric is an inorganic, non-metal polycrystalline structure formed into a solid body by high temperature sintering at 1000 to 1300°C. The resultant crystals are usually between 1 and 100 μm in diameter.

The basic oxide material for ceramic capacitors is titanium dioxide ($Ti0_2$) which has a relative permittivity of about 100. This oxide together with barium oxide ($Ba0_2$) forms barium titanate ($BaTi0_3$) which is a ferro-electric material with a high permittivity, typically 10^4. Alternatively strontium titanate may be utilised. These same materials are used to make positive temperature coefficient resistors - thermistors, where dopants are added to allow conduction.

Table 16.5. Ceramic dielectric capacitor characteristics

Dielectric class			*I* (ε_r < 500) *Low K*	*II* (ε_r > 500) *Moderately high K*		*High K*
EIA designation* IEC/CECC designation			COG CG	X7R 2C1		Z5U 2F4
Temperature range		°C	-55 to 125	-55 to 125		+ 10 to 85
Dielectric constant	ε_r		13 - 470	700	to	50,000
Temperature coefficient of C_R (typical)			(N150) -150 ± 60 ppm	(X7R) ±15%		(Z5U) +22% / -56%
Dissipation factor	tan δ		0.15% @ 1 MHz	2.5%		3%
C		nF	< 0.2	< 4.7		< 40
V_R		V	500-1k	100 to >2k		

* In EIA designation, first letter and number indicate temperature range while last letter indicates capacitance change.

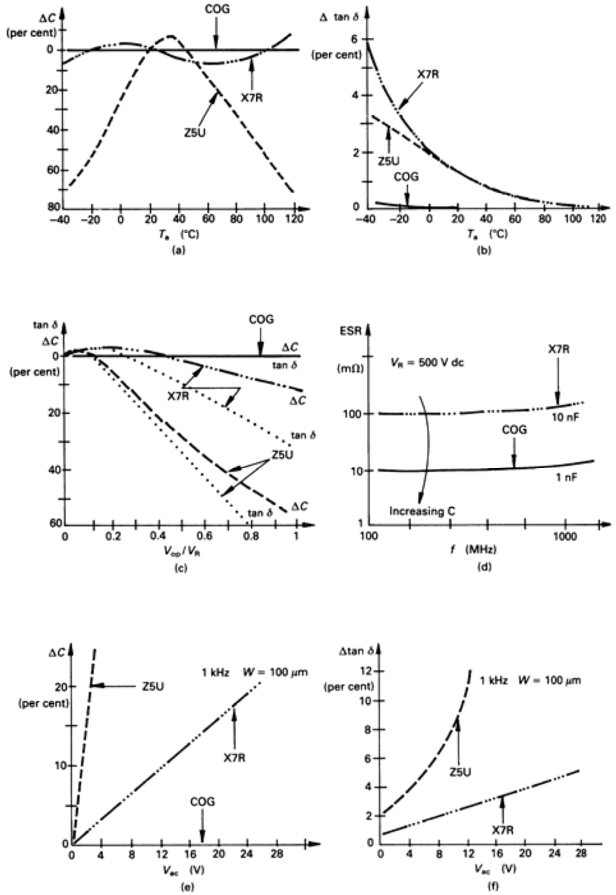
Metal plates of silver or nickel (with minimal palladium and platinum) are used to form the capacitor. Single plate, or a disc construction, is common as is a multi-layer monolithic type construction.
The ceramic dielectric is split into two classes, as shown in table 16.5.

16.5.1 *Class I dielectrics*

This class of dielectric consists mainly of $Ti0_2$ and additions of Ba0, La_20_3 or Nd_20_5, which provides a virtually linear, approximately constant and low temperature coefficient as shown in figure 16.23a.
COG capacitors belong to the class 1 dielectrics and have a low temperature coefficient over a wide temperature range, as seen in table 16.5. They provide stability and minimum dissipation properties. In attaining these properties, a low dielectric constant results and these capacitors are termed *low K*. Because of the low dielectric constant, capacitance is limited.

16.5.2 *Class II dielectrics*

Ceramic capacitors in this class are usually based on a high permittivity ferroelectric dielectric, $BaTi0_3$, hence termed *hi K*. Large capacitance in a small volume can be attained, but only by sacrificing the temperature, frequency, and voltage properties, all of which are non-linear. Typical characteristics are shown in figure 16.23. Their characteristics are less stable, non-linear, and have higher losses than class I ceramic, as seen in table 16.5. Also see table 16.6.



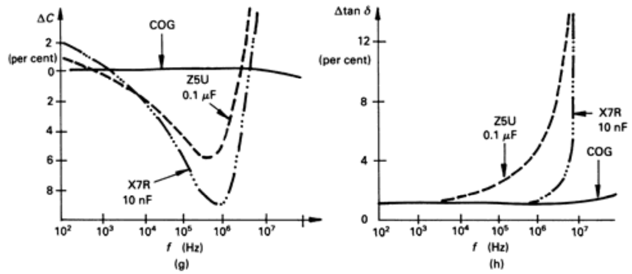


Figure 16.23. *Typical properties of commercial ceramic capacitors: (a) capacitance change with temperature; (b) dissipation variation with temperature; (c) capacitance change with dc voltage; (d) ESR change with frequency; (e) capacitance change with ac voltage; (f) dissipation factor variation with ac voltage; (g) capacitance change with frequency; and (h) dissipation factor variation with frequency.*

Table 16.6. Characteristics of class I and II type dielectrics

Class I	*Class II*
Almost linear capacitance/temperature function	Non-linear capacitance/temperature function
No voltage dependency of capacitance and loss angle	
No ageing	Slight ageing of capacitance
High insulation resistance	High insulation resistance
	Extremely high capacitance value per unit volume
Very small dielectric loss	
High dielectric strength	
Normal capacitance tolerance ±1% to ±10%	Normal capacitance tolerance ±5% to -20+80%

16.5.3 *Applications*

Flat circular disc ceramic (Z5U dielectric, high K) capacitors have a 2000 V dc, 550 V ac rating with capacitances of up to 47 nF. An exploitable drawback of such a ceramic capacitor is that its permittivity decreases with increased voltage. That is, the capacitance decreases with increased voltage as shown in figure 16.23c. Such a capacitor can be used in the turn-off snubber for the GTO thyristor and diodes which are considered in 8.1.3 and 8.1. High snubbering action is required at the commencement of turn-off, and can subsequently diminish without adversely affecting losses or the switching area trajectory tailoring. The capacitor action is a dual to that

performed by a saturable reactor, as considered in 8.3.4. Exploitation of voltage dependence capacitance is generally outside the capacitor specification. Advantageously, the disc ceramic capacitor has low inductance, but the high dissipation factor may limit the frequency of operation. Multi-layer ceramic capacitors can be used in switched mode power supply input and output filters.

16.6 Mica dielectric capacitors

The dielectric mica is a mineral which has a plane of easy cleavage enabling large sheets of single crystal to be split into thin plates, typically 50 μm thick. Stacks of mica plates are interleaved with silver metal foils as shown in figure 16.24.

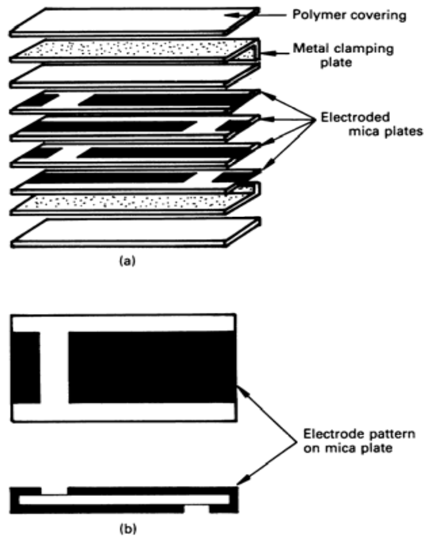


Figure 16.24. *Silver mica capacitor:*
(a) exploded construction view and (b) electrode pattern of a silvered mica plate.

The metal foils, to which the leads are spot-welded, are made of silver, copper, brass, tin or lead. The stack is held together either by the encapsulation or a metal crimp. The assembled unit is encapsulated by dipping it into high melting temperature microcrystalline wax or by coating it with epoxy resin.

16.6.1 *Properties and applications*

Mica capacitors are non-polar, low loss, and stable up to about 30 MHz, where the lead length and electrodes dominate as inductance. Because of their relatively high cost of manufacture, as a result of the high labour content and diminishing number of mines, the ceramic capacitor, particularly the monolithic multi-layer type, is favoured.

Maximum ratings are a few nanofarads at 5000 V, with dissipation factors of 0.1 per cent at 1 kHz. For capacitance less than 1 nF, a 0.1 per cent dissipation factor is obtainable at 1 MHz. An insulation resistance of 10^5 MΩ at 20°C down to 10^4 MΩ at 125°C is common for capacitance to 10 nF, after which resistance falls off. Typical operating temperature range is from -55°C to 125°C, with a capacitance temperature coefficient of 0 to +70 ppm/K.

The maximum current depends on the edge connections and electrodes, so for each physical design the factor is different and is expressed in mA/pF. This rating may range between 1.6 mA/pF for smaller packages (9×8×8 mm) down to 0.12 mA/pF for larger packages (44×32×33 mm). A maximum VA limit must also be observed, typically 50 VA for smaller sizes up to 820 VA for the larger sizes.

Mica dielectric capacitors are sensitive to pressure.

16.7 Appendix: Minimisation of stray capacitance

Unexpected component stray capacitance, and inductance, can have disastrous circuit consequences. Figure 16.25 shows four examples of electronic components which have stray capacitance between two parts of the component used at different potentials. When the isolated part rapidly changes its relative potential, a charging current flows according to $i = C\, dv/dt$. With just 1 pF of capacitance, and at 10,000 V/μs, which is possible with MOSFETs and IGBTs, 10 mA of current flows. This current coupled from the power level to the signal level would affect cmos or ttl circuitry, leading to malfunction and possible failure, if precautions are not taken.

Figure 16.25a shows a power package electrically isolated from its heatsink, which is grounded (to 0V or V_s) in order to minimise rfi radiation. Large power blocks have over 100 pF of isolation capacitance. Other than injecting noise, the level may be sufficient to activate earthing leakage circuitry, if connected to ground. Increasing the ceramic substrate or mica thickness decreases capacitance according to equation (16.3), but at the expense of increasing thermal resistance. Al_2O_3 reduces the thermal impedance compared to aluminium nitride, but at the expense of increased cost.

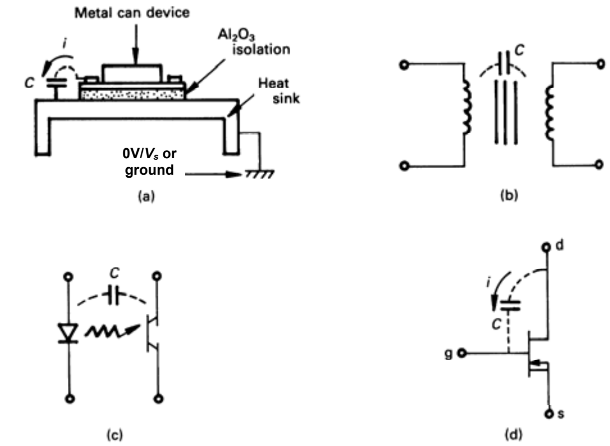


Figure 16.25 *Component stray capacitance C: (a) when isolating power devices; (b) between transformer windings; (c) in opto-couplers; and (d) between terminals of metal oxide semiconductor devices.*

Interwinding capacitance, shown in figure 16.25b, is important in switch mode power supplies and other applications using transformers. By winding the primary and secondary in different bobbin sections, the interwinding capacitance is decreased since their physical separation is increased. Alternatively, an overlapped copper foil ground shield layer is wrapped between the two windings. The copper strip is a connected to a supply rail or earthed so that charging currents bypass sensitive circuitry. Experimentation will reveal the best connection potential and location position. The copper foil overlapped turn ends must not make electrical contact, otherwise a short circuit turn results. Minimise winding start to finish turns capacitance by using the winding method shown in figure 17.19b.

A similar solution is used in opto-coupler packages. A grounded Faraday's grid is placed between the emitter and receiver in order to divert charging current. High *dv/dt* opto-couplers, with less than 1 pF capacitance input to output, are guaranteed to 15000 V/μs at 200 V dc levels. This *dv/dt* limit decreases to 1000 V/μs on a 600 V dc rail. The effects of capacitive charging current can be minimised by driving the emitting diode from a low impedance source, both when on and off. Speed and current transfer ratio can be traded for higher *dv/dt* capability by increasing separation. For high voltages and high *dv/dt* a fibre optic is an expensive alternative, but unlike the pulse transformer, has now lower cut-off frequency.

Figure 16.25d shows the Miller capacitance associated with the MOSFET and IGBT. During switching, the Miller capacitance charging and discharging currents slow the switching transition as power level current is injected into and from the gate level circuitry. A low impedance gate drives reduces the Miller capacitance effects.
A commonly overlooked capacitively injected current is that associated with the use of oscilloscope probes, when measuring power level signals. The scope probe ground should be physically connected to an appropriate power ground point, rather than signal ground. Always use the highest voltage step-down ratio probes as possible, since capacitance tends to decrease with increased step down ratio.

Reading list

Siemens, *Components,* 1986.

Mullard, *Book 3 Parts 1b and 1e,* 1984/85.

Rifa, *Capacitors,* 1986.