CHAPTER 29

Capacitors

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

- turn-off snubbering (9.3.1)
- *dv/dt* snubbering (9.1)
- RFI filtering (11.3)
- transient voltage sharing of series connected devices (11.1.1)
- voltage multipliers (13.4)
- dc rail splitting for multilevel converters (17.3)
- cascaded multilevel inverters for VAr compensation (17.3)
- power *L-C* filters (17.6)
- switched-mode power supply output filtering and dc blocking (19, 20)
- ac power factor correction and compensation (25.2)
- supercapacitors (28.10)

as well as

- dc rail decoupling
- motors for single phase supplies

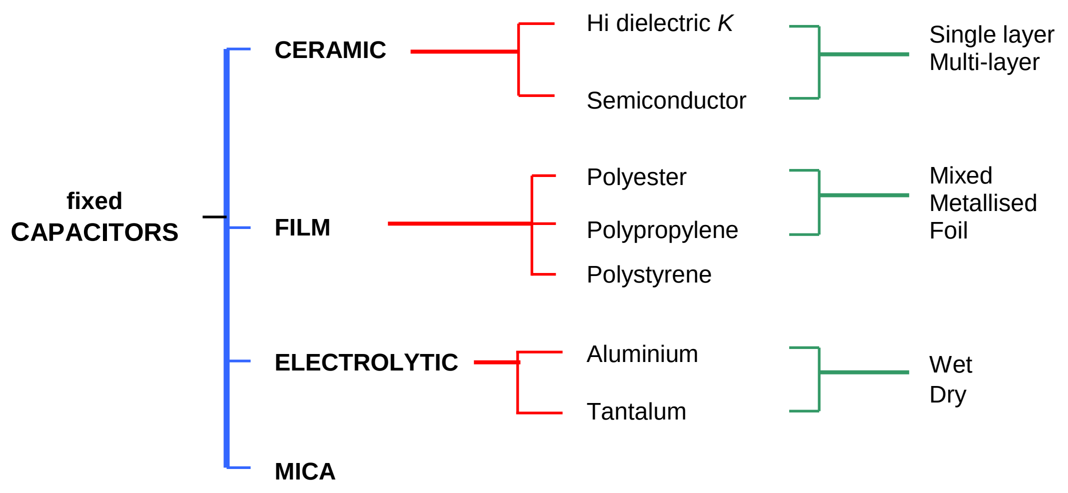
which is just to name a few uses of capacitors in electrical power applications. In each application, the capacitor is subjected to stresses, such as high temperature, *dv/dt* or high ripple current, which must be taken into account in the design and selection process. To make the correct capacitor selection it is necessary to consider various capacitor types, their construction, electrical features, and typical 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 and 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 over a wide temperature range. The voltage and capacitance ranges for the four main types of dielectric capacitors are shown in figure 29.1.



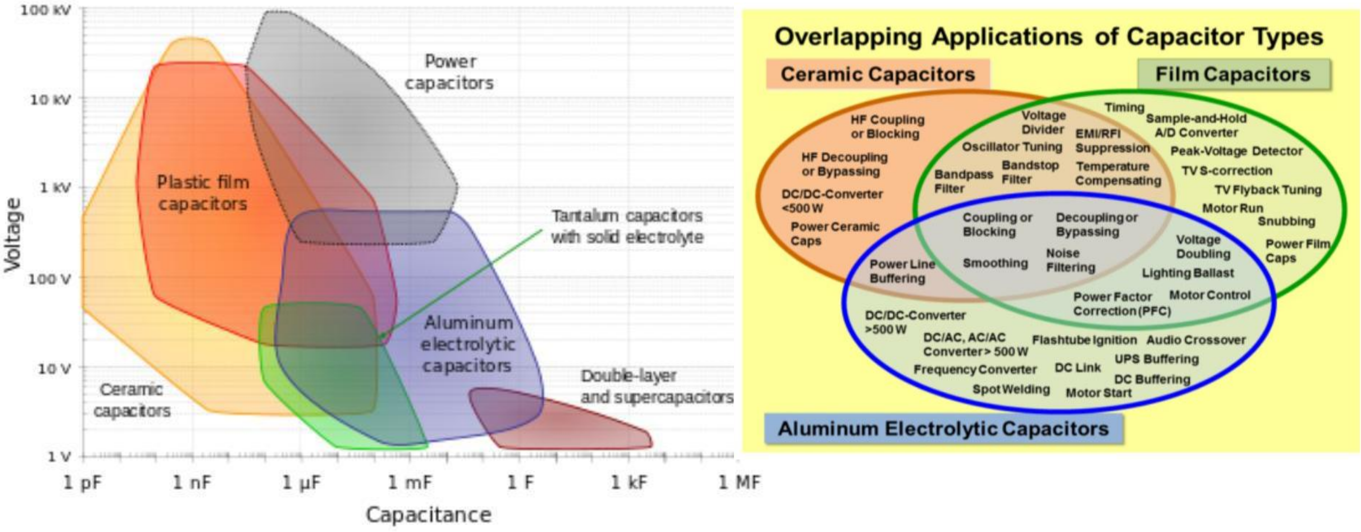


Figure 29.1. *Voltage/capacitance and applicationboundaries for the principal types of capacitors.*

29.1 General capacitor properties

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

29.1.1 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

$$Q = CV = \int i\,dt \qquad \text{(C)} \qquad [\text{or} \quad i = C\,dv/dt] \qquad (29.1)$$

while the stored energy (which is theoretically retained after the charging energy source is removed) and force between the plates are given by

$$W = \tfrac{1}{2}QV = \tfrac{1}{2}CV^2 \quad [\text{or} \quad W = \tfrac{1}{2}DE \times Aw] \quad \text{(J)} \quad F = \tfrac{1}{2}CV^2/w = \tfrac{1}{2}\varepsilon_o\varepsilon_r AV^2/w^2 \quad \text{(N)} \qquad (29.2)$$

The value of capacitance, C, is directly proportional to surface area, A, and inversely proportional to the thickness of the dielectric layer (plate separation distance), w; that is

$$C = \varepsilon_r\varepsilon_o\frac{A}{w} \qquad \text{(F)} \qquad (29.3)$$

The dielectric constants ε_r (or K) for materials in common usage, are summarised in Table 29.1.

Table 29.1: Dielectric constants for common dielectric materials

Dielectric material $\varepsilon_o = 4\pi\times10^{-7}$	*Relative dielectric constant* ε_r
Vacuum	1
Air (1 atmosphere)	1.00059
Polystyrene	2.5
Polypropylene	2.5
Polycarbonate (now obsolete)	2.8
Polyethylene-terephthalate	3
Impregnated paper	2 - 6
Mica	6.5 - 8.7
$A\ell_2 0_3$	7
Glass	4 - 9.5
$Ta_2 0_3$	10 - 25
Ceramic	20 -12,000

Dielectrics in capacitors have the property of changing the spacing effectively between two plates. This is manifested in two ways.

First, placing a dielectric between two electric charges reduces the force (Coulomb's Law) acting between them, just as if they were moved apart.

In a vacuum, the force between the two charges is:

$$F_o = \frac{q_1 q_2}{4\pi\varepsilon_o r^2}$$

With a dielectric of relative permittivity ε_r, the force between the two charges reduces to:

$$F_r = \frac{q_1 q_2}{4\pi\varepsilon_o\varepsilon_r r^2} = \frac{q_1 q_2}{4\pi\varepsilon_o\left(\sqrt{\varepsilon_r}\, r\right)^2} = \frac{F_o}{\varepsilon_r}$$

The dielectric increases the effective distance from r to $\varepsilon_r^{½} x r$, since $\varepsilon_r > 1$.

Secondly, the dielectric constant of a material affects how electromagnetic fields (light, radio waves, millimetre-waves, etc.) move through the dielectric material. A high dielectric constant increases the effective spacing. This means that light travels slower. It also 'compresses' the waves to behave as if the field has a shorter wavelength.

In a vacuum, the electric field (strength) E_o created by charge q is (D is displacement flux density, ψ/A):

$$E_o = \frac{q}{4\pi\varepsilon_o r^2} \qquad \left(= \frac{D}{\varepsilon_o}\right)$$

With a dielectric of relative permittivity ε_r, the electric field reduces to:

$$E_r = \frac{q}{4\pi\varepsilon_o\varepsilon_r r^2} = \frac{q}{4\pi\varepsilon_o\left(\sqrt{\varepsilon_r}\, r\right)^2} = \frac{E_o}{\varepsilon_r} \qquad \left(= \frac{D}{\varepsilon_r\varepsilon_o}\right)$$

The dielectric increases the effective distance from r to $\varepsilon_r^{½} x r$. In the case of a capacitor it is the electric field effect created by the dielectric that is relevant, $\varepsilon_r = E_o / E_r$. Since $C=Q/V$, the dielectric effectively decreases E (hence V), thus increases capacitance C.

The effective capacitance of parallel, C_p, and series, C_s, connected capacitors are

$$C_p = C_1 + C_2 + C_3 + \ldots$$

$$\frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots \qquad (29.4)$$

In parallel, the capacitor with the lowest voltage rating specifies the parallel combination voltage rating. In series, capacitor voltage rating is inversely related to capacitance, that is, the necessary voltage rating of each capacitor must satisfy $C_1V_1 = C_2V_2 \ldots = C_nV_n$. The lowest CV will be the limiting capacitor.

29.1.2 Volumetric efficiency

The volumetric efficiency of a capacitor is a measure of the effectiveness of a given physical construction and dielectric material. Volumetric efficiency η_v, is defined by

$$\eta_v = \frac{C_R \times V_R}{volume} \qquad \left(\text{C/m}^3\right) \qquad (29.5)$$

Dimensionally, longer is better since there is less percentage dielectric wastage of the unused dielectric ends. Cylindrical is better than oval, except an oval cross-section may allow better stacking with parallel connected capacitors or may result in lower lead inductance for pcb mounted capacitors.

29.1.3 Equivalent circuit

The impedance of a capacitor can be modelled by one of the capacitor equivalent circuits shown in figure 29.2. 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

$$\omega_r = \frac{1}{\sqrt{L_s C_R}} \qquad \text{(rad/s)} \qquad (29.6)$$

The electrical impedance Z of a capacitor is, neglecting

- R_i the leakage (insulation) resistance which is usually large,
- R_d is the dielectric loss due to dielectric absorption and molecular polarisation (significant at high frequencies), and
- C_d is the inherent dielectric absorption, only significant in electrolytic capacitors

$$Z = R_s + jX = ESR + j2\pi f \times ESL - j\frac{1}{2\pi f \times C_R} \qquad (\Omega) \qquad (29.7)$$

Since the ESL is neglected, at lower frequencies (well below resonance), when $2\pi f$ (that is ωL) is small

$$Z = R_s - \frac{j}{\omega\, C_R} \qquad (\Omega) \tag{29.8}$$

and

$$\tan\delta = \omega\, C_R R_s = \omega\, C_R \times ESR = \frac{R_s}{X_c} = \frac{1}{Q} = \frac{\text{real power}}{\text{reactive power}} \tag{29.9}$$

where *δ* is the loss angle and tan*δ* is termed the *dissipation factor, DF,* which is the reciprocal of the circuit quality factor, *Q*. The angle *δ* is that necessary to make the capacitor current lead the terminal voltage by 90° in figure 29.2c and d, as for an ideal capacitor.

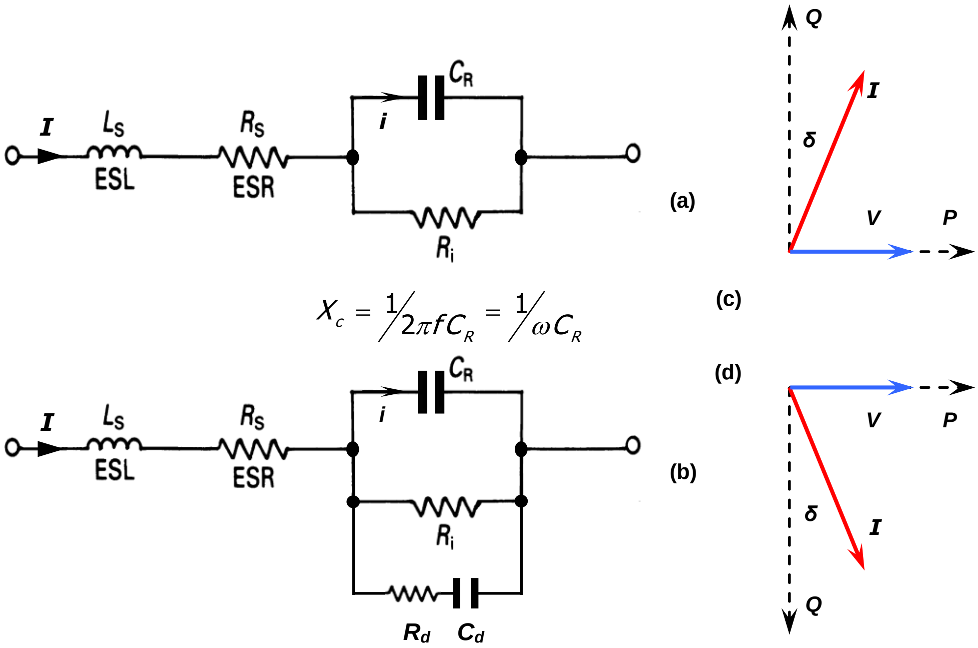


Figure 29.2. *Capacitor: (a) equivalent circuit for a film capacitor and; (b) electrolytic capacitor; and terminal V-I phasor diagram; (c) below resonance; and (d) above resonance.*

If the insulating or dielectric dc leakage resistance, $R_i\,(= \rho_i \ell/A)$, is included, then

$$\tan\delta = \frac{1}{\omega C_R R_i} + \omega C_R R_s \tag{29.10}$$

and at low frequency ($\omega << \omega_o$)

$$\tan\delta_\ell = \frac{1}{\omega C_R R_i} \tag{29.11}$$

while at high frequency ($\omega >> \omega_o$)

$$\tan\delta_u \approx \omega C_R R_s \tag{29.12}$$

Both R_s and X_c are dependent on temperature and frequency as shown in figure 29.3. Figure 29.3a 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 29.3b 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 29.3c and 29.3d. Figure 29.3c 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 29.3d shows how the dissipation factor, tan*δ*, increases approximately proportionally with frequency to a high value at resonance, as would be expected from equation (29.10). At lower frequencies tan*δ* may be considered as having a linear frequency dependence, according to $\tan\delta = \tan\delta_o + kf$.

ESR and *tan δ* dictate internal power dissipation hence self-heating, namely, for terminal voltage *V*

$$P = I^2 \times ESR = 2\pi fC \times \tan\delta \times V^2 = (2\pi fC)^2 \times ESR \times V^2 \tag{29.13}$$

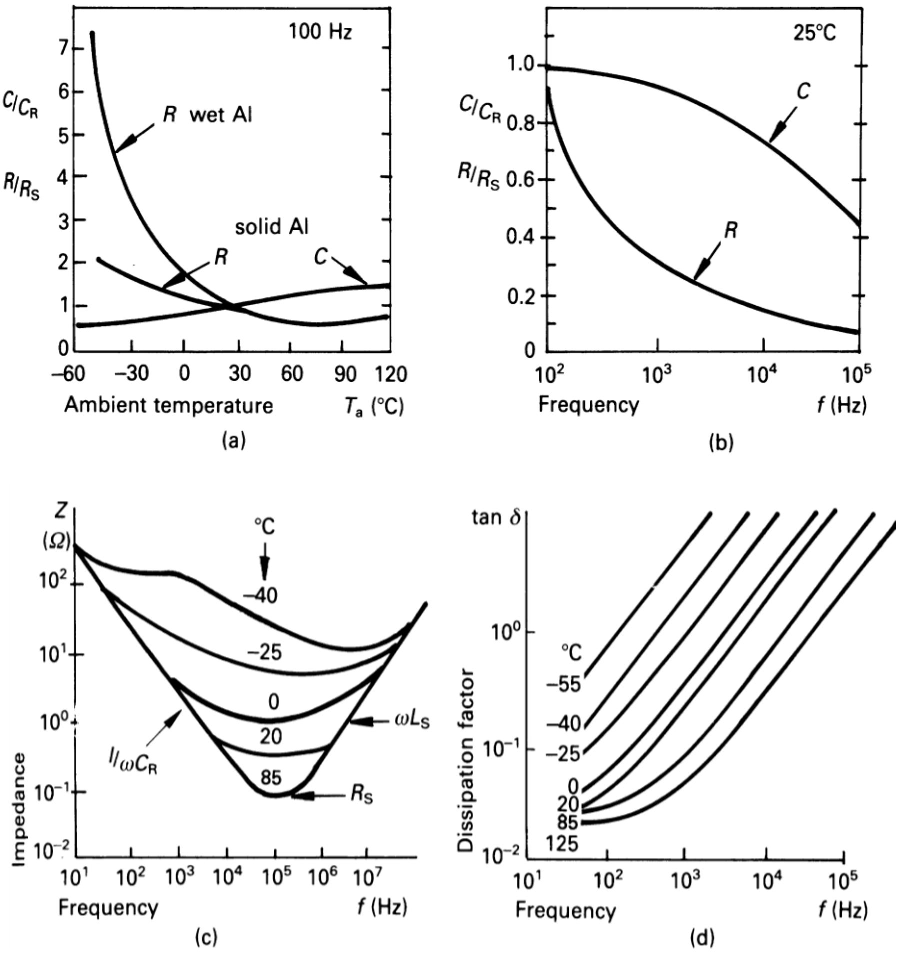


Figure 29.3. *Variation of capacitor equivalent circuit parameters with frequency and temperature for a high voltage (47 μF, 350 V) metal oxide liquid dielectric:(a) R_s and C_R as a function of temperature; (b) R_s and C_R as a function of frequency; (c) impedance Z as a function of frequency and temperature; and (d) tan δ as a function of frequency and temperature.*

For sine wave calculations

$$ESR = \frac{DF}{2\pi fC} = \text{reactance} \times DF \qquad (\Omega)$$

$$I_{rms} = 2\pi fCV_{rms} \qquad (\text{A})$$

$$\text{reactance} = \frac{1}{2\pi fC} \qquad (\Omega)$$

For pulse applications

$$I_{peak} = 1.5 \times C\, {}^{dV}\!/_{dt} \qquad (\text{A})$$

$$\text{pulse frequency} = \frac{1}{2 \times \textit{rise time}} \qquad (\text{Hz})$$

29.1.4 Lifetime and failure rate

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*.

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 (*fit* – failure in time) 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 rate λ, averaged over Δt is expressed as

$$\lambda = \frac{1}{N} \times \frac{\Delta N}{\Delta t} \qquad (/\text{h}) \qquad (29.14)$$

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 29.4, such that

$$\lambda = \frac{1}{N}\frac{dN}{dt} \qquad (/\text{h}) \qquad (29.15)$$

This figure shows the three distinct failure periods, and the usual service life is specified according to the failure λ_o, which is constant.
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 29.2 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

$$\lambda = \lambda_o \left(\frac{V_{op}}{V_R}\right)^n e^{-\frac{E_a}{K}\left(\frac{1}{T} - \frac{1}{T_o}\right)} \qquad (29.16)$$

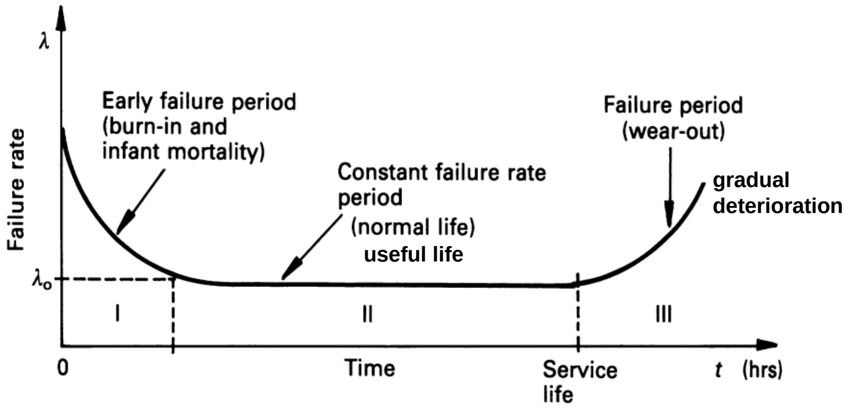


Figure 29.4. *The bathtub curve showing variation of failure rate with operating hours.*

Table 29.2: 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 29.1: ***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 29.2, 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 29.2b

$$\lambda_{55} = 2 \times \lambda_o = 4 \quad \text{fit}$$

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 29.2a. The new failure rate is

$$\lambda_{½V} = 0.2 \times \lambda_o = 0.4 \quad \text{fit}$$

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 (assuming independence and superposition of factors)

$$\lambda_{55,½V} = 2 \times 0.2 \times \lambda_o = 0.8 \quad \text{fit},$$

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 F after a service time t is given by

$$F(t) = 1 - e^{-\lambda t} \qquad (29.17)$$

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

$$\lambda_{total} = \lambda_1 + \lambda_2 ..... + \lambda_n \qquad (29.18)$$

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

$$\frac{1}{1-F(t)} \frac{dF(t)}{dt} = \lambda \qquad (29.19)$$

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

$$1 - F(t) = (1 - F_1(t)) \times (1 - F_2(t)) \times ....(1 - F_n(t)) = e^{-\lambda_1 t} \times e^{-\lambda_2 t} \times ..... e^{-\lambda_n t} = n\lambda \qquad (29.20)$$

if, since the units are identical, $\lambda_1 = \lambda_2 = \ldots = \lambda_n$.

The *mean time between failure* (*mtbf*) is given by

$$mtbf = \frac{1}{\lambda_{total}} = \int_0^\infty 1 - F(t)\, dt = \int_0^\infty e^{-\lambda t}\, dt = \frac{1}{\lambda} \qquad (29.21)$$

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

$$\tau = \frac{1}{\lambda} \ell n \frac{1}{1-F} \qquad (29.22)$$

Example 29.2: ***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

$$1 - F(1\,\text{yr}) = e^{-\lambda t} = e^{-200 \times 10^{9} \times 8760} = 0.998 \quad (99.8\%)$$

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 (29.21) is

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

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

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

The probable number of first year failures with 1000 units is

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

♣

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

29.1.5 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 (due to pores and film impurities) experiences an abnormally high electric field which may cause failure by arcing within a few tens of nanoseconds. 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 growth 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 metallised plastic film capacitor causes a continuous high pressure plasma arc which pushes the dielectric layers apart and evaporates the metallisation in the breakdown region. Temperatures can reach 6000K and insulated areas are formed around the original failure area, which after the arc self-extinguishes, isolate the faulty dielectric within 10μs.

29.1.6 Temperature range and capacitance dependence

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.

Capacitor reversible temperature dependence can be expressed in terms of a temperature dependant capacitance co-efficient α_c, by

$$C(T) = C_{20°C}\left(1 + \alpha_c\left(T - 20°C\right)\right) \qquad (29.23)$$

where the temperature co-efficient of capacitance α_c, with respect to reference C_{ref} at 20°C, is

$$\alpha_c = \frac{C_{T2} - C_{T1}}{C_{ref}\left(T_2 - T_1\right)} \qquad 10^{-6}/\text{K}$$

29.1.7 Dielectric absorption

After a capacitor is discharged from a voltage V_i, a small voltage V_r reappears, due to a polarisation process in the insulating material. [This dielectric relaxation phenomena could be considered to be equivalent to remanence flux in magnetic materials]. The voltage tends to be independent of capacitance and dielectric thickness and is defined at 20°C. The dielectric absorption factor δ_A is defined by

$$\delta_A = \frac{V_r}{V_i} \times 100\% \qquad (29.24)$$

Typical factor percentage values for various dielectric types are shown in the following table.

Dielectric type	tantalum/ aluminium	polypropylene KP	polyethylene-terephthalate (polyester) KT	mixed dielectric	ceramic X7R	ceramic Z5U
δ_A %	0.03/0.10	0.05 - 0.10	0.21 - 0.25	0.12 - 0.15	0.60 - 1.00	2.00 - 2.50

29.2 Liquid (organic) 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.

Anode material	Electrolyte	Capacitance range (µF)	Max. rated voltage at 85 °C (V)	Upper categorie temperature (°C)	Specific ripple current (mA/mm^3) 1)
Aluminum (roughned foil)	**non solid**, f. e. Ethylene glycol, DMF, DMA, GBL	0.1…2,700,000	550	150	0,05…2,0
	solid, Manganese dioxide (MnO_2	0,1…1500	40	175	0,5…2,5
	solid conductive polymere (f. e. Polypyrrole)	10…1500	25	125	10…30
Tantalum (roughned foil)	**non solid** Sulfuric acid	0,1…1000	630	125	–
Tantalum (sintered)	**non solid** sulfuric acid	0,1–15.000	150	200	–
	solid Manganese dioxide (MnO_2	0,1…3300	125	150	1,5…15
	solid conductive polymere (f. e. Polypyrrole)	10…1500	35	125	10…30
Niobium (sintered)	**solid** Manganese dioxide (MnO_2	1…1500	10	125	5…20
	solid conductive polymere (f. e. Polypyrrole)	2,2…1000	25	105	10…30

29.2.1 Construction

The capacitor dielectric layer consists of aluminium oxide $A\ell_20_3$ or tantalum oxide Tn_20_3 which are formed by an electrochemical oxidising process of aluminium foil (0.02 to 0.1mm thick) 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 $A\ell_20_3$ which represents 1.45 nm per volt, and are excellent insulators (hence result in a high capacitor loss factor). This field strength is initially maintained constant (with constant current) during the oxidising process (this electrochemical process is aided by weak phosphoric acid in the case of tantalum capacitors and chloride solution for electrolytic capacitors), then constant voltage, 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 29.5. 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.

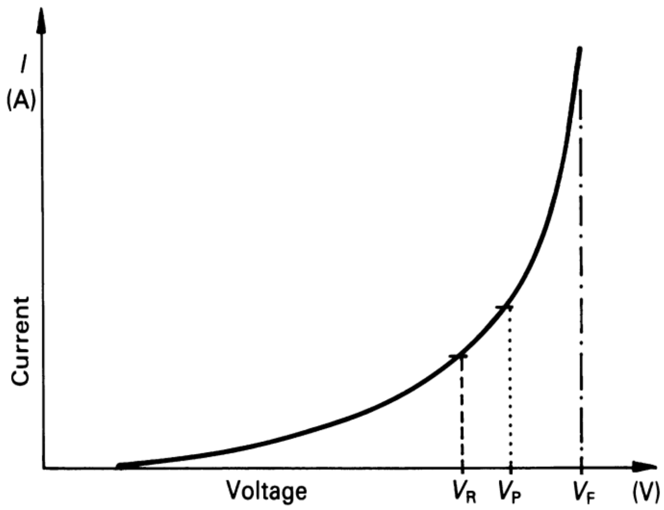


Figure 29.5. *Current (leakage) dependence on voltage of Aℓ electrolytic capacitors.*

The oxide dielectric constant ε_r is approximately 8.5 for $A\ell_20_3$ and 25 for Ta_20_3, while in comparison paper-based dielectrics have a value of approximately 5. An oxide thickness of w = 0.7µm is sufficient for high voltage capacitors (≥ 160 V) as compared with minimum practical paper dielectric thickness of about 6µm. 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 (*foil gain* - depending on the voltage – 100x for low voltage and 20x for high voltage capacitors) by electrochemical deep etching processes. In the case of tantalum capacitors, the sintered tantalum sponge like lattice structure results in the same increase of area effect. In the case of tantalum capacitors, the oxide not only grows on the surface of the tantalum, about one third grows into the porous lattice. This tends to limit the maximum voltage rating of tantalum capacitors.

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. The electrical contact to the cathode is a layer of etched aluminium, which has a thin oxide layer.
In the case of solid capacitors, (with lower voltages), a high conductive cathode is formed by a solid semiconductor metal oxide, such as manganese dioxide. This is achieved by the pyrolysis (continued dipping and baking at 200°C) of manganese nitrate into manganese dioxide. In solid oxide capacitors, the manganese dioxide is dipped into graphite which is coated with silver epoxy for soldering.

The four wet/dry oxide possibilities are shown in figure 29.6. 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 29.6. Operation at high voltages causes oxide growth and the production of hydrogen. Any gas pressure relief valve provided should be orientated upwards, just as the anode terminal should be above the cathode if the capacitor is orientated horizontally.

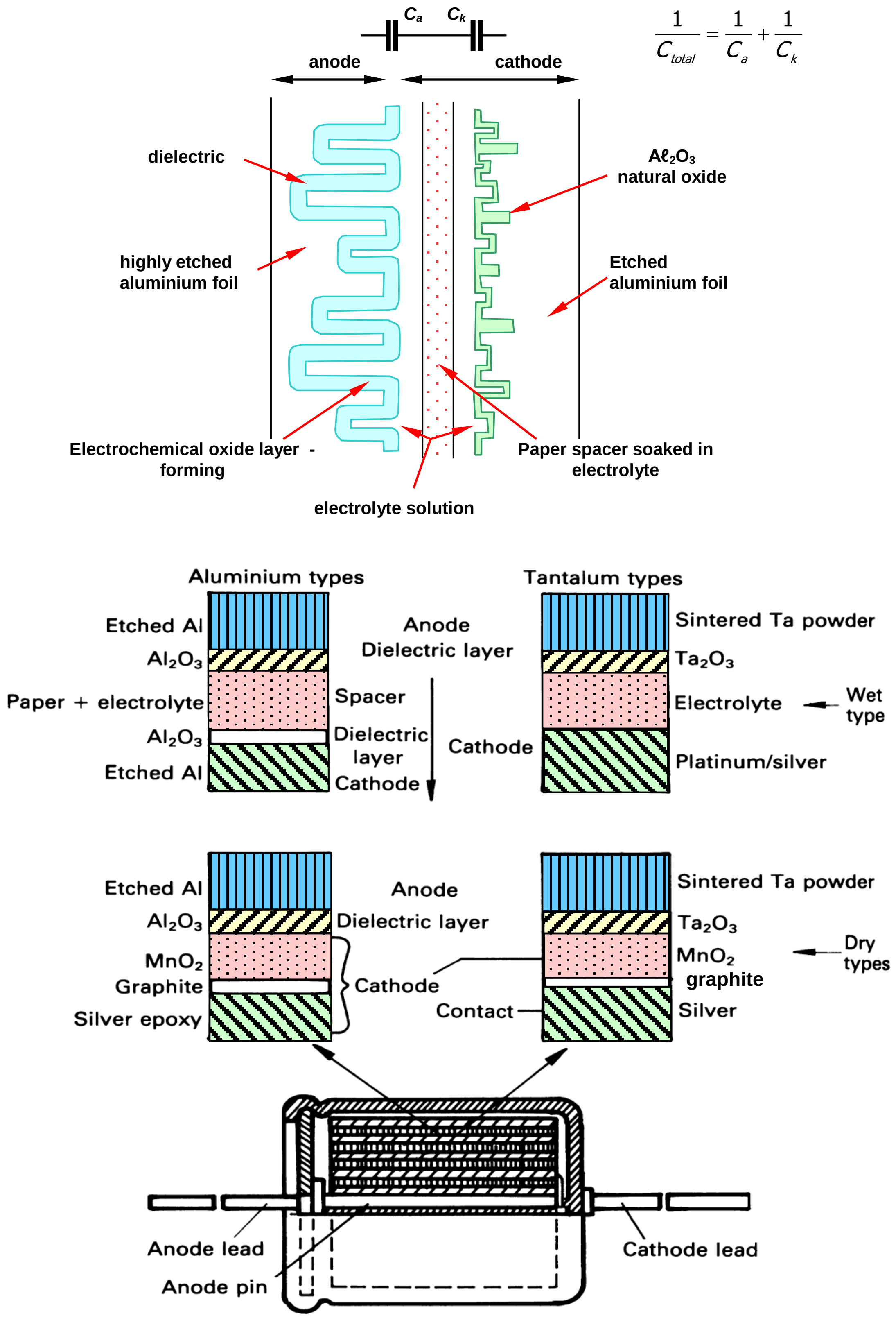


Figure 29.6. *Construction of metal oxide capacitors.*

29.2.2 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 oxidation of the cathode foil thus gas formation, gas as shown in the following formula, which can lead to failure.

$$2A\ell + 3H_2O - 6e^- \rightarrow A\ell_2O_3 + 6H^+$$
$$6H^+ + 6e^- \rightarrow 3H_{2\ gas}$$

This pressure build up may cause the safety vent to open or possibly destroy the capacitor. Deterioration is slow with a reverse voltage of a few volts.

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 29.5, where

for $V_R \le 315$V $V_P = 1.15\ V_R$
for $V_R > 315$V $V_P = 1.1\ V_R$

Both V_R and V_P, are derated with increasing temperature. Tantalum capacitors are linearly voltage derated above 85°C, to 66% at 125°C, which is the maximum operating voltage limit.

29.2.3 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 29.2. With oxide dielectric capacitors, this current is high at first and decreases with working time to a final stable, but voltage and temperature value, as shown in figure 29.7.

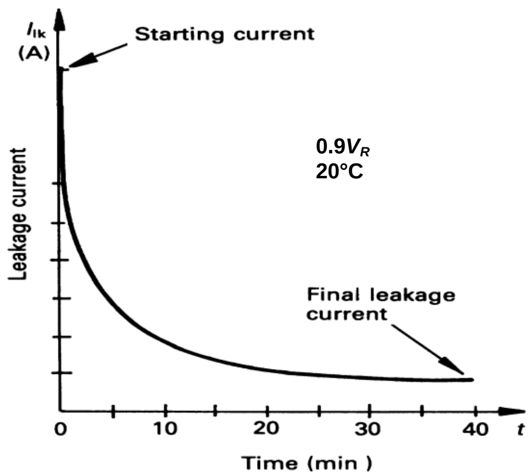


Figure 29.7. *Leakage current variation with working time for a liquid aluminium oxide capacitor.*

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 29.8. The purity of the anode metal, hence oxide dielectric determines the leakage current.

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 29.8 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 $V_F \times C_R$ (energy volume) 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 of semiconductors presented in 10.1.1, where the sharing resistance is

$$R = \frac{nV_R - V_s}{(n-1)\Delta I_\ell} \text{ where } \Delta I_\ell = 1.5\times 10^{-3} C_R V_R \qquad (29.25)$$

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.

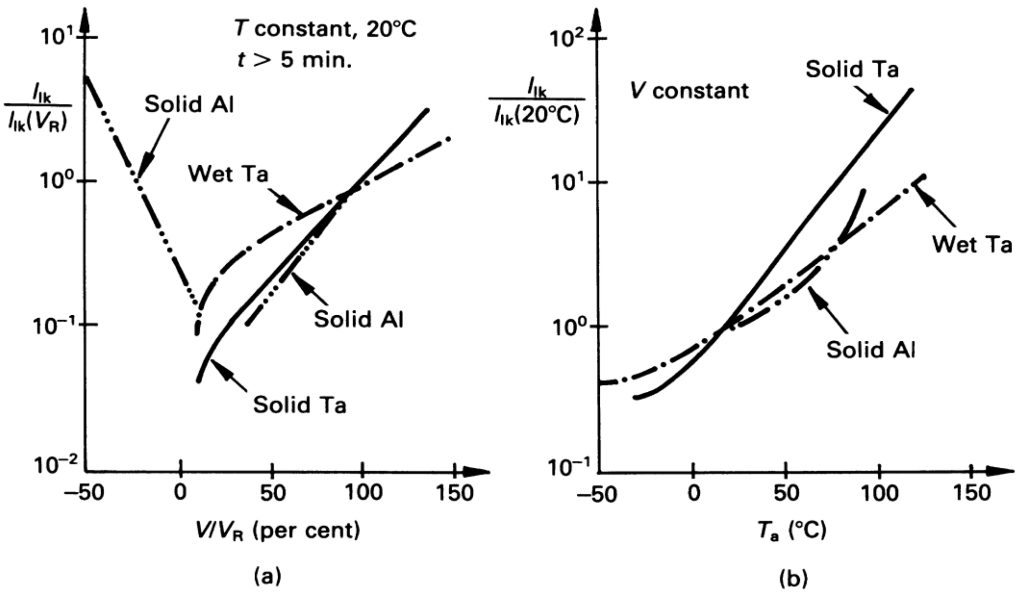


Figure 29.8. *Typical leakage current of oxide capacitors versus: (a) voltage and (b) temperature.*

29.2.4 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

$$P_d = \hat{I}_r^2 R_s \qquad \text{(W)} \qquad (29.26)$$

which results in an internal temperature rise until equilibrium with ambient occurs, see equation (29.13).
The maximum power dissipation $\hat{P}_d$ is dependent on the thermal dissipation properties of the capacitor, and from equation (5.4)

$$\hat{P}_d = h\,A\,\Delta T \qquad \text{(W)} \qquad (29.27)$$

where h = heat transfer coefficient, W/m^{2}K
A = capacitor outer surface area, m^2
$\Delta T = T_s - T_a$ = temperature difference between capacitor surface, T_s, and ambient, T_a, K

Thus the maximum ripple current is given by

$$\hat{I}_r = \sqrt{\frac{\hat{P}_d}{R_s}} = \sqrt{\frac{hA\Delta\hat{T}}{R_s}} \qquad \text{(A)} \qquad (29.28)$$

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 (29.28), conversion to other operating conditions is performed with the frequency multiplier $\sqrt{r}$ and temperature multiplier $\sqrt{k}$, such that

$$I_r = \sqrt{k}\,\sqrt{r}\,I_{ro} = \sqrt{k\,r}\,I_{ro} \qquad \text{(A)} \qquad (29.29)$$

Typical multiplier characteristics for aluminium oxide capacitors are shown in figure 29.9. It will be seen from figure 29.9a that electrolytic capacitors are rated at 85°C, while as seen in figure 29.9b solid types are characterised at 125°C. For each type, a reference frequency of 100 Hz is used.

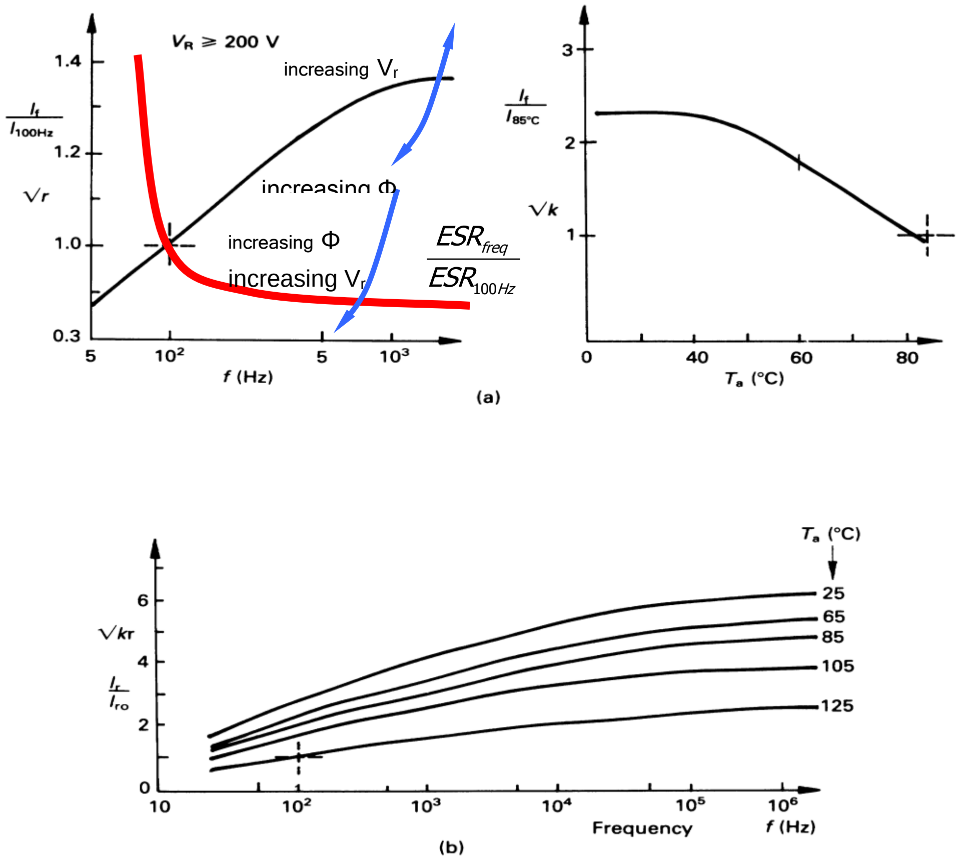


Figure 29.9. *Frequency and temperature ripple current conversion multipliers for: (a) liquid and (b) solid $A\ell_2 O_3$ capacitors.*

Alternatively, the temperature derating multiplier is expressed in terms of the ambient, core, and rated temperatures by

$$\sqrt{k} = \sqrt{\frac{T_{core} - T_{amb}}{T_{core} - T_R}} \qquad (29.30)$$

No simple expression exist for the frequency derating factor, *r*, although it may be used to infer ESR frequency derating

$$ESR_{freq} = {ESR_{100Hz}}/{r} \qquad (29.31)$$

Electrolytic capacitors usually have a thermal time constant of minutes, which can be exploited to allow intermittent overloads.

Example 29.3: *Capacitor ripple current rating*

A 1000 μF, 385 Vdc liquid, aluminium oxide capacitor has an rms ripple current rating I_{ro} of 3.7 A at 100 Hz and 85°C.

Use figure 29.9a to calculate the allowable ripple current at

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

Solution

i. Using equation (29.29)

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

where from figure 29.9a 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

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

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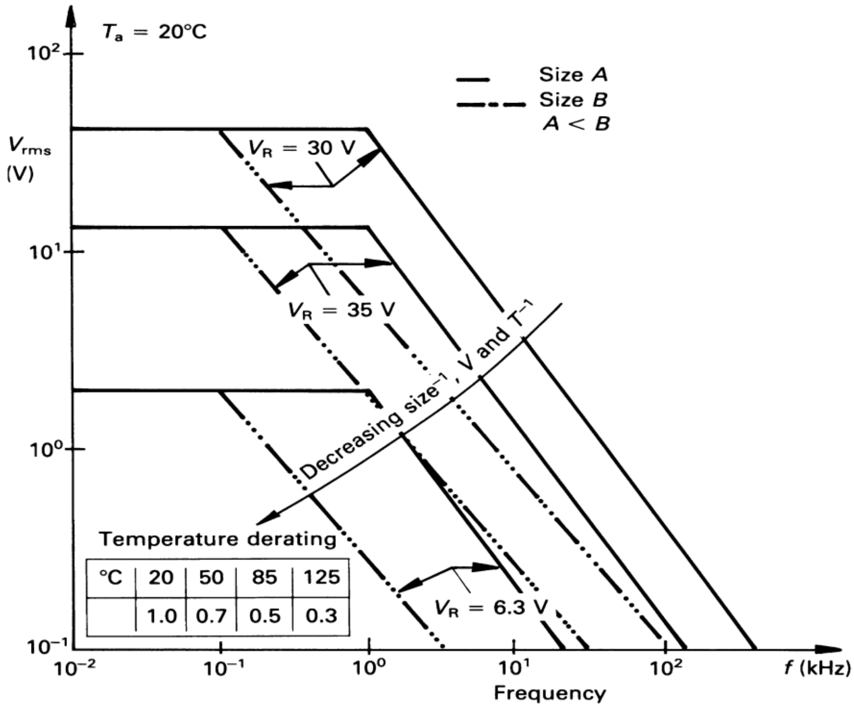

Figure 29.10. *RMS voltage limits of solid tantalum capacitors for different physical dimensions, temperature, voltage rating, and frequency.*

Non-sinusoidal ripple currents have to be analysed such that at a given temperature, the individual frequency components satisfy

$$\hat{I}_r^2 \geq \sum_n \frac{I_n^2}{r_n} \tag{29.32}$$

where $\hat{I}_r$ is for the appropriate rated ambient and reference frequency as indicated in figure 29.9.
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.

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 29.10, and any series resistance requirement, allowable ripple currents can be specified for a given temperature.

29.2.5 Service lifetime and reliability

29.2.5i - Liquid, oxide capacitors

As considered in 29.1.3, 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 and most improperly used common electronic component.

The reliability and service lifetime of an aluminium oxide electrolytic capacitor are dominated by its ripple current, operating temperature, and operating voltage. Figure 29.11 in conjunction with figure 29.9a, can be used to determine service life.

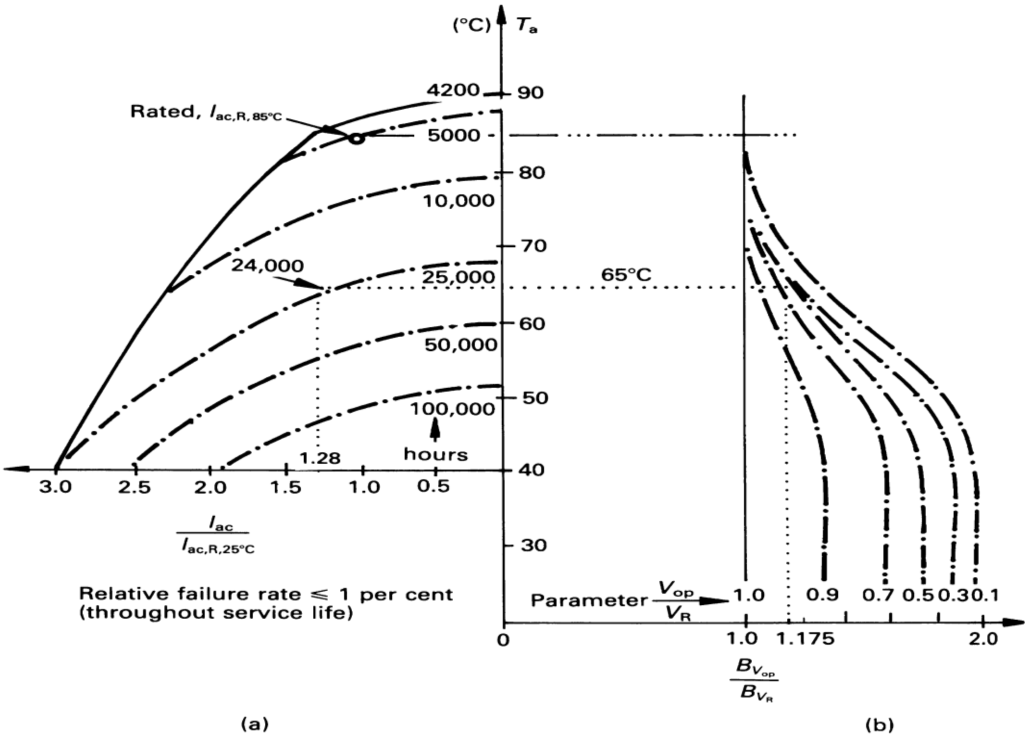

Figure 29.11. *Service life for an aluminium oxide liquid capacitor. Temperature dependence of lifetime variation with: (a) ripple current and (b) operating voltage.*

Example 29.4: $A\ell_2O_3$ *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 29.9a 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 29.11a, 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 29.11b. 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.

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

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

29.2.5ii - Solid, oxide capacitors

The failure rate of solid aluminium and tantalum capacitors is determined by the occurrence of open and short circuits (the dominant failure mode for solid tantalum capacitors) 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_20_3 and the intrinsically high effective area per unit volume due to the sintered construction
- changes in parameters (C_R, tan δ) are less because the specific resistance of $Mn0_2$ 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 (of 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 29.12.

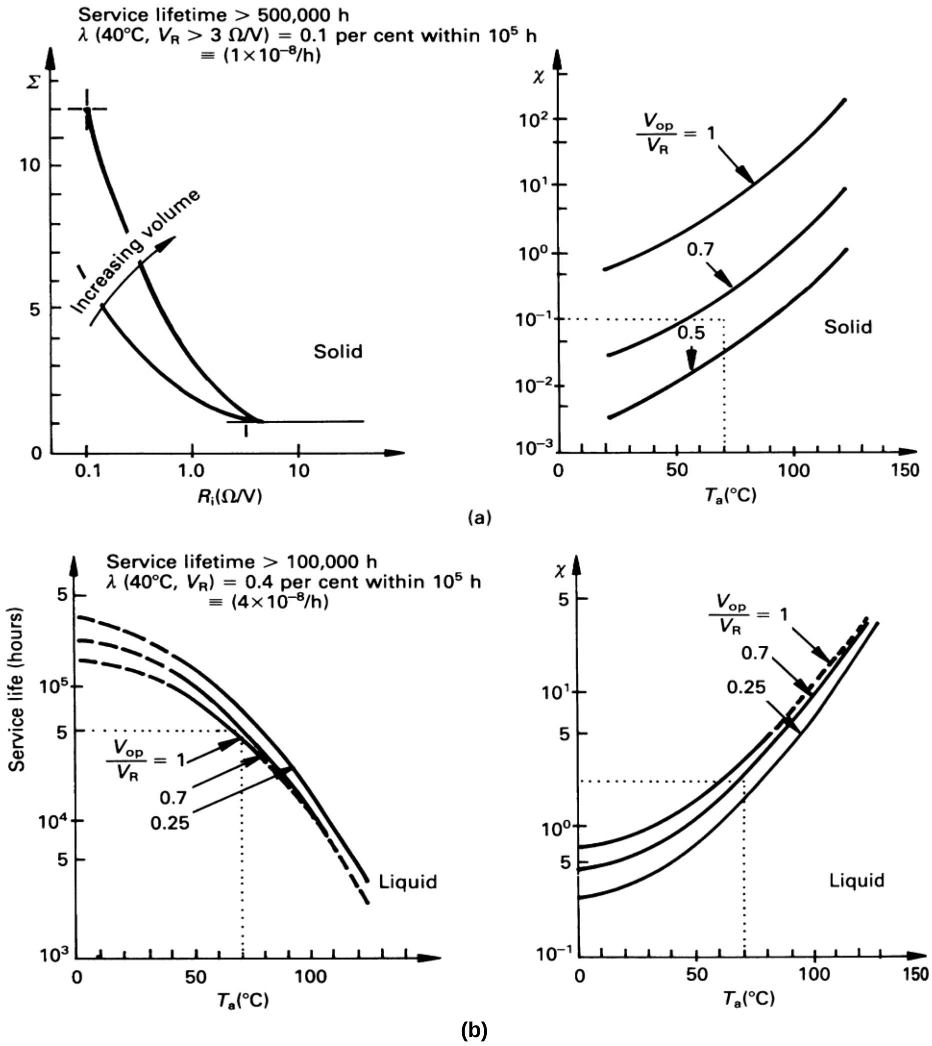

Figure 29.12. *Stress conversion factors for:*
(a) solid tantalum capacitors and (b) liquid tantalum capacitors.

Example 29.5: ***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.

		Liquid tantalum	Solid tantalum	
R	Ω	1 and 100	1	100
R_i	Ω	n/a	0.1	3
ΣR_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%)

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 29.12, the capacitor lifetime calculation is summarised the previous table.

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29.3 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 (organic, hydrocarbons, as shown in figure 29.13) are:

polye***t***hylene-terephthalate	(polyester or PEPT or PET)	T
poly***c***arbonate (now obsolete)		C
poly***p***ropylene (PP)		P
poly***s***tyrene		S
polyphenylene sulph***i***de		I
polyethylene ***n*** aphthalate (PEN)		N

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.

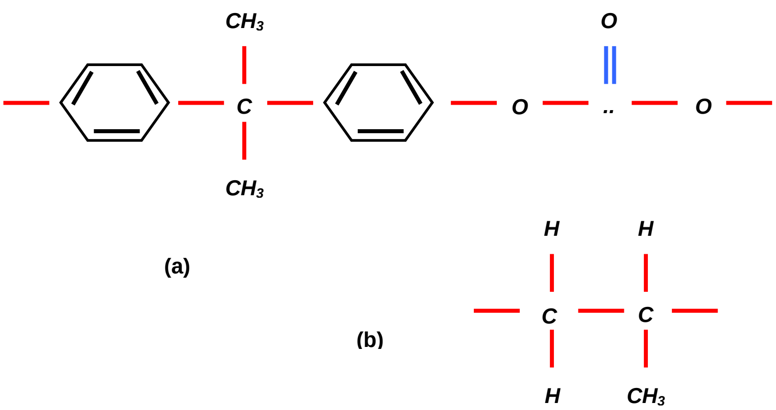

Figure 29.13. *Basic hydrocarbon structure of (a) polyethylene-terephthalate and (b) polypropylene.*

Two basic types of plastic film dielectric capacitors are common. The first type involves *metallisation* deposited onto 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 interleaved and displaced metal foil is used for the electrode. Typically such a foil capacitor would be termed KS, that is plastic - K, polystyrene – S or MFT and MFP (F - foil). The plastic type is designated by the fifth letter of the plastic name, that is the letter after poly, with two exceptions.

Table 29.3: Characteristics of plastic film dielectrics – typical values

dielectric			PEPT	PC	PP	PS	PEN
Dielectric constant, 25°C, 1kHz	ε_r		3.2	2.8	2.2	2.5	3.0
Dielectric strength		V/μm	250	180	350	150	
C drift with time	*ΔC/C*	%	3		3		2
C temperature coefficient	α_c	10^{-6}/K	+600	+150	-250	-150	+200
Max working temperature		°C	125	125	105	70	
C humidity coefficient (50% …95%)	β_c	10^{-6}/% r.h.	500 … 700		40 … 100		700 … 900
Dissipation factor @ 1kHz	*tanδ*	10^{-3}	5	1	0.6	0.2	4
Time constant, 25°C	$\tau=R_iC_R$	10^3 s	25		100		25
Water dielectric absorption		% weight	0.2	0.3	0.05	0.1	1.2
density		g/cm^3	1.39	1.21	0.91	1.05	
Specific capacitance		*FV/m^3*	400		50	140	250

29.3.1 Construction

***29.3.1i** - Metallised plastic film dielectric capacitors*

The dielectric of these capacitors consists of plastic film on to which metal layers of approximately 0.02μm to 0.1μm are vacuum deposited. A margin of non-coated film is left as shown in figure 29.14a. 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 layer extends out at one end of the roll and the next layer extends out the other end as shown in figure 29.14a. This displaced layer construction is termed *extended metallisation* and facilitates electrical contact with the electrodes. A hot lead-free 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 inductive impedance capacitor characteristics result.
The most common metallised plastic film capacitors are those employing polyester, MKT and polypropylene, MKP. All have self healing properties, hence use thinner dielectrics.
Polyester has a higher dielectric constant than polypropylene, and because of its stronger physical characteristics, is available in thinner gauges than polypropylene. High capacitance values result in the smallest possible volume. But polypropylene has a higher dielectric strength and lower dielectric losses, hence is favoured at higher ac voltages, currents, and frequencies.

***29.3.1ii** - 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 (5 to 9μm) are used as the electrodes. The thin strips are wound to form the capacitor as shown in figure 29.14b. An *extended foil* technique similar to the extended metallisation method is used to enable contact to be made to the extended metal foil electrodes. Film foil capacitors do not have self-healing properties, hence use thicker dielectrics.

***29.3.1iii** - 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 29.14c 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 29.14d, to form a *mixed layer* capacitor, with two series connected elements. 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.
Other extended layer winding designs, involving two internally series connected elements as in figure 29.14d, but single sided, are extended metallised film and extended foil with a metallised film design.

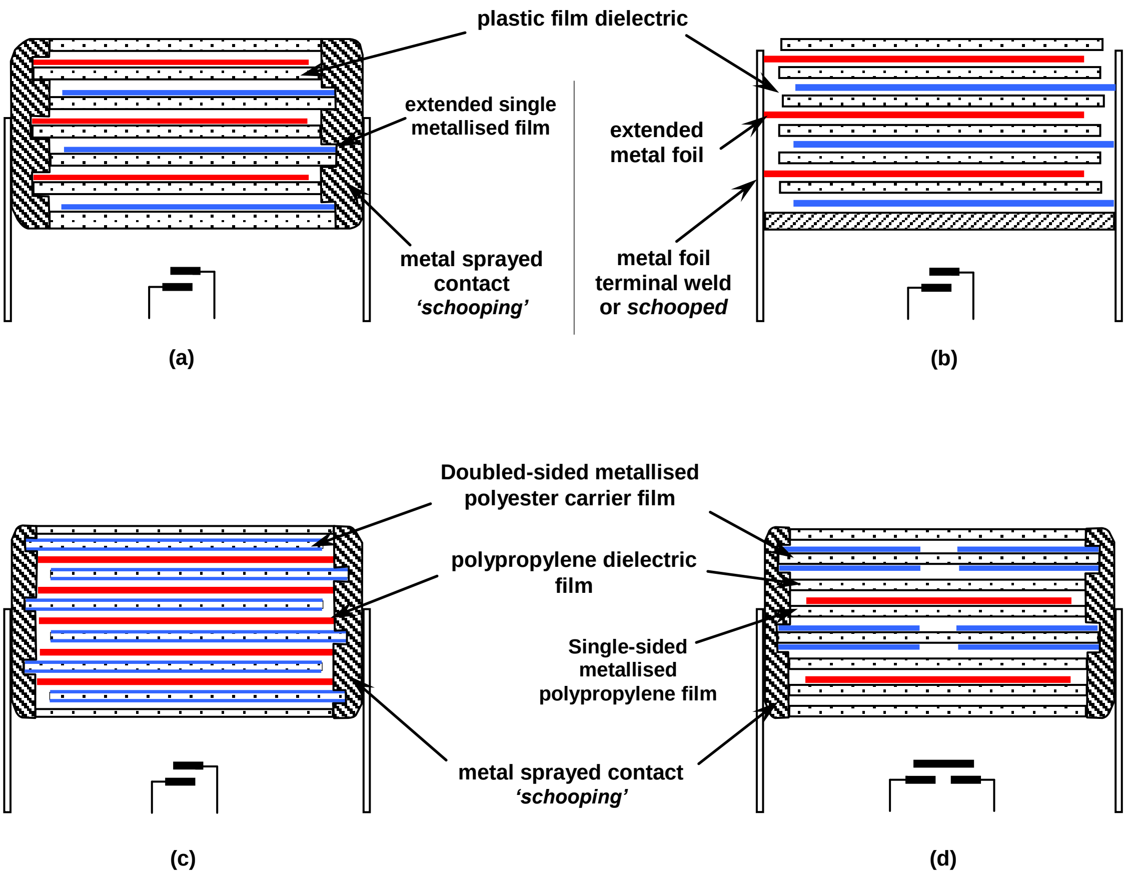

Figure 29.14. *Plastic capacitor constructions: (a) extended single metallization film; (b) extended foil; (c) mixed dielectric, extended double-sided metallised carrier film; and (d) mixed dielectric, extended double-sided metallised carrier film with internal series connection.*

29.3.2 Insulation

The dc resistivity insulation characteristics of a capacitor are indicated either as a resistance value R_i, as shown in Figure 29.2 or for capacitance greater than 0.33μF, 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, temperature, and significantly humidity, as is shown in figure 29.15. These characteristics illustrate that extremely high insulation resistance values can be obtained.

29.3.3 Electrical characteristics

***29.3.3i -** Temperature dependence*

The capacitance of plastic film capacitors changes with temperature, humidity, and frequency, as shown in figure 29.16. The dependence is strongly dependent on the dielectric film although some foil types are virtually independent of frequency. Table 29.4 summarises capacitance temperature dependence for a range of dielectrics. The temperature coefficient α_c is measured in parts per million per degree Kelvin, ppm/K.

$$\alpha_c = \frac{C_{T2} - C_{T1}}{C_{20^\circ C} \times (T_2 - T_1)} \qquad (29.33)$$

where C_{T1} and C_{T2} are the measured capacitances at temperatures T_1 and T_2. (See equation (29.23))

Any small irreversible change in capacitance at rated temperature, after a temperature variation between the allowable temperature extremes, is termed *temperature cyclic capacitance drift*.
The temperature dependence of dissipation factor is shown in figure 29.23a.

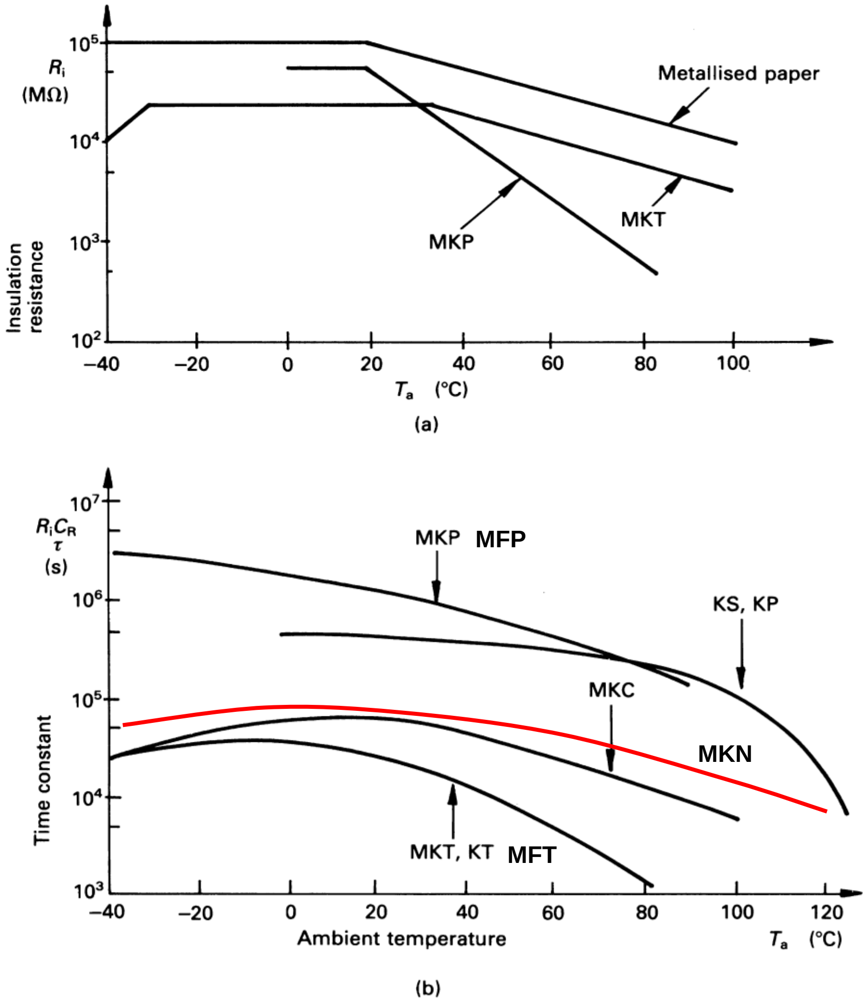

Figure 29.15. *Plastic dielectric insulation resistance temperature dependence characteristics: (a) resistance R_i and (b) time constant τ.*

29.3.3ii - *Humidity dependence*

The capacitance will undergo a reversible change in value due to ambient humidity variation. The *humidity coefficient* β_c, is define for a 1% change in humidity, at a constant temperature, by

$$\beta_c = \frac{2 \times (C_{F2} - C_{F1})}{(C_{F2} + C_{F1}) \times (F_2 - F_1)}$$

where C_{T1} is the capacitance at relative humidity F_1
C_{T2} is the capacitance at relative humidity F_2

Wide capacitance variations occur at relative humidity levels above 85%. Prolong contact of a film capacitor with high humidity or direct liquid water will produce irreversible effects due to reaction of the film metallisation. Typical plastic dielectric humidity coefficient variations are shown in figure 29.16c.

29.3.3iii - *Time dependence*

Capacitance charges irreversibly with time, where the drift coefficient $i_z = |\Delta C/C|$ is measure over a period of at least a year and at a temperature above ambient, typically a maximum of 40°C. As shown in Table 29.3, typical drift values are about 2% to 3%.

29.3.3iv - *Dissipation factor and impedance*

Figure 29.17a 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, as indicated in figure 29.18.

The dissipation factor, hence losses, are dependant on the *ESR*, as shown in equation (29.9). The *ESR* represents a complex set of loss mechanisms, many of which are strongly dependent on the measurement conditions. The *ESR* measured at the resonant frequency is not the worst-case value and is higher at lower frequencies.
Capacitor losses vary as a function of voltage, temperature, and other aspects of the applied waveform. This is because there are a variety of energy loss mechanisms which act within a capacitor. Some of these reside within the dielectric while others involve the conductors carrying the current. Some of the mechanisms and operating parameters which affect the magnitude of the losses, follow.

Dielectric losses are usually the most important losses in a film capacitor. These losses are associated with the polarization and relaxation of the dielectric material in response to the applied capacitor voltage. The magnitude of the dielectric losses in a capacitor are therefore generally both frequency and temperature dependent, when the largest losses occur at low temperatures or high frequencies, which hinder dipole orientation. Dielectric losses essentially are not voltage-dependent.
The dielectric losses of a given material can be described by its Dissipation Factor, *DF*. If the dielectric loss were the only loss mechanism operating in a capacitor, then the *DF* of the capacitor would be independent of its size, geometry and internal configuration. Capacitors of any size made with the same material would have the same *DF* under identical conditions. The *ESR* could then be computed using equation (29.9). However, the capacitor *DF* and *ESR* depend on the electrodes and their configuration.

Ferroelectric hysteresis losses are observed in certain high dielectric constant materials, most notably ceramics. These losses are a strong function of applied voltage. This loss mechanism arises when the internal polarization field has the same order of magnitude as the applied field. Under these conditions the dielectric response saturates. Capacitors made with such materials exhibit permanent polarization, variable capacitance as a function of voltage, and sensitivity to reversals of voltage.

Dielectric conduction losses are caused by the actual transport of charge across the volume of the dielectric or across internal dielectric interfaces. These losses are largest at low frequencies and higher temperatures. Because conduction in a dielectric material can be strongly nonlinear, non-Ohmic, conduction losses are often strongly dependent on applied capacitor voltage.

Interfacial polarization losses are related to dielectric conduction. Many high voltage capacitors contain two or three different materials within their dielectric arrangements, film and oil or paper, film and oil. Each material has different conduction properties and permittivity. As a result, the application of a dc voltage over a period results in a build-up of conducted charge at the internal interfaces between materials. This polarization of the dielectric is a low frequency phenomenon, hence the energy stored in this way is not available for discharge at high frequency. Again, since the conduction is nonlinear, interfacial polarization is nonlinearly voltage dependent.
This loss mechanism is important in pulse discharge applications, where the capacitor is charged over a relatively long period of time and then discharged rapidly.

Partial discharge losses can occur within gas-filled or defective solid capacitors or even in liquid-filled capacitors at high voltages. It is also common to have external corona on capacitor terminals. Partial discharges are most energetic at high rates of change of voltage (high *dv/dt*), such as during a capacitor pulse discharge. Also, reversal of the voltage such as in a highly oscillatory ringing capacitor discharge will cause more numerous, energetic, partial discharges.

Electromechanical losses result from the electrostriction, and sometimes piezoelectricity, acting within the capacitor dielectric itself and the flexing of internal wiring due to the Lorentz forces.

Ohmic resistance losses occur within the metallic electrodes, the internal wiring, and the capacitor terminals. In electrolytic capacitors, ohmic resistance in the electrolyte itself represents the largest loss mechanism. The resistance losses in the metal are constant as a function of temperature and frequency, until the skin depth in the electrodes becomes important, usually above several megahertz. Losses in the internal wiring and the terminal are important in high current applications. When high voltage capacitors are internally configured as a series string of lower voltage capacitor windings or units, the ohmic resistance within a given container size increases at the square of the voltage (or as the number of series elements).

Sparking can occur between conductors or different points on the same conductor during the discharge of pulse capacitors. For example, capacitors manufactured with an inserted tab connection to the electrode foil which is only a pressure contact exhibit points of localized melting after pulse discharge operation resulting from sparks between the adjacent metallic surfaces. This phenomenon is related to a high current rate of change, *di/dt,* during discharge, and is therefore frequency and voltage related.

Eddy current losses are important in pulse forming networks where a high magnetic field can couple into any ferromagnetic materials within the capacitor. These losses depend strongly on frequency. Usually the internal inductance in a capacitor is small and does not generate significant eddy currents.

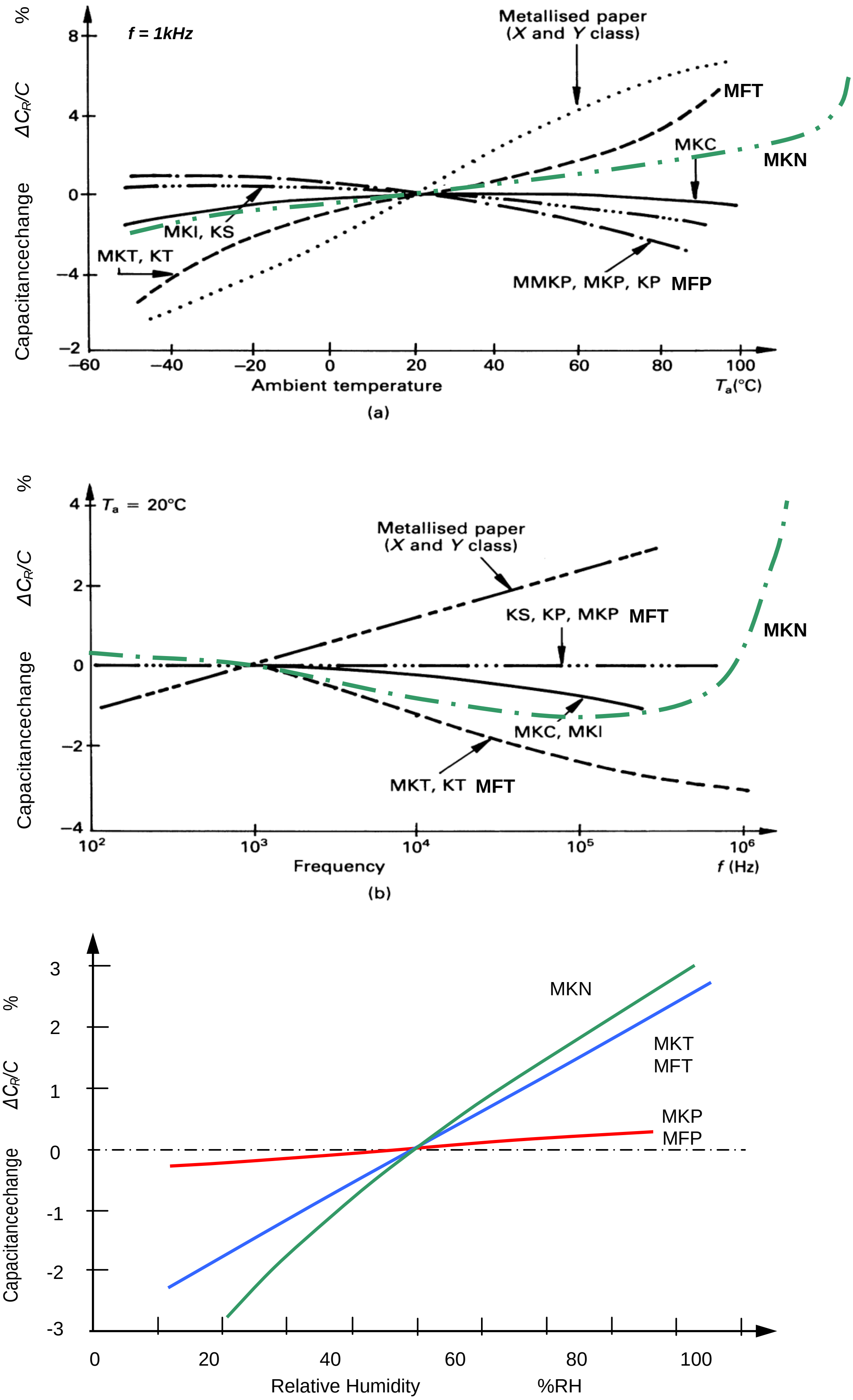

Figure 29.16. *Plastic film dielectric capacitance variation with:*
(a) ambient temperature; (b) frequency; and (c) relative humidity.

Generally, tanδ rises with increased frequency and increased capacitance. Tanδ 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 29.17b. 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 and can be used to determine the ESL, by $\omega_o = \sqrt{LC_R}$. In figure 29.17b, the full impedance curves for maximum and minimum capacitance only have been shown.

Table 29.4: Capacitor temperature coefficient for various dielectric materials

Dielectric type	*Temperature coefficient α_c (ppm/K or 10^{-6}/K)*		
	metallised	*other*	*film/foil*
Polypropylene	-170		-120
Polyester	400		400 (non-linear)
Polyethylene naphthalate	180		160
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	

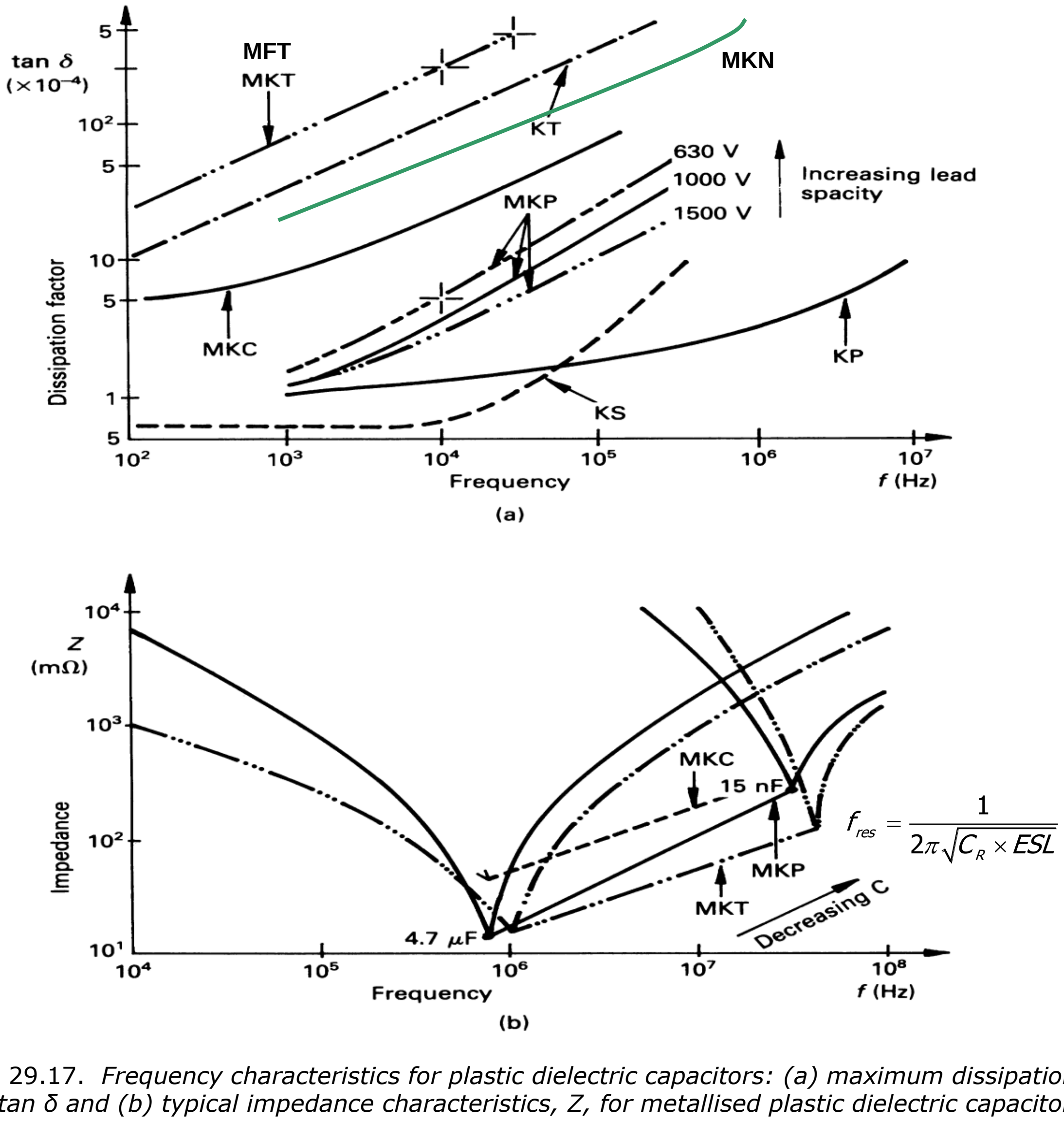

Figure 29.17. *Frequency characteristics for plastic dielectric capacitors: (a) maximum dissipation factor, tan δ and (b) typical impedance characteristics, Z, for metallised plastic dielectric capacitors.*

29.3.3v - Voltage derating with temperature

The ac and dc voltage limits 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 temperature and frequency dependence are shown in figures 29.18 and 29.20 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 R_i and ESL are neglected in the capacitor equivalent circuit shown in figure 29.2, then

$$P = \frac{V_{R_s}^2}{R_s} = I^2 R_s \qquad \text{(W)} \qquad (29.34)$$

and

$$V_{R_s}^2 = \frac{R_s^2}{R_s^2 + \dfrac{1}{\omega^2 C_R^2}} V_{ac}^2 \qquad (29.35)$$

Since from equation (29.12) for plastic dielectric capacitors

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

then equation (29.34) can be written as

$$P = \omega C_R \times \tan\delta \times V_{ac}^2 = \left(R_s C_R\right) \omega^2 C_R V_{ac}^2 \qquad \text{(W)} \qquad (29.36)$$

or alternatively

$$P = \tan\delta \;\; \omega C_R V_{ac}^2 \qquad (= I_{rms}^2 ESR) \quad \text{(W)} \qquad (29.37)$$

The value of tan *δ* for equation (29.37) is available from figure 29.17a or, alternatively, the value of $R_S C_R$ for equation (29.36) is available from figure 29.19.
The equivalent series resistance is dominated by leakage and dielectric losses (f^{-1}) at low frequency. At medium frequencies, conductor losses dominate, while at high frequencies losses are dominated by the skin effect ($\sqrt{f}$), as shown in figure 29.19b.
The maximum permissible power dissipation, $\hat{P}$ which depends on the package dimensions and ambient temperature, is given in figure 29.18d. Thus when the power dissipation, for a given ac voltage, has been calculated, figure 29.18d can be used to specify the minimum size (dimensions) capacitor capable of dissipating that power.
Example 29.6 illustrates the design approach outlined.

29.3.3vi *– Voltage and current derating with frequency*

The ac voltage/current dependence on frequency for film capacitors, has three distinct regions, as shown in figure 29.20.

Region A Below a certain frequency, f_1, the voltage threshold for corona discharge in capacitor air pockets is a limiting factor.

Region B In the mid-frequency region, the package power dissipation limit restricts the internal loss limit. The internal losses are tan*δ* dependant (equation (29.37)) while the package limit is surface area, A, and heat transfer coefficient dependant, *h*, equation 5.4.
That is, the internal generated losses are

$$P_{\text{int}} = \tan\delta \;\; \omega C_R V_{ac}^2$$

while the heat dissipation from the capacitor surface *A* with a heat coefficient *h*, is defined by

$$P_d = hA\Delta T$$

Since the internal losses must be less than that that can be dissipated, for a given internal temperature self-heating, *ΔT*:

$$V_{ac} \le \sqrt{\frac{hA\Delta T}{\omega C_R \tan\delta}} \quad \text{or} \quad I_{ac} \le \sqrt{\frac{\omega C_R \times hA\Delta T}{\tan\delta}}$$

The voltage and current are approximately related to frequency by

$$\hat{V}_{ac} \propto f^{-3/4} \quad \text{or} \quad \hat{I}_{ac} \propto f^{1/4}$$

Region C At higher frequencies, above f_2, with smaller capacitances and short contact lengths, the ac voltage is limited by the maximum current capabilities I_2 of schooped plating connections.

$$V_{rms} \le \frac{I_c}{2\pi f \times C_R} \quad \text{or} \quad I_{rms} \le I_c$$

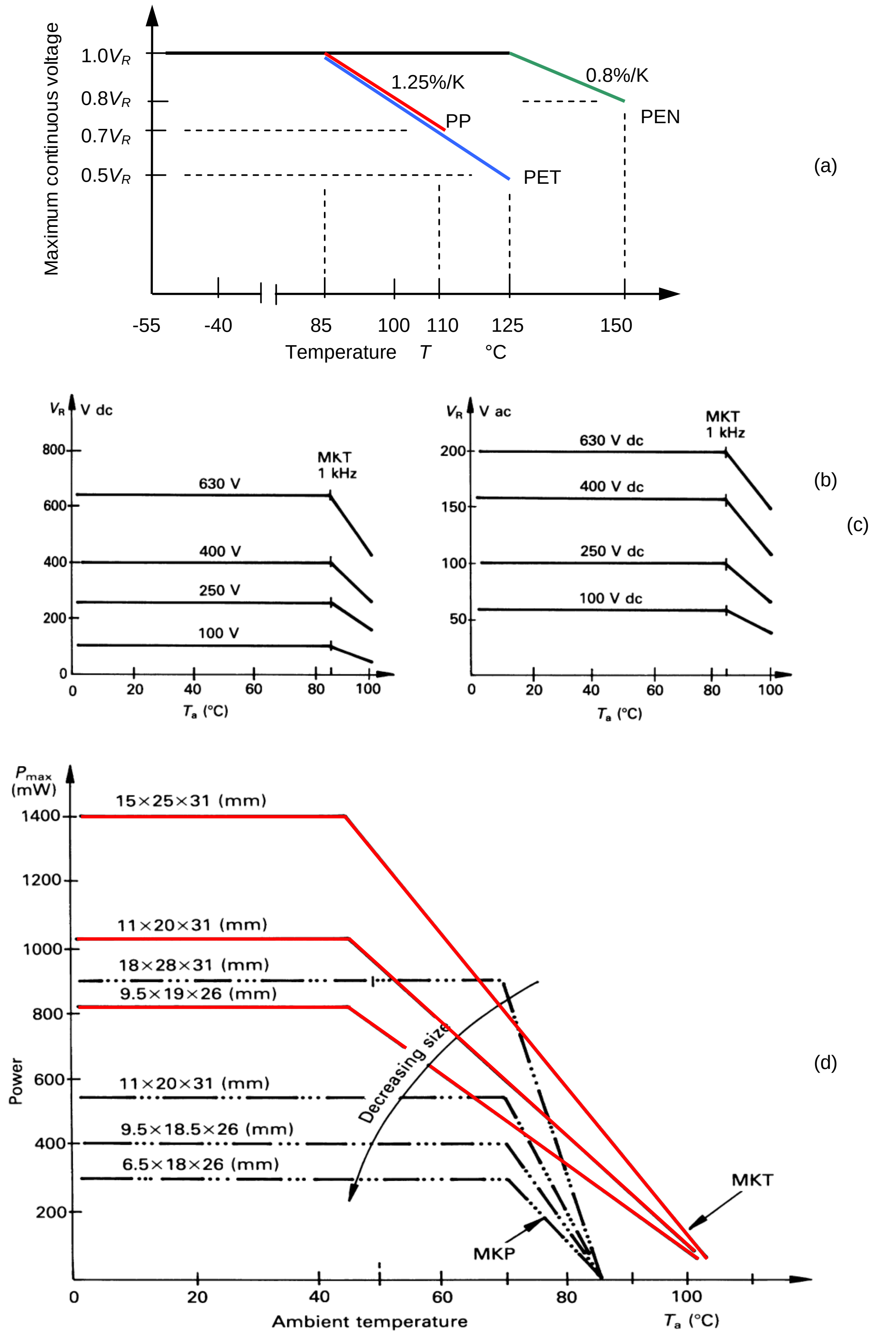

Figure 29.18. *Plastic dielectric capacitor, temperature derating characteristics: (a) general dc voltage derating; (b) dc voltage derating with ambient temperature; (c) ac voltage derating with temperature; and (d) power derating with temperature as a function of capacitor dimensions.*

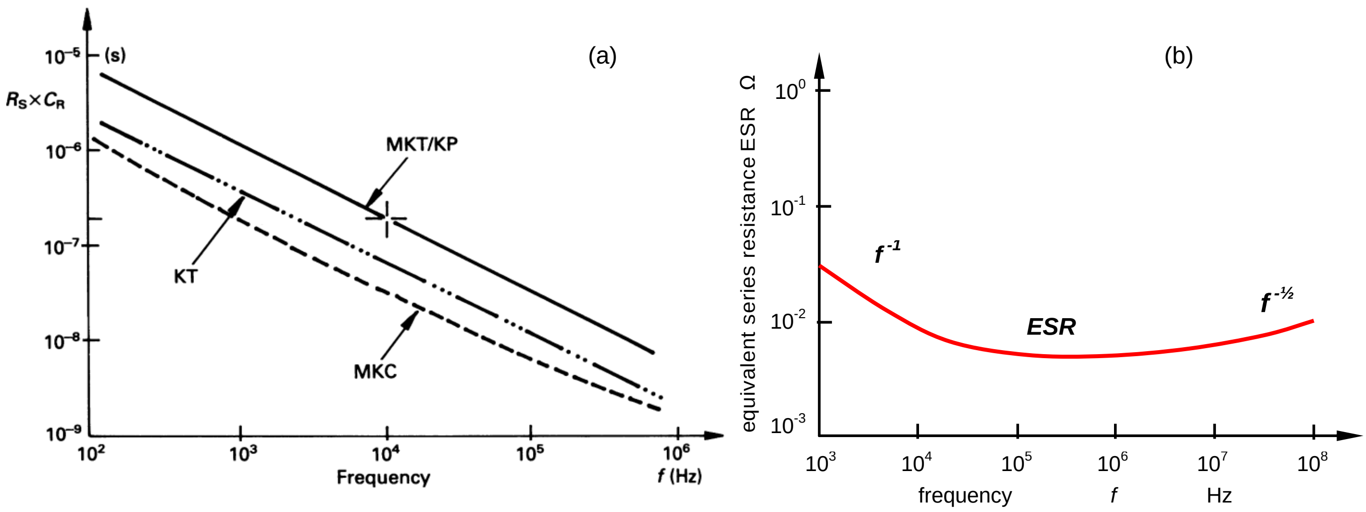

Figure 29.19. *ESR characteristics: (a) maximum product of series resistance, R_s, and rated capacitance, C_R, and (b) ESR as a function of frequency.*

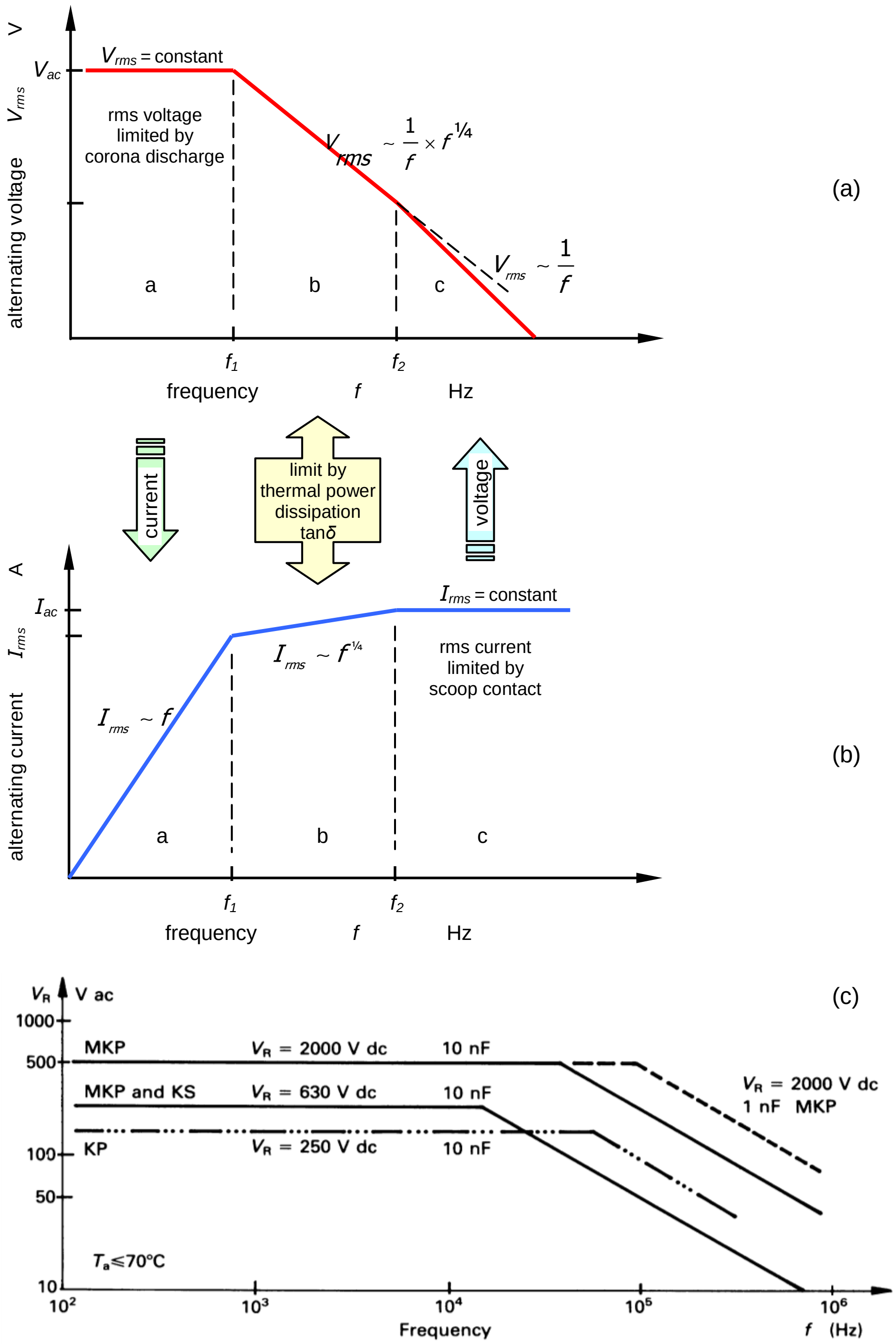

Figure 29.20. *Capacitor rating limits: (a) maximum ac voltage; (b) ac current; and (c) ac voltage derating with frequency of different metallised plastic capacitors.*

Example 29.6: ***Power dissipation limits - ac voltage***

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

Solution

i. Metallised polyester capacitor (MKT)
From equation (29.36)

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

From figure 29.19a, $R_sC_R = 2 \times 10^{-7}$ 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 29.18d, 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 100V ac. From figure 29.20c, it can be seen that a 0.1μF, 400V dc MKT capacitor is necessary, given that the dimension constraints are met.

ii. Metallised polypropylene capacitor (MKP)
From equation (29.37)

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

From figure 29.17a, tan *δ* = 4.0 × 10^{-4} at 10 kHz, for a 600V 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 29.18d, at 50°C, the smallest volume MKP capacitor, of dimensions 6.5×15×26 mm, can dissipate 300 mW. From figure 29.20c it can be seen that a 0.1μF, 630V dc (250V ac) MKP capacitor is necessary.
From figure 29.20c, a 250V dc 0.1μF polypropylene foil capacitor (KP) is capable of 160 V ac at 10 kHz. Figure 29.17a shows the dissipation factor of KP type capacitors to be under half that of the metallised equivalent. That is, the expected losses are only

$$P = \ (1.4\times10^{-4}) \times (2\pi\times10^{4}) \times (0.1\times10^{-6}) \times 100^2$$
$$= 9 \text{ mW}$$

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***29.3.3vii** - 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

$$R = \frac{V_R}{C_R\, dV/dt_{\max}} = \frac{V_R}{\hat{I}} \qquad (29.38)$$

where *R* is the minimum series resistance including the ESR. The rating test is an accelerated test, carried out for 10,000 pulses at a 1Hz repetition rate. The capacitor is then *dv/dt* rated at 10% of that at which the pulse test was performed.

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

$$\frac{dV_{op}}{dt} = \frac{dV_R}{dt} \times \frac{V_R}{V_{op}} \qquad \text{(V/s)} \qquad (29.39)$$

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 (diminishing availability) offer slightly better *dv/dt* properties than those of metallised polyester. Metallised paper capacitors can withstand high levels of *dv/dt,* 30 to 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 29.14d, a 1μF metallised polypropylene capacitor with V_R of 2000V dc and 1000V ac, a 2500V/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 29.17a. Under such high *dv/dt* stresses, it is important to ensure that the power dissipated (whence rms current) does not exceed the package limit.

29.3.4 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 29.21. The design approach is illustrated by example 29.7.

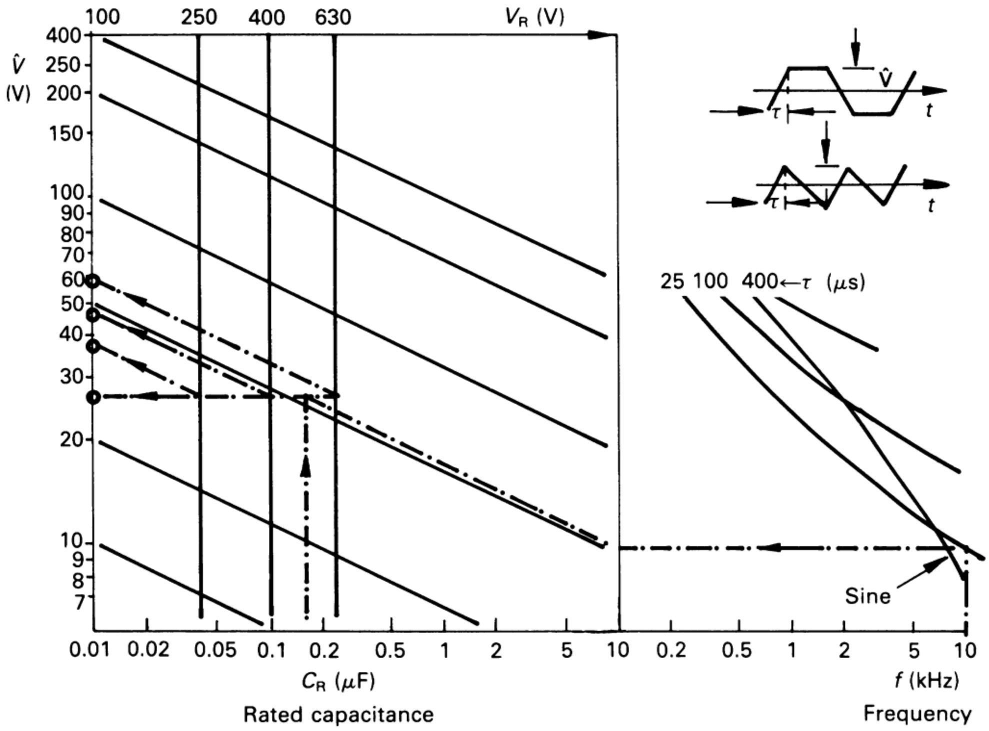

Figure 29.21. *Metallised polyester capacitor selection graph for sinusoidal and non-sinusoidal voltages.*

When capacitor voltages are more abstract, the concept of pulse characteristic can be applied for frequencies lower than 10kHz and low duty cycles, which is based on the internally generated heat.

$$W = \int_o^\tau I^2 R_i dt = \int_o^\tau C^2 \left(\frac{dV}{dt}\right)^2 \times R_i dt = ½C^2 \times R_i \times k_o$$

Thus k_o, relating the heat energy and pulse slope, is defined as

$$k_o = 2\int_o^\tau \left(\frac{dV}{dt}\right)^2 dt \qquad \text{V}^2/\text{s} \qquad (29.40)$$

where τ is pulse width and R_i is the effective internal resistance, dominated by the contact resistance.

For a ramp voltage change

$$\frac{dV}{dt} \approx \frac{V_{pp}}{\tau}$$

such that equation (29.40) gives

$$k_o \cong 2\frac{V_{pp}^2}{\tau} \quad \text{and} \quad \frac{dV}{dt} \cong \frac{V_{pp}}{\tau} = \frac{k_o}{2V_{pp}} \qquad (29.41)$$

This equation (29.41) shows that for a given capacitor, that is, a given k_o, the lower the source peak to peak voltage, the higher the allowable *dv/dt*, hence higher peak current.

For passive RLC type discharges and short-circuit configurations, k_o is

$$k_o = \frac{V_{ch}^2}{RC}$$

where R is the discharge circuit resistance and V_{ch} is the source charging voltage.

Example 29.7: *Capacitor non-sinusoidal voltage rating*

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

Solution

Worst-case conditions are at maximum frequency, 10kHz, and minimum risetime, 25μs.
With reference to figure 29.21, use

f = 10 kHz (repetition frequency)
τ = 25 μs (rise-time)
C = 0.15 μF (capacitance)

According to the dashed line in figure 29.21, 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.

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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

$$v = \sum_{\forall i} V_i \sin\left(i\omega t + \phi_i\right) \qquad (29.42)$$

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 (29.12) and (29.36), assuming capacitance is frequency independent

$$P_i = \left(R_s C_R\right)_i \omega_i^2 C_{R_i} v_i^2 \qquad (29.43)$$

or

$$P_i = \tan\delta_i \; \omega_i C_{R_i} v_i^2 \qquad (29.44)$$

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 29.17a and 29.19, 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 29.8: *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 third harmonic voltage Y?

Solution

From equation (29.44), 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 29.16b we may assume that capacitance is independent of frequency for polypropylene types. From figure 29.16a, at 50°C, rated capacitance has reduced by only 1 per cent - thus temperature effects on C_R may be neglected.
From figure 29.17a, 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 29.18d it can be seen that 880 mW can be dissipated in the largest package at 50°C.
Total power is given by

$$0.88\text{W} = 2.5\times10^{-4}\times2\pi\times10^4\times1\times10^{-6}\times100^2$$
$$+\; 4.2\times10^{-4}\times6\pi\times10^4\times1\times10^{-6}\times Y^2 \qquad \text{(W)}$$

Solving for Y, Y = 30.2 V rms.

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29.3.5 DC plastic capacitors

Significant increase in capacitance per unit volume per unit volt can be gained if plastic based capacitors are designed specifically for dc applications. Such applications include dc-link decoupling where electrolytic capacitors are avoided because of lifetime constraints and high-energy discharge capacitors; where voltage reversal is a critical parameter. Voltage reversal is the changing of the relative polarity of the capacitor terminals, such as experienced during ringing or oscillating pulse discharge, during ac operation, or as the result of dc charging the capacitor in the opposite polarity from which it had been previously dc charged.

Voltage reversal is the percentage of the peak voltage that is experienced in the reverse polarity. In an ac application, the reversal is 100 %. Oscillating pulse discharges usually have between 0% and 100% voltage reversal. DC capacitors are designed for the highest level of voltage reversal (normal or fault) that may be experienced in service. Adversely, high reversal ratings result in significant reductions in energy density and increases in size and cost.

The damage inflicted on a dc capacitor by a transient voltage reversal is a nonlinear function of the degree of reversal. As shown in Figure 29.22a, the change in life with between 80% and 85% reversal is much greater than the change between 20% and 30% reversal. The magnitude of the damage also depends on the rate of change of voltage during the reversal. The least deterioration is when the rate of change of voltage is slow, as in the case of dc charging the capacitor with the terminal connections reversed. The greatest damage occurs when the capacitor voltage ‘rings’ or oscillates at a high frequency, with the effect of frequency on life is shown in Figure 29.22b.

Capacitor life is extended by minimizing the degree of voltage reversal in the normal operating mode. A diode and series resistance in parallel with the capacitor can reduce voltage reversal. The smaller the series resistance, the lower the reversal on the capacitor.

Operating mechanism during voltage reversal

i. Electric Fields

Voltage reversals impact on the electric field magnitude in the capacitor dielectric. Dielectric over-stresses result from the superposition of the applied reverse electric field and the remnant polarization field from the original dc polarity. At typical pulse capacitor discharge rates, the electronic, atomic, and permanent dipole polarizations reverse virtually in phase with the applied field. However, inherently ‘slow’ polarization mechanisms acting in the dielectric, such as interfacial polarization associated with charge injection and ionic conduction, do not. The longer the capacitor remains dc charged, the greater the remnant polarization field magnitude. This field (which is anti-parallel to the applied dc field) is added to the applied field during a voltage reversal, increasing the total field within the dielectric. Excessive fields can result in immediate breakdown or may produce partial discharging, treeing, or other degradation.

Even in ac applications, where interfacial polarization may not have time to build up, charge can be injected from the electrodes into the adjacent dielectric, especially at sharp edges, one half-cycle, and then return to the electrode in the next half-cycle in a partial discharge process. Such discharges degrade the dielectric locally and eventually result in breakdown. Therefore, long-life ac capacitor elements are designed to operate at voltage levels where such charge injection is negligible. DC capacitors, on the other hand, can usually be operated at much higher stresses and can therefore be made smaller.

ii. Heating

The current waveform is used to determine the internal heating of a capacitor due to various energy loss mechanisms.

The energy dissipated in the capacitor during a single charge/discharge cycle (J_{cap}) depends on the I^2t integral of the current waveform and the equivalent series resistance (ESR) of the capacitor. The action involves the Joule's integral:

$$J_{cap} = ESR \times \int_0^T I^2(t)\,dt \qquad [\text{Joules}]$$

The ESR is not a true ohmic resistance and is a function of frequency, voltage, voltage reversal, temperature, and other parameters. The ESR includes a number of energy loss mechanisms, the two most important of which, in terms of voltage reversal mechanisms, are dielectric loss and electrode resistance.

- The dielectric loss results from motion of bound charge within the dielectric (displacement current) such as molecular dipole rotation, in response to an applied electric field. It is the dissipation factor (DF), since the losses vary linearly with capacitance.

- The electrode resistance is purely ohmic, with the skin effect becoming important at high frequencies. There are two basic types of electrodes used in film capacitors, discrete foils and metallisation. Foil electrode capacitors provide minimum ESR at high frequencies. Metallised electrodes can be used for relatively low frequency discharges (less than 10 kHz) where the ESR is dominated by the dielectric loss.

Capacitor design for voltage reversal

The critical aspects of the capacitor design in relation to voltage reversal effects are the dielectric materials, the rated voltage and rated electric field, and the type of electrode and internal connections.
The resistance of different dielectrics to voltage reversal effects vary.

- A paper dielectric is suitable for high reversal discharge applications. Mixed dielectrics such as paper and polypropylene laminates are more susceptible to damage in voltage reversal than all-paper dielectrics because of interfacial polarization. All-polypropylene dc capacitors are highly susceptible to foil edge failure at moderate voltage reversal.
- Dry capacitors should be used in high reversal applications only at low voltage (less than 1kV) and low stress. A liquid impregnant should be incorporated in the dielectric to suppress partial discharges. Some impregnant materials are able to absorb gases and other decomposition products better than others.
- Metallised capacitors are more robust than foil capacitors in terms of ability to survive high reversal discharges without immediate failure. As long as ratings are not exceeded, high reversals simply accelerate the rate of capacitance loss. If peak current or ratings are exceeded, however, failure of the internal connections may occur, resulting in large capacitance loss, increased DF and ESR, and reduced voltage capability.

Capacitors designed to operate for long lifetimes (>10^7 pulses) at relatively low electric field stresses are more robust in the event of fault condition reversals, and capacitors being operated at well below their rated voltage are more likely to survive.

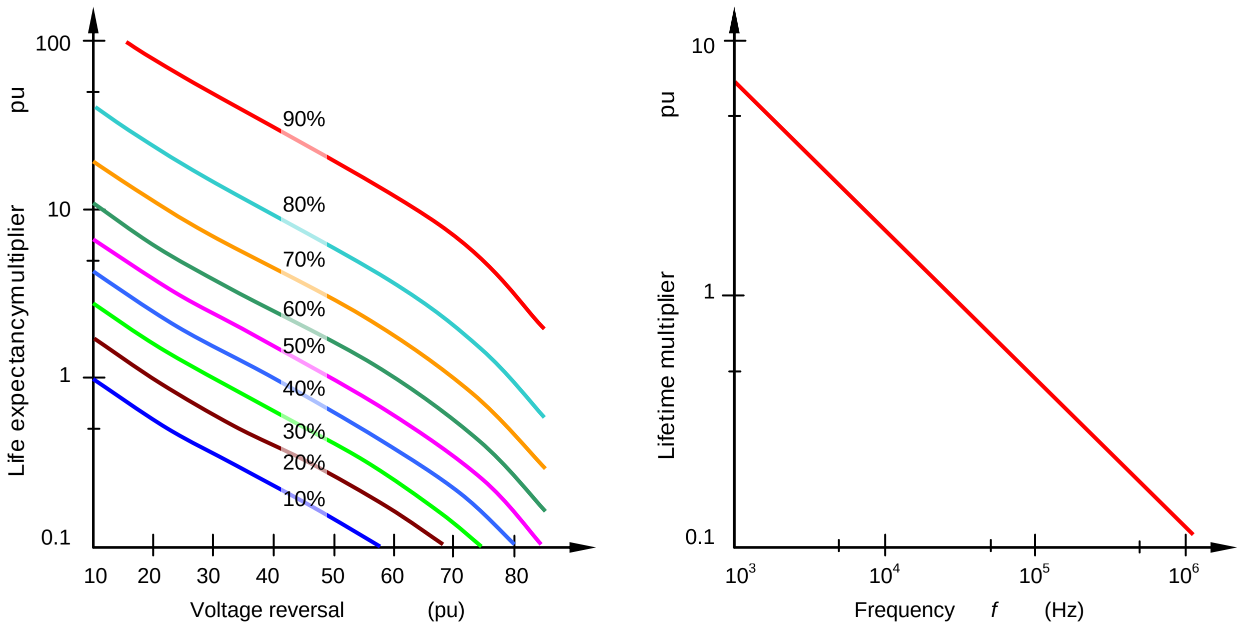

Figure 29.22. *Effects of: (a) dc capacitor voltage reversal on lifetime and (b) lifetime versus frequency of voltage reversal oscillation.*

The key properties of plastic type non-polarised capacitors are summarised in Table 29.5. The excellent dielectric properties of polypropylene lead to metallised polypropylene capacitors being extensively used in power applications.

Polycarbonate film based capacitors (KC and MKC) are obsolete. Mixed dielectric alternatives, based on polyethylene-terephthalate and polypropylene are recommended, but no alternative matches the excellent temperature and high frequency properties of polycarbonate.

Table 29.5: Properties of non-polarised plastic type capacitors

dielectric type	ε_r	tanδ	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

29.4 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 (7 classifications in all, IEC60384-14) used between line and neutral are termed class X while those used to earth (either line L or neutral N, to ground, G) are termed class Y.

29.4.1 Class X capacitors L-N

X capacitors are suitable for use in situations where failure of the capacitor would not lead to danger of electric shock. X capacitors, for 250V ac application, are divided into three subclasses according to the ac power line voltage applied.

- The X1 subclass must support a peak voltage in excess of 2.5 kV (<4kV) in service, while
- X2 capacitors have peak service voltage capabilities of less than or equal to 2.5 kV and
- X3 ≤ 1.2kV.

In order to obtain the peak voltage requirement of X1 capacitors, a construction comprising impregnated paper dielectric and metal foil electrodes is essential. The common X1 capacitance range is 10nF to 0.2μF. Class X1 is impulse tested to 4kV, and 2.5kV for X2. Both are tested to higher voltages if C ≥ 1μF. 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 29.17a. These films also offer good insulation properties as shown in figure 29.15. Variation of capacitance with frequency and temperature is shown in figure 29.16, while percentage variation of losses, tan δ, with frequency and temperature is shown in figure 29.23. The typical capacitance range of X2 capacitors is from 10 nF to 1 μF, rated for 250 V ac application.

29.4.2 Class Y capacitors L-G or N-G

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 2.5nF and 35nF are extensively used. Capacitance as low as 0.5nF is not uncommon.
A Y-class capacitor for 250V ac application can typically withstand over 2500V dc for 2s, layer to layer. On an ac supply, 425V ac ($\sqrt{3}\, V_R$) for 1000 hours is a common continuous ac voltage test.

- Class Y1 is impulse voltage tested to >8kV,
- > 5kV for Y2
- Y3 n/a, and
- Y4 > 2.5kV.

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 29.15a.
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.

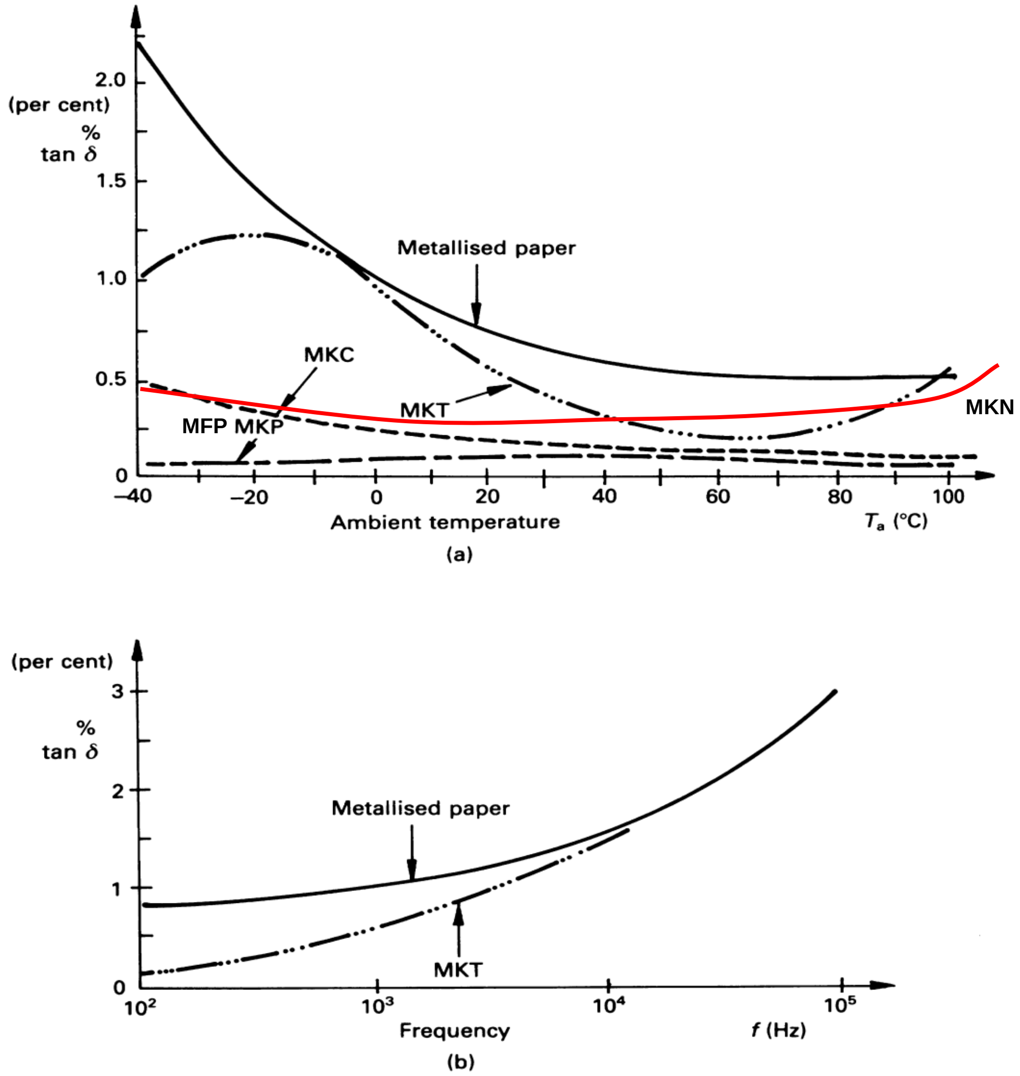

Figure 29.23. *RFI capacitance variation with:*
(a) ambient free-air temperature and (b) frequency.

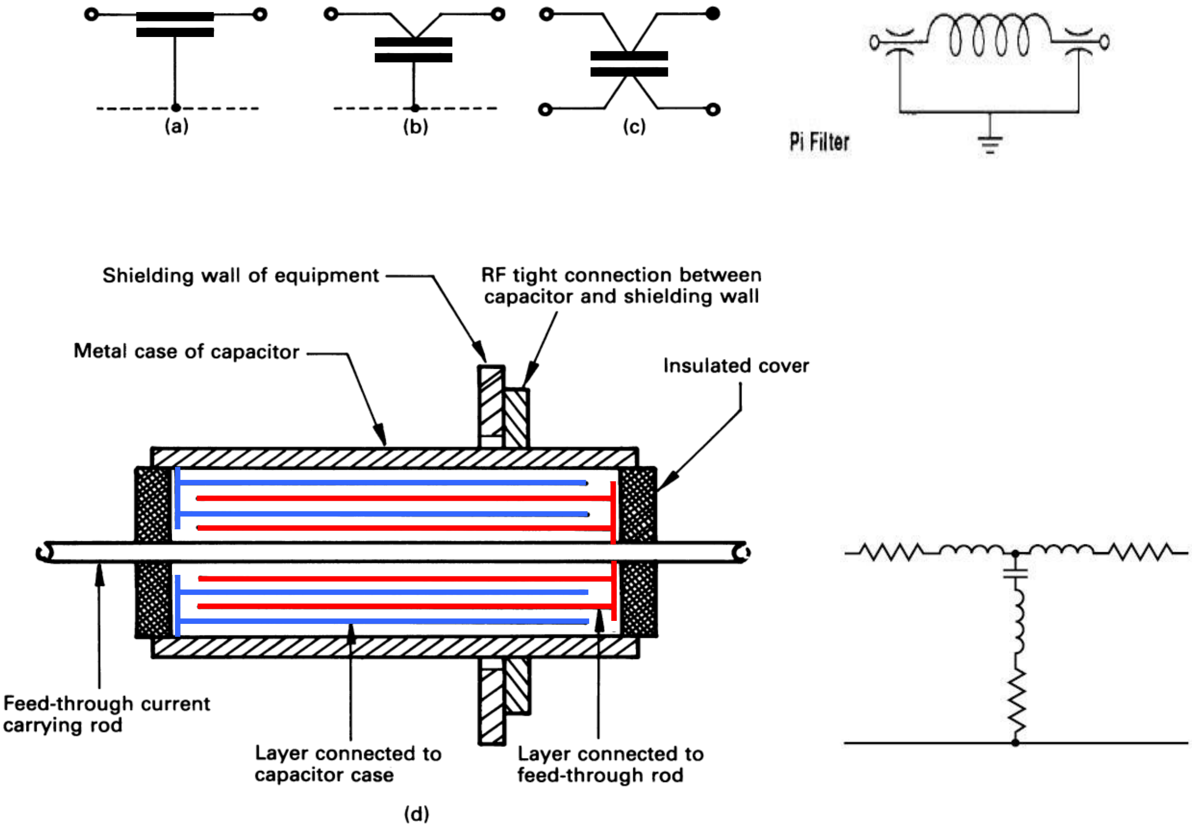

Figure 29.23. *Feed-through capacitors for RFI attenuation:*
(a), (b) three user terminals; (c) four terminals; and (d) coaxial feed-through capacitor construction.

29.4.3 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 capacitor 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 29.23a and b show three terminal feed-through capacitors while figure 29.23c is a four-terminal capacitor. A three-terminal coaxial feed-through, wound capacitor cross-section is shown in figure 29.23d. 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 X1 and X2, rated at 240 V ac, 440 V ac, and 1000 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 X and Y class capacitors does not imply those requirements necessary to conform to governmental safety and design standards.*

29.5 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 1μm and 100μm 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 at the tens of kVs level, for example, dielectric class I, 2.1nF at 50kVdc, tanδ=0.2% (TC: Y5S). These same materials are used to make positive temperature coefficient resistors - thermistors, where dopants are added to allow conduction. They also exhibit piezoelectric/electrostrictive properties.

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 29.6.

Table 29.6: 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	see table 29.8		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%
Capacitance	C	nF	< 0.2	< 4.7		< 40
Rated voltage	V_R	V	500-1k	100 to >2k		

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

Table 26.6a: Class *I* ceramic material properties

composition	$MgNb_2O_6$	$ZnNb_2O_6$	$MgTa_2O_6$	$ZnTa_2O_6$	$(ZnMg)TiO_3$	$(ZrSn)TiO_4$	$Ba_2Ti_9O_{20}$
Permittivity ε	21	25	28	38	32	37	40
Temperature coefficient 10^{-6}/K	-70	-56	18	9	5	0	2

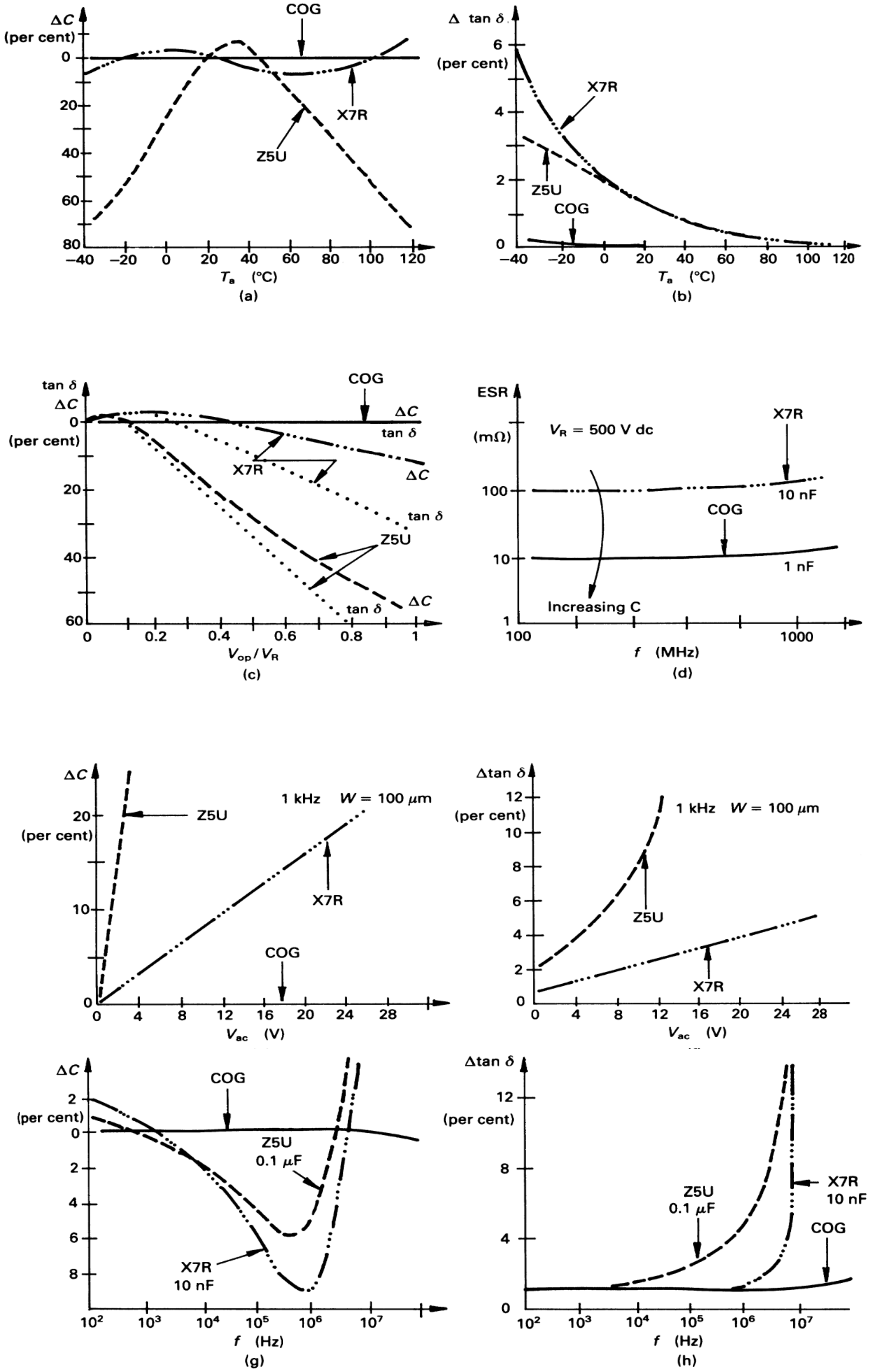

Figure 29.25. *Typical properties of commercial ceramic capacitors: (a) capacitance change with temperature; (b) dissipation variation with temperature; (c) capacitance change with dc voltage; (d) ESR change with frequency; (e) capacitance change with ac voltage; (f) dissipation factor variation with ac voltage; (g) capacitance change with frequency; and (h) dissipation factor variation with frequency.*

Table 29.7: 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%

Table 29.8: Class II ceramic capacitor parameter coding – EIA designation

Dielectric class II (and higher) capacitor ceramic code					
Letter code	lower temperature	Number code	upper temperature	Letter code	ΔC over temperature range, *ΔT*
Z	+10°C	2	+45°C	A	±1.0%
				B	±1.5%
		4	+65°C	C	±2.2%
Y	-30°C			D	±3.3%
				E	±4.7%
		5	+85°C	F	±7.5%
				P	±10.0%
		6	+105°C	R	+15.0%
X	-55°C			S	±22.0%
		7 8 9	+125°C +150°C +200°C	T	+22% to -33%
				U	+22% to -56%
				V	+22% to -82%

29.5.1 *Class I dielectrics - Low K (ε_r < 500)*

This class of dielectric consists mainly of TiO_2 and additions of BaO, La_2O_3 or Nd_2O_5, which provides a virtually linear, approximately constant and low temperature coefficient as shown in figure 29.25a.
COG [EIA or industry code alternative NP0] capacitors belong to the class I dielectrics and have a low temperature coefficient over a wide temperature range, as seen in Table 29.6. They provide stability and have 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.

29.5.2 *Class II dielectrics - K, ε_r > 500*

Ceramic capacitors in this class are usually based on a high permittivity ferroelectric dielectric, $BaTiO_3$, 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 29.25. Their characteristics are less stable, non-linear, and have higher losses than class I ceramic, as seen in Table 29.6. See Table 29.7 for a comparison between types and Table 29.7

for class II dielectric coding for capacitance variation for different temperature ranges, e.g. X7R, Z5U.
The mean time between failure λ_o is transformed from the rated voltage and temperature conditions to the operating conditions by equation (29.16), that is

$$\lambda = \lambda_o \times \text{acceleration factors} = \lambda_o \left(\frac{V_{op}}{V_R}\right)^n e^{-\frac{E_a}{k}\left(\frac{1}{T}-\frac{1}{T_O}\right)}$$

where the activation energy E_a and voltage index n are shown in Table 29.9. k is Boltzmann's constant, 8.625x10^5 eV/K.

Table 29.9: Accelerated MTBF factors

	E_a	n
Dielectric type	activation energy eV	voltage index
NP0	1.15	2.9
X7R	1.15	2.9
Y5V	1.07	2.4

29.5.3 *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 29.25c. Such a capacitor can be used in the turn-off snubber for the GTO thyristor and diodes which are considered in 10.1.3 and 10.1. 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 10.3.4. 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. *Piezoelectric effects* (change of physical size when an electric field is applied) can cause failure due capacitor cracking in traditional X7R class *II* ceramic capacitors.

29.6 Mica dielectric capacitors

The dielectric mica can be one of 28 mica types. It is a naturally occurring inorganic, chemical resistant, clear mineral aluminosilicate (usually India Ruby muscovite, is a hydrated silicate of potassium and aluminium, $H_2KA\ell_3(SiO_4)_3$) which has a plane of easy cleavage enabling large sheets of single crystal to be split into thin 20μm to 100μm plates, typically 50μm.
The general formula for mica is AB_{2}-$_{3}$(Aℓ, Si)Si-$_{3}$ O-$_{10}$ (F, OH)-$_{2}$. In most micas the A is usually potassium, K, but can be calcium, Ca, sodium, Na, barium, Ba, or some other elements in the rarer micas. The B element in most micas can be aluminium, Aℓ, and/or lithium, Li, and/or iron, Fe, and/or magnesium, Mg. Phlogopite mica is a hydrated silicate of potassium and magnesium.

Ultra thin silver electrodes are screen printed on to both sides of the mica (and over the edge), as shown in figure 29.26b, which is then fired in an oxidisation atmosphere to obtain a permanent plated adhesive bond between the mica and silver. Variation of silver electrode thickness affects the dissipation factor, while the overlapped printed silver area and mica thickness control the capacitance.
A number of different techniques (and combination of different techniques) are used to parallel connect (parallel stack) the silver coated mica plates in order to give high capacitances.

- Multiple layers of over-the-edge printed mica plates are stacked together (without any interposing foils), as shown in figure 29.26a. The printed silver at each opposite edge is bonded with silver paste, on to which the terminals are directly soldered.
- Multiple silver printed plates are stacked interleaved with metal outer foils for contacts. The foils are made of silver, copper, brass, tin or lead. The foil alternately extends from each end and covers a portion of the plated area. Joining the extended foils at each end, parallel connects each individual mica plate. The stack is held and compressed together either by the encapsulation or by bending the extended foils over the top of the stack which is held by a brass metal (tin coated) crimp, which also acts as a heat sink. Copper clad (for at least 30% conductivity) steel leads are spot-welded to each clip, which is then solder coated.

The assembled unit is encapsulated by dipping it into high melting temperature microcrystalline wax or by dipping in phenolic resin, then vacuum impregnating with liquid epoxy resin.
Mica capacitors are non-magnetic, non-polar, low loss, and stable up to about 30 MHz, where the lead length and electrodes dominate as inductance, typically 5 to 10nH. They are characterised by extremely low capacitor coefficients of temperature and voltage over a wide parameter operating range. Mica has a typical impregnated relative permittivity of 4.5 to 6.5 and a density of 1.65 g/ cm^3.

Alternatively, synthetic fluorine mica, fluorophlogopite $KMg_3(A\ell Si_3O_{10})F_2$, contains no $(OH)^-$ of the natural phlogopite $KMg_3(A\ell Si_3O_{10})(OH)_2$. The $(OH)^-$ is fully substituted with F^-. Large fluorine mica crystals of high quality are grown using platinum crucibles with seeds. It has properties similar to natural mica:

Melting temperature	^oC		1378
Density	g/cm^3		2.8
Dielectric strength	kV/mm		~180
Volume resistivity	Ω-cm		$4x10^{16}$
Surface resistivity	Ω -cm		$3x10^{12}$
Dielectric constant	ε		~6
Dielectric loss	tanδ	1MHz	$3x10^{-4}$
Tensile strength	kg/cm^2		~1500

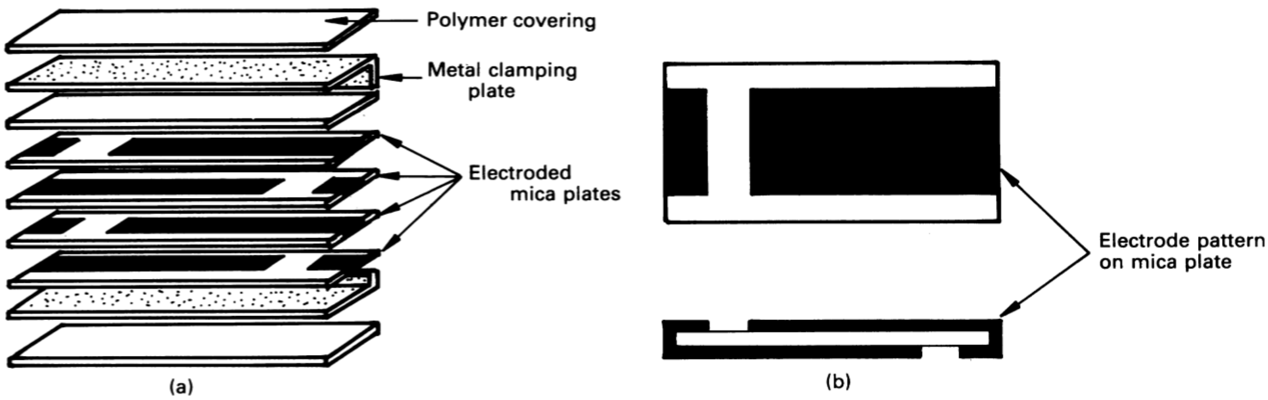

Figure 29.26. *Silver mica capacitor:*
(a) exploded construction view and (b) electrode pattern of a silvered mica plate.

29.6.1 *Properties and applications*

Maximum ratings are a few nanofarads at 50 kV, to 5μF at 1500V, with dissipation factors of 0.1 per cent at 1 kHz. Low dissipation factor is countered by poor dielectric absorption. A 10nF, 50kV mica capacitor in a cylindrical volume of $\Phi = 150$mm×$H = 120$mm, has <100nH of internal inductance and is capable of 1kA-200ns pulses. For capacitance less than 1nF, 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 10nF, after which resistance falls off. Typical operating temperature range is from -55°C to 125°C, with a low capacitance temperature coefficient of 0 to +70 ppm/K. The Indian Ruby mica itself, is thermally stable to 500°C. A capacitance voltage coefficient of ±0.1% over the full voltage range is typical. 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. Because losses are low, typical 0.05% of the throughput VA, energy densities of between 15 and 125 mJ/cm^3 are readily attained.
In power applications, mica capacitors are used to produce stable, high current pulses at high *dv/dt* (20kV/μs), as for NMR MRI coils, because of its excellent high voltage breakdown properties and corona resistance. Mica dielectric capacitors are sensitive to pressure.
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.

22.7 Capacitor type comparison based on key properties

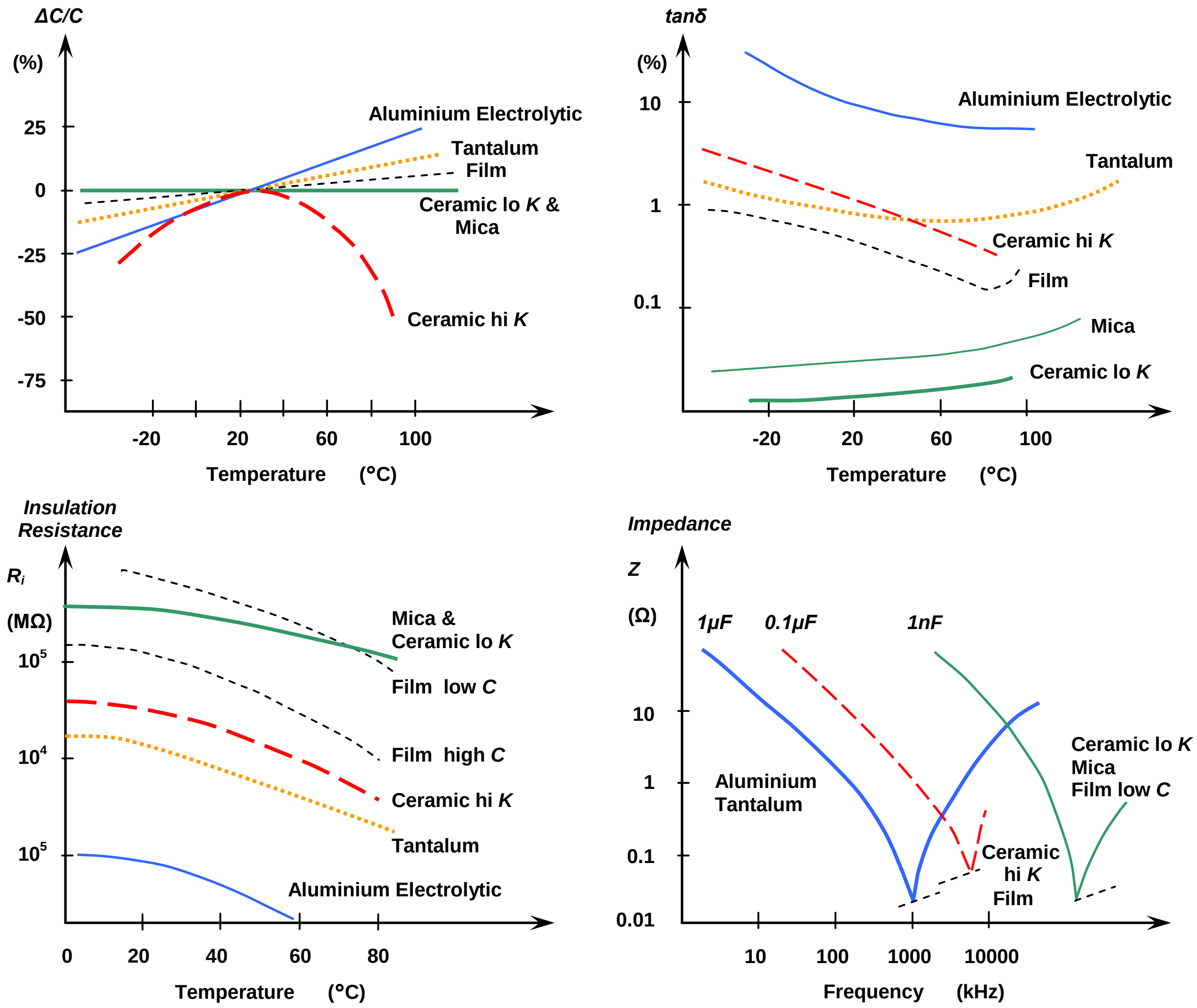

Figure 29.27. *Capacitor type characteristic comparison.*

29.8 Appendix: Minimisation of stray capacitance

Unexpected component stray capacitance, and inductance, can have disastrous power circuit consequences. Figure 29.28 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 1pF of capacitance, and at 10,000V/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 29.28a 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 100pF 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 (29.3), but at the expense of increasing thermal resistance. Aluminium nitride reduces the thermal impedance compared to $A\ell_2 0_3$, but at the expense of increased cost.

Transformer interwinding capacitance, shown in figure 29.28b, 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 connected to a transformer terminal, 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 20.23b. Coil inter-turn capacitance is also a source of capacitive *dv/dt* current injection.

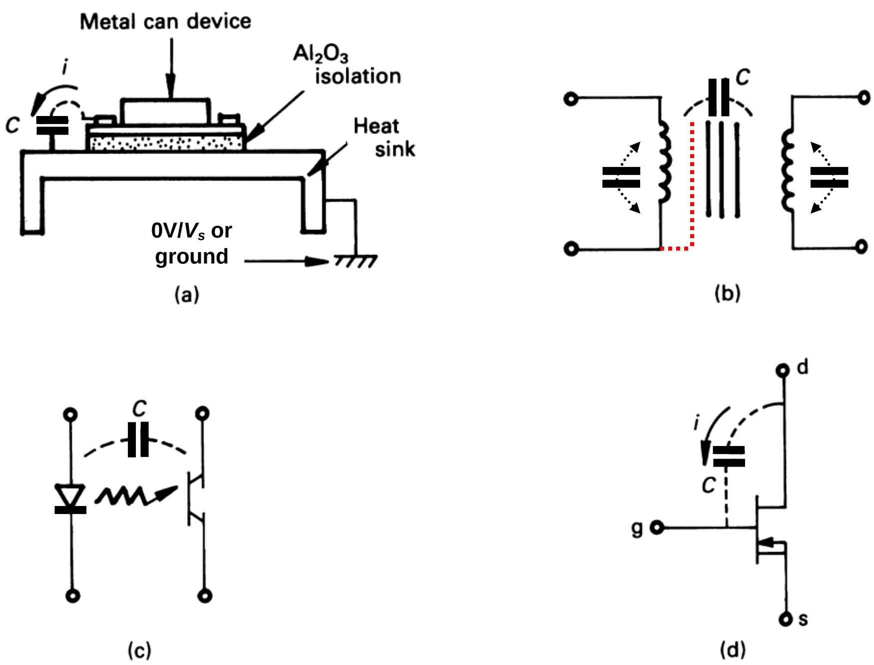

Figure 29.28 *Component stray capacitance C:*
(a) when isolating power devices; (b) between transformer windings; (c) in opto-couplers; and (d) between terminals of metal oxide semiconductor devices.

A similar solution is used in opto-coupler packages. A grounded (with respect to the transistor) 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 15000V/μs at 200V dc levels. This *dv/dt* limit decreases to 1000V/μs on a 600V 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 isolation separation. For high voltages and high *dv/dt*, a fibre optic is an expensive alternative, but unlike the pulse transformer, has no lower cut-off frequency.
Two performance enhancement techniques are used in optocouplers:

- Indium Tin Oxide - Faraday Shield

  The use of the oxide as a Faraday shield on top of the detector die improves the common mode, CM, transient immunity behaviour of optocouplers. The physical property of this material makes it transparent to light, but electrically conductive, so that the transient current, which might turn the detector on or off, is shunted to ground. This decreases the effective isolation barrier capacitance roughly by a factor of 10, and therefore improves the CM properties significantly.

- Transparent Ion Shield - Field Effect Stable Optocouplers

  This shielding makes the optocoupler stable against field effects, but has no influence on fast transients. The advantage of the ion shield are realised when static electrical fields are applied to the optocoupler. The ion shield helps in high electrical fields to prevent excessive dark or leakage current or current gain drops and thus maintains the performance of the optocoupler in these harsh environments.

Figure 29.28d 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 possible voltage step-down ratio probes, since capacitance tends to decrease with increased step down ratio.

29.9 Appendix: Capacitor lifetime derating

General formulae for estimating lifetime τ dependence on operating temperature T_{op} and voltage V_{op} are:

Film capacitor

$$\tau\left(V_{op},T_{op}\right)=\tau_R\times\left(\frac{V_R}{V_{op}}\right)^{7\text{ to }8}\times 2^{\frac{T_{core}-T_R}{7^\circ\mathrm{C}}} \qquad (29.45)$$

where τ_R, V_R, and T_R are rated lifetime, voltage, and temperature. T_{core} is the capacitor core temperature.

Ceramic capacitor

$$\tau\left(V_{op},T_{op}\right)=\tau_R\times\left(\frac{V_R}{V_{op}}\right)^{3}\times\left(\frac{T_R}{T_{op}}\right)^{8} \qquad (29.46)$$

Aluminium electrolytic capacitor

$$\tau\left(V_{op},T_{op}\right)=\tau_R\times\left(\frac{V_R}{V_{op}}\right)^{1}\times 2^{\frac{T_{core}-T_R}{10}} \qquad (29.47)$$

The voltage multiplier term may be expressed in a more specific capacitor type form, for example

$$4.3-3.3\times{}^{V_{op}}\!/\!_{V_R} \qquad (29.48)$$

Solid tantalum capacitor

$$\tau\left(V_{op},T_{op}\right)=\tau_R\times\left(\frac{V_R}{V_{op}}\right)^{3}\times 2^{\frac{T_{core}-T_R}{10}} \qquad (29.49)$$

Reading list

Siemens, *Components,* 1986.

http://my.execpc.com

Rohm.com

Kemet.com

AVXcorp.com

Vishay.com

Epcos.com

Evox-Rifa.com

Cornell-Dubilier.com

illinoiscapacitor.com

mfdcapacitors.co.uk

wima.de/en_index.php