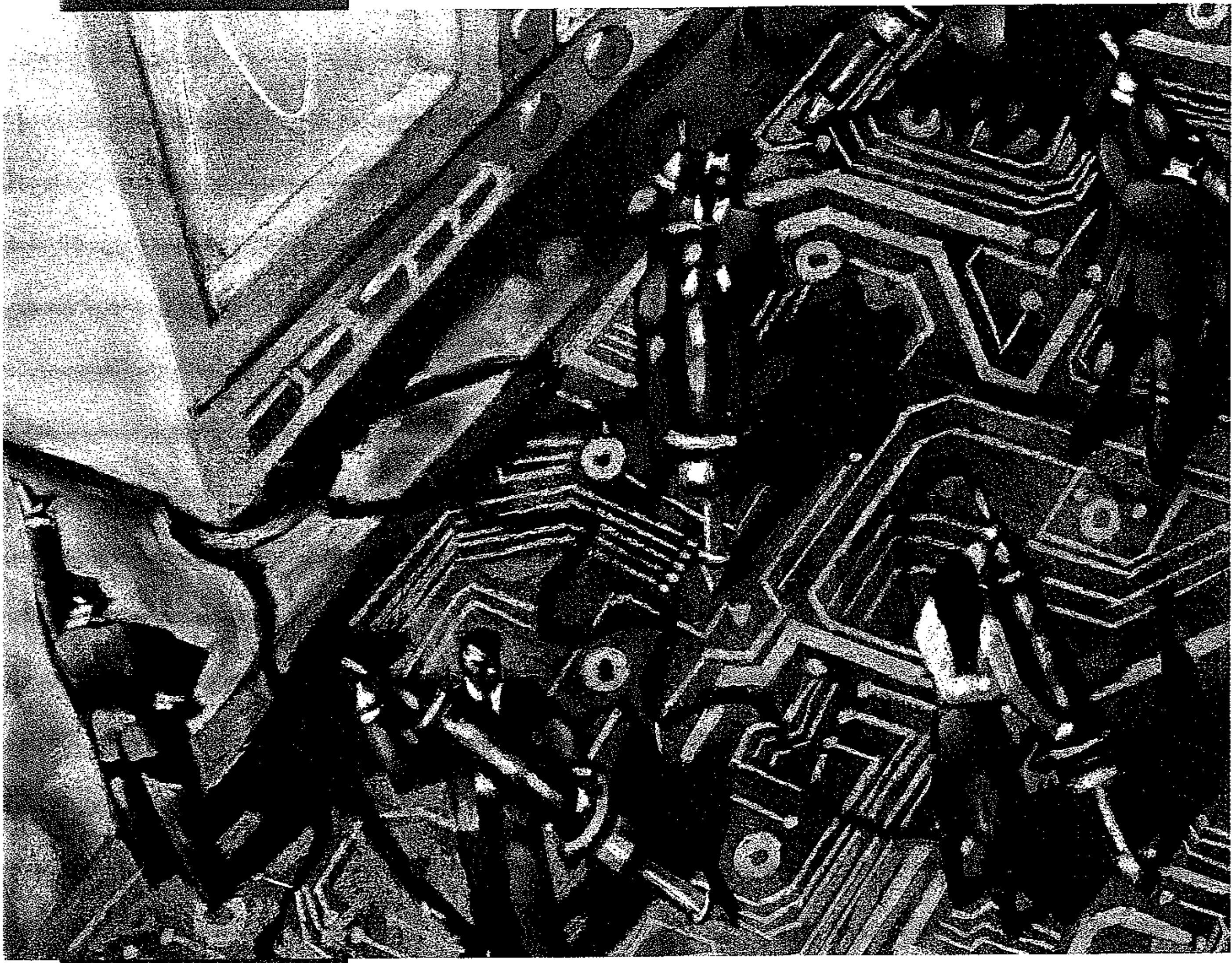


Check Cs *in situ*

If you think that the best way to check an electrolytic capacitor is to measure its capacitance, think again. Cyril Bateman explains why it isn't, and starts a discussion on how to identify failed electrolytic capacitors without removing them from the board. This discussion ends next month with a design for a radically different in-circuit electrolytic tester.

Any capacitor that fails open or short circuit can be quickly identified without removing it from its circuit board. Most non-electrolytic capacitor failures result in a permanently short-circuited component.[1]

The traditional aluminium electrolytic capacitor though is different. While it is self-repairing, it also has a built-in ageing mechanism.[2]

Such a capacitor's useful life ends when the oxygen needed to maintain or repair its dielectric oxide film can no longer be provided by the electrolyte. At this point, the conductivity of the electrolyte is much reduced, increasing the capacitor's equivalent series resistance, or ESR, at all frequencies.

Failed aluminium electrolytic capacitors exhibit four common symptoms. The first two are visual and hence easily identifiable.

- Leakage of electrolyte, usually around one termination. This can result from internal gas pressures, caused by internal reverse cathode bias voltage.
- Discoloured insulating sleeve caused by excess heat. This may result from adjacent components raising the local ambient temperature or from the capacitor self-heating.
- Electrolyte exhaustion, commonly called 'drying up'. The measured capacitance may be little changed and still within tolerance. The electrolyte may still be liquid, but have insufficient conductivity for the capacitor to function properly.
- Cathode-foil oxide growth, called 'forming up', results when the cathode foil's normal voltage, 'reverses' to some 1.5V positive, relative to the electrolyte. This internal 'reverse bias' induced cathode oxide growth can provoke the other symptoms.[2]

Aluminium electrolytic capacitors used correctly within their ratings usually fail due to the electrolyte being exhausted. Such capacitors are frequently described as 'dried up'.

Electrolyte exhaustion has two causes. These are consumption of the available oxygen by the capacitor leakage currents, and permeation of electrolyte through the capacitor seals.

Electrolyte exhaustion results in increased ESR, increase of tanδ and a measurable increase of impedance at higher frequencies. Aluminium electrolytic failures that result in a short circuit are rare. I have never seen one.

Understanding electrolytics

To identify a failed aluminium capacitor, you need to understand how the capacitor works. Capacitor ESR is a combination of three frequency-dependent mechanisms. These are the electrolyte resistance, the electrode foils with their connection resistances, and the anode and cathode foils' dielectric loss factors expressed as a series resistive loss, **Fig. 1**.

There's more on this in the panel entitled 'Equivalent series resistance.'

Figure 1 illustrates a conventional 'polar' electrolytic capacitor.[2] Both anode and cathode foils posses capacitance. The capacitance of the cathode is very much larger than that of the anode. The measured value of the capacitor is the series sum of both values.

A 'bi-polar' or reversible electrolytic capacitor differs by having two anode foils formed to the same voltage. The diodes then have the same breakdown voltage. Both foils have similar capacitance values, each double the capacitor's marked value.

Leakage currents

This equivalent circuit of an electrolytic capacitor merits exploration. Aluminium is a 'valve' metal, so called because in the 1850s, researchers first noted that insulating oxide films, grown on the anode metal in a bath of suitable electrolyte, exhibited a rectifying action. While this metal is connected to a positive voltage, the oxide film is an excellent insulator.

Immersed in electrolyte and connected to a few negative volts, this oxide film becomes a conductor.[2] Current flow releases oxygen which travels to this negative voltage on the oxide film. If prolonged, hydrogen chemically 'reduces' some oxide back to aluminium, degrading its insulating properties.

Oxides of many other materials including niobium, zirconium, hafnium, uranium and silicon exhibit similar characteristics. Traditionally only aluminium and tantalum have been used to manufacture capacitors.[3]

Capacitor diodes?

Following my last series of articles, one reader asked how capacitor dielectric oxide could rectify. Alumina substrate used to manufacture thick film hybrid circuits is an excellent insulator. He posed the question, "Could this rectifying behaviour result from the electrolyte?" An explanation appears in the panel entitled, 'Substrates versus dielectric.'

Aluminium electrolytic capacitors do exhibit this rectifying behaviour. It easily demonstrated. Simply measure a polar capacitor's leakage current with forward and reverse DC bias applied. Under DC bias, if the dielectric film were non-rectifying, then regardless of polarity, similar leakage currents would flow. Any rectifying behaviour must result from the oxide films.

Take a new polar aluminium electrolytic capacitor and subject it to a low direct voltage of the correct polarity. To prevent any re-forming of the oxide films from influencing the results, charging currents should be limited. Supply this voltage via a 1kΩ current limiting resistor in series with the test capacitor.

Wait two minutes for the capacitor to charge and for the leakage current to stabilise. Increment this voltage and again allow the current to stabilise. Then plot leakage current from zero to the capacitor's rated or surge voltage.

Now reverse the polarity of the DC supply and measure and plot leakage current from zero to, say, negative 5V in 1V steps. Leakage current for negative voltages is considerably higher than for the same positive voltage.

To avoid any possibility of oxide formation, as well as for safety, the stabilised capacitor leakage currents should not be

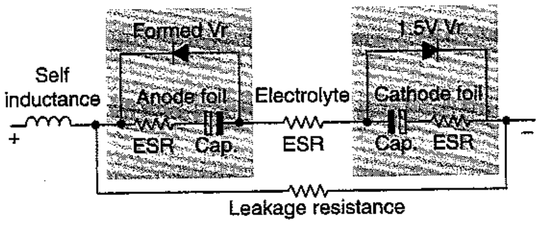


Fig. 1. Equivalent circuit of a polarised aluminium electrolytic capacitor. The cathode foil is etched, not formed. Its natural atmospheric oxide roughly equates to 1.5V electrical formation. Using similar foil thickness and etch ratio as the anode foil, a 6V rated capacitor's cathode capacitance will exceed that of the anode by a good margin. CV products on the other hand will be similar.

Alumina substrate versus dielectric oxide

The oxide dielectric of an aluminium electrolytic capacitor is grown on the surface of the anode foil by connecting to a positive voltage while it is immersed in a bath of suitable electrolyte.[2]

Oxygen, freely available from the electrolyte, combines with aluminium from the surface of the foil to form an aluminium oxide, namely Al_2O_3. This oxide is extremely thin, attaining some 14 ångstroms thickness for each volt applied.[3]

The best purity materials are used both for the aluminium anode foil and for the forming electrolyte, so the resulting oxide is extremely pure. It has a dielectric strength approaching the theoretical strength predicted by the ionic theory of crystals.

Growing anodically under this DC voltage stress ensures consistent alignment of the extremely small aluminium oxide particles as they form. This oxide growth is self-limiting. As thickness approaches 14Å for each volt applied, anode current falls. Oxide growth slows and almost stops.

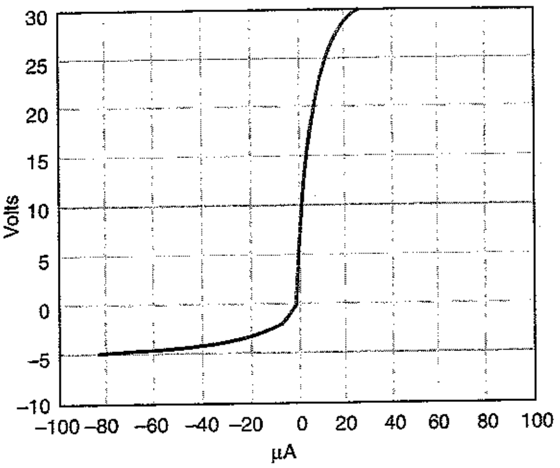
A typical capacitor dielectric has an oxide thickness less than 1μm. For example, a 10V capacitor has a dielectric oxide thickness of some 0.02μm.[2]

A thick-film hybrid substrate is made in similar fashion to the ceramic capacitor dielectric, described in an earlier article.[7] The Erie company, for which I then worked, was almost certainly the first major UK maker of thick-film circuits. Having considerable ceramic development and production resources, the company used these facilities to make alumina substrates for hybrid production.

The various processes of milling, spray drying, pressing or casting, followed by sintering, ensure a random alignment of alumina particles. These particles are much larger than those grown as the electrolytic capacitor dielectric.

The spray drying process typically produces dried powders in the form of minute hollow spheres. Subsequent processes of pressing or casting flatten these spheres, ensuring the deposited grains have a completely random alignment. Most substrates incorporate a significant glass or frit content. This acts as a flux during the sintering process, when these grains clump together and grow in size.

Typically manufactured as a 0.5mm thick ceramic plate, alumina substrates comprise a large number of randomly-aligned grains, electrically in series with each other, to build up the required thickness of substrate. This makes them a good insulator.



Philips 135-4700μF/25 volt
Forward/reverse 'diode' voltage characteristic
100kHz impedance – red 25mΩ

Value measured wilh 1kΩ limiting resistor
Unused capacitor.
Capacitance 4 743μF, tandelta 0.0927

Fig. 2. Typical 'diode' forward/reverse characteristic common to all polar aluminium electrolytic capacitors. This capacitance value and voltage rating was plotted to answer the question Chris Green posed in the letters pages of the October 1998 issue. It was selected to provide easily measurable leakage currents for forward and reverse bias voltages.

The rectification effect permitted by the extremely thin, electrolytically grown capacitor dielectric oxide is easily measured, **Fig. 2.**

If you are interested in this topic, I recommend that you try this. The rate that leakage current increases when the capacitor's voltage is reached and exceeded is a good indication of the 'formation' voltage margin used, and hence the potential life time of the capacitor. Traditionally, long life or professional capacitors are built using foils with higher formation voltages than those used for miniature and commodity capacitors.

allowed to exceed 1mA. The resulting graph displays typical diode behaviour, **Fig. 2.**

Should a suitable microammeter not be available, the voltage drop across this resistor can be used. A 200mV DMM measures 1μA as 1mV.

Component quality

The quality of many components such as inductors and low-loss capacitors is usually defined by their 'Q' factor. Q is the result of dividing a component's measured AC reactance by its AC resistive losses.

The reciprocal of Q, called tanδ, is defined as the capacitor's ESR/reactance ratio. Tanδ is used to describe the quality of almost all general-purpose capacitors.

$$\tan\delta = \text{abs}\frac{ESR}{X_C}$$

$$X_C = \frac{1}{2\pi fC}$$

Conversely, $ESR = X_C \tan\delta$.

The capacitor's reactance reduces in proportion to its capacitance value and frequency. Being a combination of fixed and variable losses, ESR also reduces with frequency but to a lesser extent.[2] Having reached its minimum value, ESR then increases with frequency.

The measured tanδ of a capacitor therefore must always increase with frequency. From the first equation, tanδ has no upper limit. It can exceed unity.

Equivalent series resistance is related to the construction of the capacitor, its voltage rating and capacitance value. A capacitor's ESR varies with frequency. At any frequency, ESR and impedance of each capacitor value and voltage rating varies widely. No single global good or bad figure can thus be assigned. ESR or impedance can be used to identify a worn capacitor, but only by comparison against known good identical capacitors.

At 100 or 120Hz depending on supply frequency, tanδ is used by capacitor makers to indicate aluminium electrolytic capacitor quality. Every capacitor is tested for tanδ in production. While many makers also table a 10kHz or 100kHz impedance or ESR value by capacitor, these parameters are not tested.

Variation of tanδ for capacitor size and voltage rating is small compared to the wide range of ESR and impedance.

ESR is not a fixed value

One extremely common mistake is to consider that a capacitor's ESR has a fixed value.

Electrolytically-formed aluminium oxide is a low-loss dielectric, changing little with frequency.[3] Expressed as the equivalent series loss, its contribution to ESR reduces with increasing frequency. The resistances of the metal foils and the electrolyte/paper combination, tend to increase but more slowly, with frequency.

Dominated at low frequencies by the tanδ of the oxide system, the capacitor's measured ESR initially reduces with frequency. With further increase of frequency, resistances of the metal foils and the electrolyte/paper combination, dominate. The capacitor's ESR and impedance become almost constant, finally rising with frequency, **Fig. 3**.

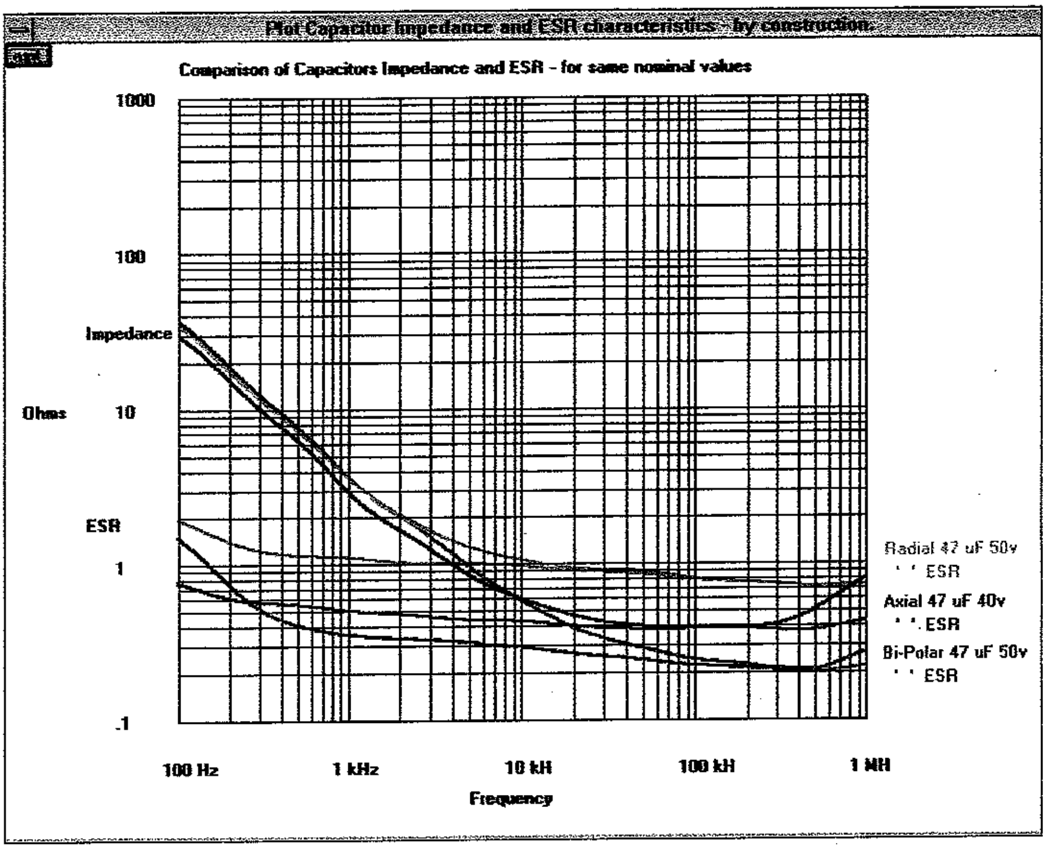


Fig. 3. Plots of impedance and ESR against frequency for three 47μF capacitors, typical of the range of impedances and ESR found at 100kHz with medium voltage electrolytic devices. Lower and higher voltage capacitors will further increase this spread.

Tanδ provides a good figure of merit for all capacitors.

ESR is of interest to a capacitor designer to determine ripple current or power rating.[4] But where capacitor quality issues are concerned, 100Hz tanδ is the criterion used – not ESR.

From equation 1, tanδ responds to change of capacitance or ESR. A bad or failing aluminium electrolytic's capacitance usually reduces slightly, while ESR increases significantly. Tanδ reflects both changes.

Temperature effects

Capacitor leakage currents are temperature dependent, roughly doubling for each 10°C increase, according to Arrenhuis' law. Since the consumption of free oxygen from the electrolyte determines a capacitor's service life, so does its working temperature.

Subject to an AC ripple current, the capacitor's ESR results in the dissipation of real power as the product of I^2ESR. This raises the capacitor's internal temperature. Each aluminium electrolytic capacitor has a sinusoidal ripple-current rating, usually based on a frequency of 100 or 120Hz. Correlation factors for other frequencies and change of ambient temperature are provided.

Assuming the circuit that the capacitor is used in applies a sinusoidal or other similar easily defined waveform, then compliance with the capacitor makers ratings is easily confirmed.

These ideal waveforms rarely occur in practical circuits though. Given a repetitive voltage or current waveform, power dissipation can be calculated, but this can be difficult.

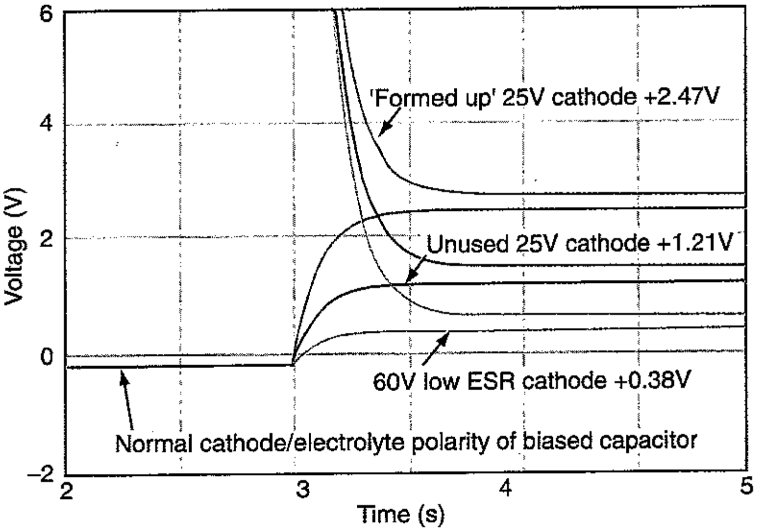


Fig. 4. Simulations of capacitors charged to 25V then discharged via a 10Ω resistor demonstrate how the cathode foil's voltage becomes positive, with respect to the electrolyte. With positive anode bias voltage, the cathode voltage stabilises slightly below that of the electrolyte. With similar anode and cathode foil CV product, the cathode foil charges to a positive voltage, compared to the electrolyte as in the green trace. When the cathode foil CV exceeds the anode's, red trace, a much lower voltage develops. In the blue trace, the cathode has 'formed up' and only half of original capacitance value remains.

In many instances – especially with non-repetitive waveforms – the only practicable method is measurement of the working capacitor's case temperature rise.

A full treatment of a mathematical method, applicable to any repetitive waveform, has already been published in *Electronics World*.[4]

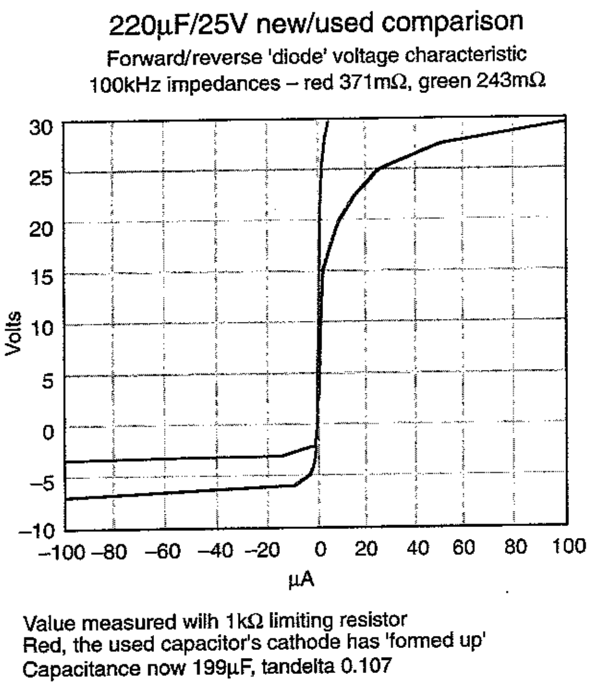


Fig. 5. The red curve shows the degraded forward leakage and increased reverse voltage sustain of a capacitor that has suffered from internal reversed cathode bias. The cathode foil has clearly 'formed up'. Total capacitance at 100Hz has reduced to 199µF, but is still within tolerance. The cathode capacitance of this worn out capacitor has reduced to 30% of its initial value while tanδ has increased to 0.107. The green curve provides comparison with a similar unused capacitor, having 218µF and a tanδ of only 0.044, a 2.4:1 ratio of tanδ. The 100kHz impedances were 371 and 243mΩ, a ratio of only 1.5:1. Clearly, tanδ is the much more sensitive test.

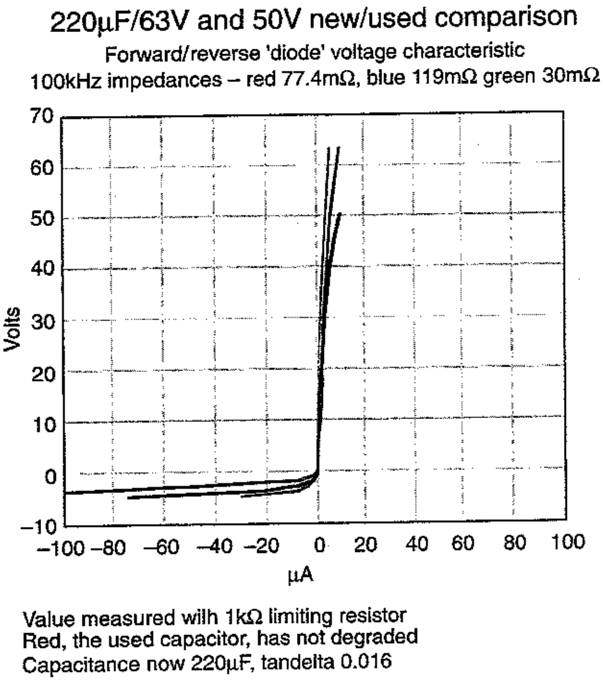


Fig. 6. The red curve for the used low ESR 220µF compared with two unused general-purpose capacitors. This shows that after four years service, this higher voltage, low ESR replacement has not degraded. Measured values, red 220µF, 0.016 tanδ; blue 213µF 0.024 tanδ; green 214µF, 0.028 tanδ.

Used correctly within its ratings, an aluminium electrolytic capacitor's leakage current will slowly consume the oxygen available from its electrolyte. Its capacitance value will change and ESR will increase. A capacitance change of ±10% or tanδ or impedance increasing by 1.2 times the rated limits indicates that the capacitor's useful life has ended.

A capacitor used within its published ratings should provide many years of service though. Recently, I refurbished an elderly Hewlett Packard test instrument. Because of its age, as is good practice, I replaced all of its 43 aluminium electrolytic capacitors. These were all dated 1974 or 1975. Only two failed to meet their specifications when tested on a bridge.

Why then do some capacitor applications cause such a drastic reduction in a capacitor's life? Ignoring those obvious reasons – excess ambient temperature, voltage, ripple current or reversed polarity – most premature aluminium electrolytic capacitors failures occur because their cathode foil has become reverse biased internally. The foil has become what is known as 'formed-up'.

Internal cathode reversed bias

Forming up cannot easily be observed using an oscilloscope, except by manufacturing special capacitors to allow measurement of the electrolyte's voltage relative to the anode and cathode foils. Using the circuit of Fig. 1, though, it can be simulated.

The anode and cathode foil diodes can be represented by the 'default' diode in PSpice. I used 'BV=1.5' to represent the unformed cathode foil diode and the capacitor's rated voltage for the anode foil diode. For accuracy, I also selected 'RS' values, which replicate the measured DC leakage current/voltage plots.

If prolonged, internal reverse bias can cause the cathode foil to form up above its natural atmospheric oxide's equivalent electrical value. This reduces its capacitance.[2]

Both anode and cathode foils exhibit capacitance. They are connected in series internally, back to back, by the electrolyte. When a capacitor is charged or discharged, charge transfers between anode and cathode foils. This develops voltages between the anode foil and electrolyte and between electrolyte and cathode foil, according to each foil's capacitance value, **Fig. 4.**

Under normal positive anode bias voltages, the cathode voltage is slightly negative with respect to the electrolyte voltage. When the capacitor is discharged, the charge transfer develops a cathode voltage which is positive compared to the electrolyte. The cathode has become internally reverse biased, relative to normal operation.

This transfer of charge may cause the cathode foil voltage to approach or exceed that sustainable by the cathode foil's naturally occurring oxide film. Considerable leakage current then flows between cathode foil and electrolyte, causing oxide growth on the cathode.

Once initiated, this oxide growth enters a runaway condition. With repeated capacitor discharge, the reducing cathode capacitance develops an ever higher voltage. Cathode foil oxide growth, cathode voltage, ESR, tanδ and leakage currents all increase until the capacitor fails.

Heavy-duty capacitors

Repetitive crash discharging, as needed for photoflash, requires a specially constructed capacitor. While photoflash presents an extreme case, many circuit applications use electrolytic capacitors to couple irregular waveforms but without ensuring adequate bias voltage.[2]

Depending on the applied waveform, these uses are considered as repetitive charge/discharge or AC applications. Commercial polarised capacitors are not suitable for either application so special capacitors are needed for each.

Frequently, the base drive waveforms of switching transistors include a small capacitor in parallel with a resistor to shape and couple the drive current into the transistor base. My satellite receiver's power supply originally had a 1μF electrolytic paralleled with a 1kΩ resistor to drive the base of a *BUT11A* transistor. This capacitor failed very quickly, destroying the power supply.

This is a well known design fault. Replacing the component with a 1μF polyester film capacitor provided a permanent remedy.

Similarly, my TV set had a 220μF, 25V capacitor paralleled with a 12Ω resistor to drive the base of its *BU508* line-scan transistor. After only four years service, this TV exhibited an underscanning display area.

Causes of rapid failure

Capacitor anodes are made using super-pure aluminium. Cathodes are deliberately made using lower purity foils. This is done to discourage cathode formation under the normal charge/discharge cycles found during equipment switch-on or off.

Capacitors described as charge/discharge proof in compliance with CECC 30 300 are tested to survive a million switch-on or off cycles using a time constant of 0.1s.

When a capacitor is internally or externally reverse biased, abnormal amounts of oxygen are consumed from the electrolyte. The consequent excessive free hydrogen can force electrolyte past the capacitor seals.

Hydrogen collecting at the anode foil degrades its dielectric oxide, increasing leakage current when re-biased correctly. The cathode foil can form up, reducing its capacitance.

Capacitance values drop while leakage current, ESR and tanδ all increase, until the capacitor or the equipment fails. For example, see the red plot of the 220μF, 25V capacitor removed from my TV in 1995. While its measured capacitance was still in tolerance, the display no longer filled the screen.

This damaged capacitor has changed dramatically. Its cathode foil has formed up and the cathode's capacitance has reduced to 30% of its original value, **Fig. 5**.

For this article I removed and measured the low-ESR 63V capacitor that replaced the damaged original one. Although it had seen a similar length of service, as can be seen from the leakage current plots, the replacement has survived undamaged, **Fig. 6**.

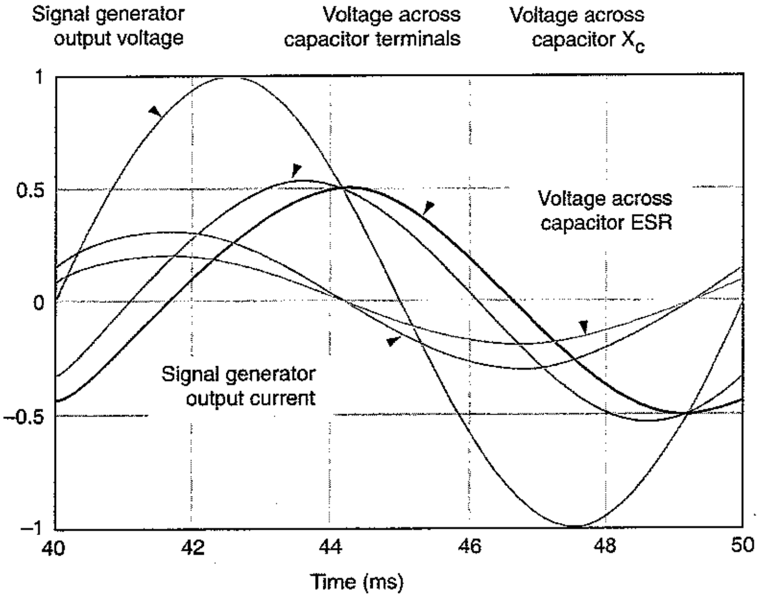


Fig. 7. PSpice simulation showing voltages and currents of a 1000μF, 0.4 tanδ capacitor. Note how the peaks of the voltage waveform for the capacitor's ESR coincide exactly with the generator's current waveform. The peak of the capacitor X_C voltage waveform is separated by exactly 90° phase. Similar simulations confirmed that these relationships hold over the range of tanδ. The generator voltage/current phases vary widely though, depending on the capacitor's ESR and the generator's source resistance.

Anode foil is considerably more expensive than cathode foil. To ensure meeting the charge/discharge requirements and reduce costs, aluminium electrolytic capacitor designers ensure the CV product of the cathode exceeds that of the anode. This maximises the available capacitance at minimum cost.

To avoid cathode formation in capacitors that could be subjected to internal cathode reverse bias, the CV product of the cathode foil should be increased. The best solution is to use a bi-polar capacitor. Alternatively, a low ESR capacitor of higher voltage than required for the circuit voltages may be the answer.

Low-ESR capacitors are made using high-gain cathode foils with more conductive paper and electrolyte relative to standard capacitors. This cathode foil provides more capac-

Electrolytic capacitor ESR

Capacitor electrolytes are conducting solutions, usually a neutralised weak acid in a solvent. This electrolyte must not freeze or boil at the extremes of the capacitor's working temperature range, nor attack pure aluminium at any temperature. Very pure ethylene glycol was for many years the standard solvent used in capacitors.[2]

Most modern electrolytes are made without added water. Using only dry ingredients, such as super purity ammonium borate crystals, some water appearing as water of crystallisation is inevitable.

Low-voltage electrolytes have a low resistivity – typically a few millisiemens – and are not polarity sensitive. In a capacitor, some electrolyte is contained within the minute voids and channels in the anode and cathode foils' oxide coatings. These can be tenuous and very long relative to their cross section,[2] so the effective electrolyte resistance in them increases quickly with frequency.

Most of the electrolyte however will be absorbed in the separator. This is usually a paper tissue, interwound with the anode and cathode foils during assembly. Resistivity of the electrolyte/paper separating tissue is increased compared to the bulk electrolyte, according to paper type and thickness used.

Low-voltage capacitors use very low resistivity paper and electrolyte. To help lower ESR, a single open weave 'rag' tissue is often used. Higher voltage capacitors incorporate a higher resistivity paper/electrolyte combination, and more than one tissue thickness.

As the capacitor's rated voltage increases, electrolyte, paper and cathode-foil thickness are varied to minimise tanδ losses, capacitor case size and production costs while ensuring a satisfactory capacitor service life and performance.

Low-ESR capacitors use thicker, higher surface gain cathode foils together with more conductive paper/electrolyte combinations than standard capacitors of the same voltage. Naturally, these carry a size and cost penalty.

Electrolyte/paper resistivity varies with temperature. Above room temperature, this resistivity reduces, but due to the paper's influence, it perhaps only halves by 85°C. Below 0°C though, resistivity increases rapidly as the solvent approaches its freezing point.

itance, and hence CV product, for a similar foil area. Increasing capacitor voltage increases foil area. These contribute a much improved service life, **Fig. 6**.

In-circuit capacitor diagnosis

Having removed a suspect capacitor from a circuit board, you can confirm whether it has failed by measuring its tanδ using a bridge.[5] But it is usually easier, quicker and much cheaper simply to remove and replace all suspect capacitors.

If you do this though, you will no doubt be throwing away a lot of good capacitors. Is there a better way?

Measuring a capacitor *in situ* poses three main problems. To avoid false readings, the test voltage must be sufficiently low that adjacent semiconductor junctions are not turned on. Measurement times must be much less than needed to remove and replace a suspect capacitor. The test result should be unambiguous, needing little or no interpretation.

Measurement of capacitance is of little help. As with my TV, most failed aluminium electrolytic capacitors still have a measurable capacitance and can appear well within tolerance.

At present, a few commercial in-circuit impedance testers, incorrectly called ESR meters, are available. These measure the capacitor's impedance at high frequency, whcih is a much easier measurement – and not its ESR.

A capacitor's impedance, |Z|, comprises the vector sum of its ESR and its capacitive/inductive reactances. At low frequency, capacitor self-inductance matters little. But as frequency increases, every capacitor ultimately becomes a DC-blocking inductive reactance. Its reactance then increases rapidly with frequency.

$$|Z| = \sqrt{ESR^2 + \left(X_{C(s)} - X_{L(s)}\right)^2}$$

$$X_{L(s)} = 2\pi F L_{(s)} \text{ and } X_{C(s)} = \frac{1}{2\pi F C_{(s)}}$$

At any one frequency, the term $X_{C(s)}{}^2 - X_{L(s)}{}^2$ can be simplified to $\pm jX_s$, giving the fundamental vector capacitor equation for impedance,

$$|Z| = ESR_s \pm jX_s.$$

Many writers assume that capacitive reactance at 100kHz is so small that impedance is the same as ESR. This is not correct. Many larger electrolytics – especially axial types – may be above resonance, hence inductive. At 100kHz, a theoretical 1μF capacitor has a reactance of around 1.6Ω. A practical electrolytic capacitor's reactance will be considerably above this theoretical value, **Fig. 3**.

Most so-called ESR meters with a pre-set good/bad buzzer cause confusion when used to measure smaller value electrolytic capacitors.[1] But smaller capacitors are the ones most frequently measured. Often the value and voltage of the capacitor being measured is not visible, making judgement difficult.

Because of the range of impedances involved, an 'ESR' meter's results require considerable interpretation and comparison against known good capacitors. Since 100kHz impedance values for known good electrolytic capacitors range from 0.01Ω to 24Ω, it is clearly not possible to define an impedance value representing 'good' or 'bad', **Table 1**.

Compared to these impedance variations, the tanδ of a good capacitor is a reasonably constant number. For a typical commercial aluminium electrolytic capacitor, tanδ ranges from a low of 0.02 to a high of 0.3 for very large low voltage parts.

Philips' capacitor data handbook requires general-purpose capacitors subjected to endurance testing to have a tanδ of ±1.5 times the catalogue limits or 0.4, whichever is larger.[6]

As a general guide, the tanδ for typical good board mounted capacitors should be less than 0.1. Medium sized capacitors having a tanδ of 0.2 or more should be replaced for reliability, **Table 2**.

Advantages of looking at tanδ

Does in-circuit tanδ measurement have any particular disadvantages? Using the internet and various trade publications, I have been unable to locate a suitable low cost in-circuit tanδ meter, so I decided to build one to supplement my conventional capacitor bridges.

Using PSpice I plotted the waveforms simulating an electrolytic capacitor with 0.4 tanδ, representing a failed capacitor. These demonstrate the difficulty measuring tanδ or true ESR, compared to the easy measurement of impedance.

While the vectors representing the capacitor's ESR and reactance remain separated by 90°, their phase relationship to the signal generator's voltage varies according to source impedance and test capacitor tanδ, **Fig. 7**.

This PSpice simulation confirmed that the signal generator's current and the current, and hence voltage waveforms, of the capacitor's ESR, do remain in phase. Simulation also confirmed that the voltage waveform for the capacitor's reactance is delayed by exactly 90° relative to that of the capacitor's through current.

Encouraged by these PSpice analyses, I set out to investigate the design of a suitable in-circuit tanδ tester. Its design proved rather more difficult than I at first expected. But I have managed to design and develop an easy to use tanδ in-circuit tester. It will be described in my next article. ■

Table 1a). Typical impedances measured at 100kHz – low capacitance values.

Capacitor	**1μF**	**2.2μF**	**4.7μF**	**10μF**	**22μF**	**47μF**	**100μF**
50V bipolar Al.	4.0Ω	3.2Ω	1.4Ω	0.9Ω	0.35Ω	0.3Ω	0.22Ω
63V polar Al.	4.3Ω	3.5Ω	1.8Ω	1.4Ω	0.5Ω	0.4Ω	0.28Ω
450V polar Al.	24Ω	11Ω	5Ω	3.8Ω	1.5Ω	1.0Ω	

Table 1b). Typical impedances measured at 100kHz – high capacitance values.

Capacitor	**1000μF**	**2200μF**	**4700μF**	**10 000μF**
25V polar Al.	0.090Ω	0.07Ω	0.045Ω	0.022Ω
63V polar Al.	0.050Ω	0.025Ω	0.015Ω	0.010Ω

Table 2a). Typical tanδ values of new stock capacitors measured at 100Hz – low capacitance values.

Capacitor	**1μF**	**2.2μF**	**4.7μF**	**10μF**	**22μF**	**47μF**	**100μF**
50V bipolar Al.	0.05	0.05	0.05	0.05	0.05	0.05	0.06
63V polar Al.	0.04	0.04	0.035	0.035	0.035	0.045	0.04
450V polar Al.	0.1	0.1	0.08	0.05	0.05	0.05	

Table 2b). Typical tanδ values of new stock capacitors measured at 100Hz – high capacitance values.

Capacitor	**1000μF**	**2200μF**	**4700μF**	**10 000μF**
25V Polar Al.	0.06	0.075	0.09	0.1
63V Polar Al.	0.03	0.05	0.06	0.07

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