You may know which capacitor technology to choose for a given task, but do you know why it's the best choice? Having spent thirty years designing, specifying and troubleshooting capacitors, Cyril Bateman shares his expertise.

Understanding capacitors

To my surprise, recent review of my publications library revealed a scarcity of capacitor articles. Perhaps I should have anticipated this since on reflection, many text books and circuit simulators all consider capacitors as ideal, so why delve further. On the other hand, capacitors have also been called 'strange devices', i.e. *unfamiliar*, which this article seeks to remedy.

Thirty years of experience as a capacitor design and applications engineer has convinced me that over-stressed or mis-applied capacitors are involved either directly or indirectly in most circuit failures. All components wear out in time, but mis-applied capacitors can fail extremely quickly. Worse still, before the capacitor ultimately fails, it can directly contribute to failure of semiconductors, masking the prime failure mechanism.

The best way to understand unfamiliar components is to perform measurements on representative samples, then dismantle them to understand their differing constructions. But with capacitors, not all the significant details are immediately apparent.

Capacitor overview

The fundamental definition of capacitance relates to charge and voltage, measured statically. Descended from the Leyden jar, a capacitor is essentially an energy storage device. Since its stored energy can be charged or discharged extremely quickly, alternative common usage ac definitions have been derived, as discussed in the panel entitled 'Defining capacitors'.

Of these definitions, the most important relates a capacitor's impedance to frequency,

$$|Z| = \sqrt{R_s^2 + (Xc_s - Xl_s)^2} \tag{1}$$

Where,

$$Xl_s = 2\pi F L_s \tag{2}$$

and,

$$Xc_s = \frac{1}{2\pi F C_s} \tag{3}$$

Throughout this article, the series equivalent expressions are used, denoted as Xc_s, R_s etc., unless otherwise stated.

At any frequency, the term Xc_s–Xl_s can be simplified to jX_s, giving the fundamental vector equation for impedance, $Z=R_s \pm jX_s$.

This vector equation leads to the common usage expressions for impedance magnitude |Z|,

$$|Z| = \sqrt{R_s^2 + X_s^2}$$

and phase angle,

$$\theta = \tan^{-1}\frac{X_s}{R_s}$$

This phase angle definition results in the second most important quantity for capacitors – loss factor,

$$\tan\delta = \text{abs}\frac{R_s}{X_s}$$

An ideal capacitor would have a phase angle, hence tanδ, that remained constant regardless of frequency. Since by definition, eqn 3, a capacitor's reactance, Xc_s, is totally dependent on frequency, so also must be the capacitor's series resistance, R_s, known as esr. This is clearly demonstrated by the results measured for a very high quality polystyrene capacitor, **Table 1**.

Table 1. Clear demonstration of how esr changes significantly with frequency. Measured results of a high quality 10nF polystyrene foil/film capacitor, made using a four terminal Wayne Kerr 6425 precision component analyser at a test voltage of 1V.

Frequency	Capacitance (nF)	Tanδ	'Q'	ESR (Ω)
100Hz	9.9982	0.00010	9000	17.0
1kHz	9.9988	0.00005	20000	0.8
10kHz	9.9986	0.00015	6000	0.26
100kHz	10.0000	0.0005	3000	0.05

What is a capacitor ?

Any two conducting surfaces, separated by an insulator, exhibit capacitance. The value of this capacitance increases with surface area and reduces with separation.

The fundamental definition of capacitance assumes this insulator is a vacuum, thus directly relating to the permittivity of free space.

$$\textit{Capacitance} = \textit{Free space permittivity} \times \frac{\textit{Area}}{\textit{Separation}}$$

But area and separation alone are insignificant compared to the contribution provided by a change of insulation material. Each insulation material used is rated for dielectric constant, or

'K value. This represents its permittivity relative to free space.

In practical materials used to make commercial capacitors, this 'K' ranges[1] from 1.00059 for air, 2 to 4 for plastic films, 8 for aluminium, 28 for tantalum electrolytics, and from 6 up to 12000 for differing ceramic formulations.

Given this wide range of dielectric constants, it is natural to loosely categorise all capacitors by the dielectric material used. While in general this is valid, the final capacitor's size and electrical properties also vary according to the construction methods used.

For a given dielectric, thickness – or rather thinness – is all important in determining the capacitance achieved in a given physical size. Usable dielectric thinness is limited by its ability to sustain the required voltage as well as surviving manufacturing methods. Common plastics which can be manufactured in micrometre thicknesses[2], withstand around V dc per micrometre, at room temperature, short term.

Since the dielectric for electrolytic capacitors is 'formed' in situ on the base foil, it doesn't need a minimum thickness to provide handling strength, as do plastic films. Together with certain multilayer and disc ceramic construction techniques, electrolytic dielectric thinness is limited only by the voltage that needs to be sustained.

To minimise the final size, the dielectric together with its conducting surfaces – the electrodes – may be compacted using winding, stacking, folding or layering techniques. These processes lead to supplementary descriptions including wound, stacked and multilayer.

Electrodes formations

The conducting surface for paper or plastic dielectric materials is produced by one of two common techniques. In one of them, an extremely thin, visually transparent coating of tal, generally aluminium, is vapour deposit- on to the insulator in a vacuum chamber, resulting naturally in the description metallised capacitor. This method however cannot be used with polystyrene.

When the dielectric itself is not metallised, the alternative and electrically superior method uses thin flexible soft metal foils or discrete metallised plastic foils, as electrodes. These foils are interlaid with the dielectric during assembly.

The surface of ceramic dielectrics is generally made conductive by coating with suitable metal inks. After air drying, these are 'fired' at high temperature.

With aluminium electrolytics, the aluminium base anode foil has the dielectric oxide, i.e. Al_2O_3, pre-formed electrolytically on its surface prior to assembly. The anode foil acts as one conducting electrode.

This electrolytically formed dielectric's thickness is self regulating, attaining some 14Å for each volt applied in manufacture. At V working for example, this represents only 0.02µm dielectric thickness (1µm, or micron, is 0.00394in). The true second electrode is the electrolyte material with which the separating tissue paper is impregnated.

Assuming a polarised capacitor, connection to the electrolyte is made using a second, usually thinner, aluminium foil or cathode. While this cathode is not deliberately formed, it inevitably possesses a much thinner naturally occurring aluminium oxide, electrically equivalent to a few volts. In this way, a pair of back to back capacitors is created. One has the desired capacitance and voltage capability while the other has a much greater capacitance but only a few volts capability, applied in reverse.

With a non-polarised, or bi-polar capacitor, this unformed cathode is replaced by a second deliberately formed anode foil. This results in two capacitors back to back, usually having the same capacitance and voltage capability.

Depending on the desired life-length characteristics, the pre-forming voltage used can range from 1.2 times to more than double the working voltage, trading size and cost against leakage current, and hence endurance.

Properties of capacitors

Every capacitor needs conducting surfaces, or electrodes, which inevitably have some intrinsic resistance. Having a physical cross section and length equates automatically to inductance, called self-inductance. As a result, a capacitor must be represented as a series *CLR* combination circuit.

This *CLR* network results in a circuit whose resonant frequency depends on the capacitor's value and construction. At the resonant frequency, the capacitor represents a dc blocking low value resistance, and a dc-blocking but inductive reactance at frequencies above this resonance.

At any frequency, a perfect capacitor, having neither resistance nor inductance, would sustain a voltage in quadrature with the applied current. Analysed on a polar display, voltage would be –90° and current 0°, so the complementary angle delta would be zero. Having no resistive element, this perfect capacitor cannot lose or dissipate energy.

The self-inductance results in a voltage at +90°. This subtracts magnitude from the capacitive voltage, increasing the apparent capacitance value which would be measured.

With a near perfect capacitor, the above resistance, appearing in series with the capacitive reactance, degrades this –90° angle, resulting in the complementary angle delta increasing. This change in phase angle represents the resistive element which dissipates energy as heat in the capacitor, **Fig. 1**.

With capacitors, it is usual to refer only to this delta loss angle, which is generally described as tanδ.

Dielectrics

Unfortunately, all dielectrics other than vacuum contribute their own particular degradations from this near ideal capacitor. In general the more highly stressed the dielectric, in volts per micron, the greater the degradations.

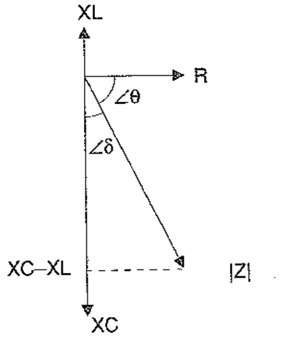


Fig. 1. This simple vector diagram shows the relationship between tanδ and cosθ. Both are essentially equal only with small loss angles. The interaction between the capacitance Xc and inductance Xl vectors is also visible.

Since the characteristics of both vacuum and air capacitors depend principally on the particular insulators used to support their assembly, they are excluded from these discussions.

Depending on the symmetry of its molecular structure, each plastic dielectric can be described as having either polar or non-polar characteristics. A symmetrical-molecule plastic, or other non-polar dielectric, has electrical characteristics effectively constant with changing frequency, and exhibits minimal dielectric absorption effects.

If this polymer molecule is not symmetrical, it has a dipole moment resulting in increased dielectric constant. Similarly, ferroelectric ceramic crystal poles and domains can produce extremely high dielectric constants. Such types are known as high-K dielectrics.

Both result in polar characteristics, i.e. a capacitance that reduces and a tanδ that increasing with frequency. These are functions of the basic materials used – not to be confused with the constructional terms polarised and non-polarised or bi-polar, as applied to electrolytic capacitors.

While manufacturing techniques cannot change a polar dielectric into a non-polar, they can enhance the polar effect. Stressed with dc voltages, polar materials exhibit a reluctance to accept or release their full charge instantaneously – a behaviour called dielectric absorption.

What is dielectric absorption?

If a capacitor is fully charged, to say 10V, for a considerable time, briefly discharged using a short circuit, then left to recover, a voltage is found which develops with time. The ratio of this resultant voltage compared to the initial charge voltage, is described as dielectric absorption.

In past years dielectric absorption was only

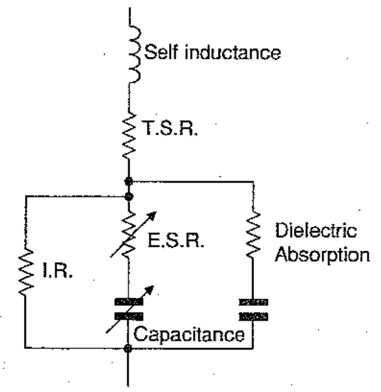


Fig. 2. Full equivalent circuit for a practical capacitor. In practice esr includes the tsr resistance, which is only shown separately to aid explanation.

considered relevant to high voltage capacitors, as a safety hazard. With modern techniques it becomes relevant at very low voltages.

Measured values of dielectric absorption vary with measurement technique, but more importantly with dielectric stress applied, in volts per micron. Typical figures range from 0.05% for polystyrene[2], 0.25% for polyethylene terephthalate, or PET, to 5% for aluminium.

Some dielectric materials also have a small degree of piezoelectric effect, which can result in a voltage when they are mechanically constrained, whether physically or from temperature changes while rigidly or surface mounted. Some care is needed to differentiate this effect from that of dielectric absorption.

Both effects are small and are irrelevant for most applications. However when working with sample/hold circuits, charge amplifiers, etc., capacitor choice should account for these effects.

According to manufacturing techniques used, every practical capacitor exhibits some dielectric absorption effect. However polystyrene or polypropylene film/foil and COG NPO dielectric ceramic capacitors, show minimal effects.

With the inclusion of this dielectric absorption mechanism, it is now possible to deduce the equivalent circuit for a practical capacitor, **Fig. 2**.

How temperature affects capacitors

Ceramic COG NPO type capacitors are restricted to ±30ppm/°C change of capacitance with temperature and are the most stable available. With the exception of these, all dielectrics show easily measured larger capacitance changes over their temperature range.

General-purpose ceramic capacitor dielectrics are categorised under the EIA classification scheme. The popular X7R material is thus restricted to a box envelope allowing ±15% change in capacitance over its working temperatures. However the exact profile within this envelope, differs with manufacturer.

Change in temperature also results in a change of measured tanδ for most common dielectric materials. Non-polar dielectrics show very small changes, but with a polar dielectric, the maker's data should be consulted.

The behaviour of plastic-film capacitors however tends to be consistent according to the materials used and less dependent on specific manufacturer.

Voltage effects

Many polar dielectrics have a capacitance which changes with applied ac or dc voltage. With voltage, capacitance tends to increase above that measured at 1V then declines. Since this behaviour depends on the precise dielectric chosen and manufacturing technique, makers data should be consulted.

Frequency effects

As shown in published data, almost all capacitors exhibit a frequency-dependent capacitance change. Less well known, the dielectric strength or voltage withstand of film dielectrics, can reduce[2] with increasing frequency. For many applications this is not important since the power or current rating constraints which should be applied, dominate.

With pulse waveforms having large peak-to-mean ratios, power constraints no longer dominate, so it is essential to consult makers' data when choosing a capacitor for pulse duty

More significant for general applications, every capacitor regardless of dielectric has frequency dependent tanδ losses, which increase with frequency.

Power limitations

Having mentioned power ratings, surely since current and voltage are in quadrature, no power is dissipated in a capacitor?

I mentioned that a near ideal capacitor has

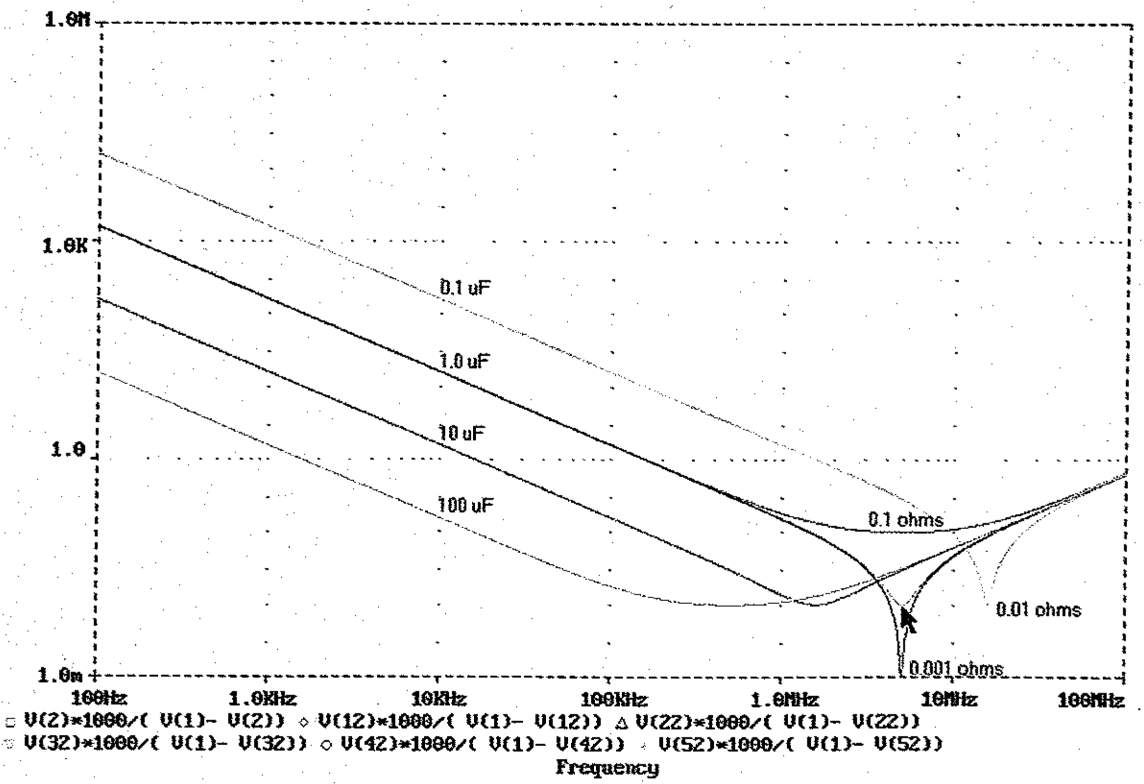


Fig. 3. This PSpice simulation shows the affect of 1nH inductance with 0.01Ω esr or tsr on four near ideal capacitors, 100µF through 0.1µF. The 1µF capacitor highlighted also shows comparison of increased esr of 0.1Ω and reduced esr of 0.001Ω, giving dramatically changed plot shape, with small values of esr.

conducting surfaces with a finite resistance. These electrodes must connect to the outside world using one of a variety of means, inevitably adding resistance. The sum of these metallic resistances, true series resistance, or tsr, is a very low value fixed resistance. For convenience, since it cannot be otherwise separately measured, it is sometimes viewed as being the minimum impedance, seen at resonance, on a conventional impedance and frequency plot, **Fig. 3**.

However other, usually much larger, loss resistances are found in practical capacitors. Every capacitor exhibits a leakage current, which is voltage and temperature dependent. A rule of thumb based on the Arrenhuis law, is to assume this current doubles for each 10°C increase in temperature. Obviously this current can be represented by a high value insulation resistance in parallel with the dielectric. More conveniently, following the parallel-to-series conversion rules, it equates to a very small fixed value series loss resistance.

With most capacitors, the dielectric's tanδ, frequency, voltage and temperature related losses dominate. These are also expressed as series resistance.

The sum of all these resistances, at any one frequency, is called the equivalent series resistance or esr. As can readily be seen, esr is frequency, voltage and temperature dependent, so when quoted in makers' data, it only applies to the particular conditions quoted.

To aid understanding, it is perhaps easier to consider esr as a combination of the above leakage resistance and tsr, together with a

Defining capacitors

The fundamental definition[1] of capacitance *C* in farads is the ratio of charge acquired in coulombs *Q* to the applied voltage *V*.

$$C=Q/V$$

For two flat conductive plates separated in vacuum, the fundamental capacitance formula becomes,

$$Capacitance = Free\ space\ permittivity \times \frac{Area}{Separation}$$

where free-space permittivity, ε0, is 8.854188×10^{-12}F/m

All other insulating materials have a dielectric constant, K, relative to this free space value,

$$Capacitance = K \times Free\ space\ permittivity \times \frac{Area}{Separation} \quad F/m$$

$$= 0.0885 \times K \times \frac{A}{S} \quad pF/cm$$

In essence any two conducting surfaces, separated by an insulator, exhibit capacitance, with a value which increases with surface area and reduces with separation. Subjected to an ac voltage, an ideal capacitor resists or impedes the passage of current according its reactance value,

$$Xc = \frac{1}{2\pi FC}$$

developing a voltage lagging the current by 90°.

In practice, every capacitor incorporates a resistive component. Expressed using the conventional series notation, this resistance further resists or impedes the passage of current,

$$Z = \sqrt{R^2 + Xc^2}$$

Each practical capacitor also incorporates an inductive element, which incorporated in the above provides the full equation for impedance,

$$Z = \sqrt{R^2 + (Xc - Xl)^2}$$

where $Xl=2\pi FL$.

At any given frequency, the term $Xc–Xl$ can be simplified into its series equivalent, j*Xs*, giving the vector equation, $Z=Rs \pm jXs$. This results in the magnitude/angle expressions,

$$|Z| = \sqrt{R_s^2 + X_s^2}$$

$$\angle\theta = \tan^{-1}\frac{X_s}{R_s}$$

In the above expressions the *R* term represents the equivalent series resistance of the capacitor, while the *X* term represents the series reactive component. When viewed as a vector diagram, a polar plot, or on a Smith chart, this *X* term has a negative value for capacitors, Fig. 1.

The commonly used expressions,

$$\tan\delta = \text{abs}\frac{R_s}{X_s} \quad \text{and} \quad C = \frac{-1}{2\pi FX_s}$$

also apply.

Series or parallel?

The impedance vector of a practical capacitor at any one given frequency can be represented using an equivalent circuit of the device with a resistor. The resistor, used to degrade the phase angle to that measured, can be either a high value in parallel with the device, or a low value in series with the device, leading to the term 'equivalent series resistance' or esr.

While the parallel equivalent values have use for certain calculations, the series equivalent values are more commonly used. Throughout this article, the series equivalents are used unless otherwise stated.

Take this practical example. An impedance vector, magnitude 100Ω and phase angle −84.3° at 1kHz, represents a capacitor having a tanδ of 0.1 and a Q of 10. This vector would result from a series combination of 9.95Ω resistive and −99.5Ω reactive, i.e. a 1.6μF capacitor or a parallel combination of 1005Ω and 1.584μF. A difference in equivalent capacitance value of 10%. The equivalent series resistance would be 9.95Ω.

Parallel impedances

Certain measuring instruments or mathematical calculations are more suited to the equivalent parallel expression, which can easily be converted to or from the series values.

$$R_p = \frac{R_s^2 + X_s^2}{R_s} \quad \text{and} \quad X_p = \frac{R_s^2 + X_s^2}{X_s}$$

Sometimes the measured results are needed as admittance rather than impedance; conversion from the parallel impedance expression is simple,

$$Y = \frac{1}{R_p \pm jX_p} = G_p \pm jB_p$$

$$G_p = \frac{R_s}{R_s^2 + X_s^2} \quad \text{and} \quad B_p = \frac{X_s}{R_s^2 + X_s^2}$$

The conversion from parallel impedance back to series impedance format, following,

$$R_s = \frac{R_p \times X_p^2}{R_p^2 + X_p^2} \quad \text{and} \quad X_s = \frac{R_p^2 \times X_p}{R_p^2 + X_p^2}$$

is equally simple.

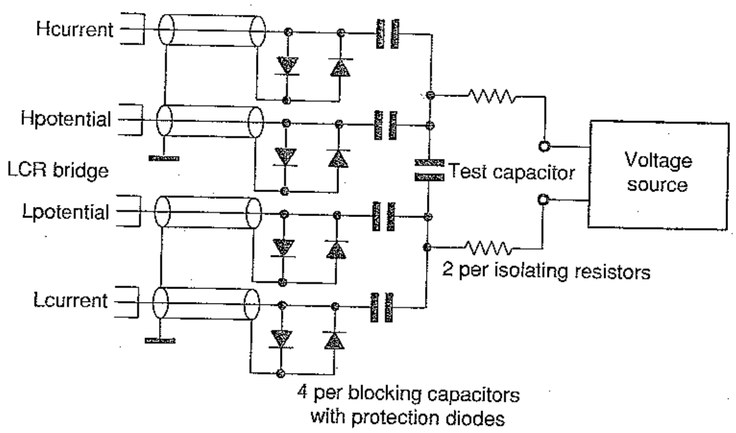


Fig. 4. This simple dc blocking buffer circuit allows measurement of capacitance change with applied dc volts. The isolating resistors should each present at least ten times greater impedance than the test capacitor. Likewise, the dc blocking capacitors must withstand the dc test voltage and have at least ten times the test capacitor's capacitance.

number of variable contributions dependent on frequency, voltage or temperature. This esr, together with the alternating current passing through the capacitor, can be used to calculate the power dissipated in the capacitor.

When the capacitor is subjected to a sinewave, simple calculations suffice. Given a complex waveform, the only method[3,4] that ensures accurate results is to use Fourier transforms to characterise the waveform into its discrete frequency components.

Only when a capacitor is measured at its final working frequency, temperature and voltage can its esr be derived directly from bridge measurements of $\tan\delta$ and capacitance But in most applications it is not practicable to make bridge measurement under such conditions. Consequently esr must be estimated taking account of each variable in turn.

I have stressed that esr is frequency dependent, but does it really change by a significant amount, or am I simply being pedantic?

Consider the esr of a high-quality 10nF polystyrene foil/film capacitor. I selected such a device as one of the standard capacitors when building my capacitance bridge. All measurements were taken using a four terminal Wayne Kerr *6425* precision component analyser, with a test voltage set to 1V, Table 1.

These results show clearly how esr values do change significantly with frequency, for this high quality capacitor. Many writers on this topic have confused these esr and tsr terms. Obviously they differ substantially, except at that frequency when the capacitor is self resonant.

Since correct understanding of esr is essential to avoid over-stressing capacitors, I make no apology for labouring the point.

Implications of voltage ratings

Many years ago, when impregnated metallised paper capacitors were the standard workhorse, it was considered that a capacitor rated for 400V dc or above could be used on 250V ac mains. Since these capacitors were impregnated, this was just about feasible. Unfortunately this premise tends to continue even today.

When the then new unimpregnated metallised PET capacitors became commonly available thirty years ago, 400V dc parts were used for many of these 250V ac mains requirements. Result – misery. If you were lucky, the end terminations eroded, disconnecting the capacitor. If you were unlucky, the capacitor caught fire.

Even today, I have vivid recollections of this unhappy time, when my task was to withdraw from all 250V ac applications and re-rate the capacitors to 160V ac, on behalf of my employer, for this particular construction.

Why should this problem arise ?

Given an impregnated or otherwise solid, void free, capacitor construction, 250V ac and above causes no insuperable problems. However with non-impregnated non-solid constructions, air voids occur within the capacitor.

According to Paschens curve of ionisation, an air-filled void having optimum size and air pressure can exhibit ionisation inception at voltages as low as 185V ac. This is why 160V ac was adopted in the previously-mentioned application to provide a safety margin.

Once triggered, the ionisation current is self sustaining at lower voltages – in fact almost to zero volts. Thus once triggered, the resulting discharge continues for at least 50% of the periodic waveform.

This ionisation discharge is damaging to almost all dielectric materials, resulting ultimately in a short circuited capacitor.

From these experiences, international and national safety rules for class X capacitors, used across the 250V ac domestic mains, were developed. Two main capacitor styles emerged. These were a much updated resin impregnated metallised paper capacitor[5] and the two-in-series metallised polypropylene style, which worked since its two series capacitor elements shared the applied voltage.

Manufacturing measurements

National and international capacitor approvals require manufacturers' measurements to be 'true' values, i.e. traceable to nationally held standards. In general, this means that measurement equipment must have an inherent accuracy ten times better than any claimed component parameters. Measured values must be 'inset' sufficient to eliminate all known measuring equipment errors.

With low-loss or close-tolerance capacitors, these requirements are not easily attained. A test frequency of 1kHz is standard for capacitors of value greater than 1nF except for electrolytic types, which are generally tested at 100Hz. Resulting from their high impedance at 1kHz, capacitors equal to or less than 1nF are tested at 1MHz. In general, test voltages of 1V ac or lower are used.

Experimenters' measurements

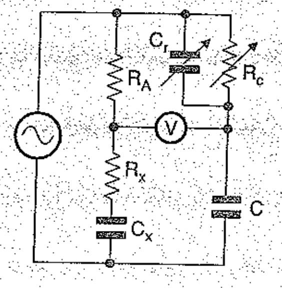
Commercially available capacitance test equipment can supply a DC polarising voltage to the component, but is generally restricted to a maximum of 20V dc.

However an adapter permitting much higher voltages can be simply made. Hewlett Packard application note 346 – a Guideline for Designing External DC Bias Circuits[6] – provides details of adapters for their ranges of precision meters. However these principles can easily be extended to any equipment

Wheatstone bridge

A capacitance bridge[7] that can be used at audio frequencies to directly measure capacitance and esr is shown. It is easily built using standard resistor and capacitor decade boxes together with one known high-quality standard capacitor.

With range switching resistors to replace R_A and three switchable standard capacitors, this circuit has been used to measure both capacitance and esr from a few picofarads to a hundred thousand microfarads. For best accuracy with the larger capacitors, four-terminal connections and switching of the low-impedance current paths is advised.



Power stress circuit

When designing switching supplies, much benefit derives from measuring a capacitor at its final working voltage and frequency. While low power measurements using a bridge are possible, other techniques are essential for higher powers or voltages.

These power or voltage limitations result because taking current in quadrature with voltage stresses any power amplifier. The amplifier's power dissipation increases rapidly when driving a capacitive load, leading to instability or failure.

If this capacitive load is resonated using a suitable inductor, the power amplifier is presented with a zero phase load. The inductor provides either the voltage needed to the capacitor, or the current. Since it also needs to supply only voltage or current and not both, amplifier power dissipation can be low, **Fig. 5**.

Using a series-resonant circuit, the amplifier supplies the required through current but at a much reduced voltage. With a parallel resonant circuit, the amplifier supplies the required voltage at a much reduced current. The inductor's stored energy supplies the missing voltage or current drive required by the capacitor. The amplifier only supplies the power needed to replace that lost due to capacitor dissipation, inductor resistive losses and the protection resistor.

Using a stable air cored inductor with a Q of ten or better, and a 100W mosfet audio power amplifier, capacitor voltages of 250V can be easily attained using the series circuit. An air cored inductance provides the stability needed for meaningful calculations.

Conversely the parallel configuration easily provides 5A. The schematic circuit suggests using a series resistor to protect the amplifier in the event of capacitor failure. Much higher levels are possible if this resistor value is reduced.

Capacitance change with frequency, voltage or current can be calculated from the circuit's change in resonant frequency, the voltage drop and through current measurements of the test capacitor.

which might need to be used, **Fig. 4**.

Commercially available capacitance testers can often measure using more than 1V ac test voltage, but they rarely extend above 20V ac. Higher test voltages are possible using Wheatstone bridge methods but care is needed not to overload either the test source or the bridge measurement arms – especially with increasing frequency.

A low accuracy alternative method which can measure to very high voltages and frequencies requires use of a power amplifier together with suitable high 'Q' inductors. Depending on whether higher voltage or greater current than can be sourced by the amplifier is needed, these inductors are used to either series or parallel resonate with the capacitor. Using these techniques, satisfactory measurements to 500V ac and several amps at frequencies to 1MHz have been performed, **Fig. 5**.

Capacitor life

Qualification testing requires capacitors to survive continuous operation at maximum ratings and maximum temperature for typically 1000 hours. In some instances the capacitors are required to be stressed in excess of claimed levels, or for much longer times. To understand the implied life-test claims, you need to read the specification.

Compared to actual end use 1000 – and even 10 000 – hours endurance is extremely short. But components in end use are not generally continuously stressed, certainly not to their maximum capability and temperature.

Arrenhuis law suggests that insulation resistances halve, alternately leakage currents double, for each 10°C increase in temperature. Consequently 1000 hours at 125°C can represent a useful life[4] under normal end use conditions, of 10 to 20 years – even assuming maximum applied voltage.

A secondary benefit results from reduced voltage. All capacitors, including electrolytics, exhibit prolonged life with reduction in operating voltage, even to zero dc, provided any applied ac does not otherwise contravene the capacitor specifications.

One common mis-statement – that electrolytics exhibit no capacitance with zero or reverse bias – is completely unfounded. The dielectric film is chemically robust and cannot in the short term be changed. Long term, assuming reverse voltage is within the permitted levels, leakage current increase can result in parametric failure.[4]

However if an electrolytic which has been operated for some time at reduced voltage, is then subjected to increased voltage, a temporary increase in leakage current results. The capacitor may then fail to meet its specification. Since the converse also applies, any capacitor subject to excess temperature, voltage or current or mechanical stress, will fail quite quickly.

One special aspect which certainly causes electrolytic failure, is unwitting excessive repetitive reverse bias. This can arise when a polarised capacitor is used to couple the drive waveform into a switching transistor base and at the same time block dc. This mis-use is especially common. I have personally experienced this failure mechanism many times, in both television and satellite receivers.

With switching power supplies, an early indication of an electrolytic being reverse biased is increased transformer noise and notable temperature increases. However with television line and frame timebase generators being less audible, the first indication can be either reduced drive amplitude or semiconductor failure.

Such abused capacitors usually show visible signs of overheating or electrolyte leakage, measurable loss of capacitance and increased esr and reverse voltage withstand. I hope to delve further into this topic in a subsequent article which explores and measures various capacitor constructions. ■

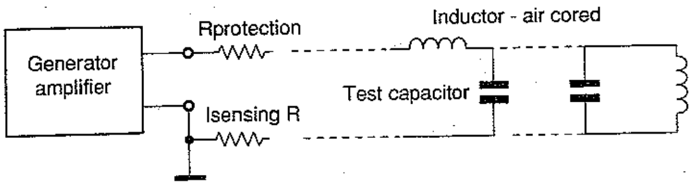


Fig. 5. Taking advantage of inductor Q to produce high test voltages on the capacitor while maintaining the amplifier load near unity power factor. Variations on this circuit enable much investigation into capacitor behaviour using only minimal equipment.

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