Capacitor Misunderstandings.

Cyril Bateman investigates common capacitor fallacies.

If the perfect capacitor existed, then many common capacitor misunderstandings would never occur, unfortunately the perfect capacitor simply can never exist, outside our tutor's lectures or in simulations which use only the basic SPice supplied models.

Many years ago when tasked to investigate serious capacitor failings which had resulted in many fires, I was reminded of the opening phrase used by my lecturer to introduce his capacitor lectures. "Capacitors don't take power", he explained that a perfect capacitor, having 90° phase difference between the applied voltage waveform and the capacitor through current, was able to create a voltage drop without dissipating any power. However "don't take power " could also mean that capacitors are unable to sustain any significant power dissipation, which sadly is only too true.

Every practical capacitor exhibits a not quite 90° phase angle, the result of two loss mechanisms. Caused by inevitable resistance R in it's connecting leadwires and metal electrodes together with fundamental dielectric losses tanδ. While these metallic loss resistances remain reasonably constant with frequency, the dielectric losses are strongly frequency dependant. Both loss mechanisms combine to degrade this nominal 90° to a lesser angle. With increasing frequency, the capacitor's self inductance, XL in the figure, acts to reduce the measured impedance as shown by the XC - XL vector. At some higher frequency when XL = XC the capacitor becomes series resonant. With further increase of frequency, our capacitor becomes an inductive impedance which increases with frequency. For example, the Elna 47,000µF 63v electrolytic, popular in amplifier power supplies, measured inductive as 23.7nH, +7.58° at 10kHz so was clearly inductive at audible frequencies even below 10kHz and 83.7nH, +78° at 100kHz.

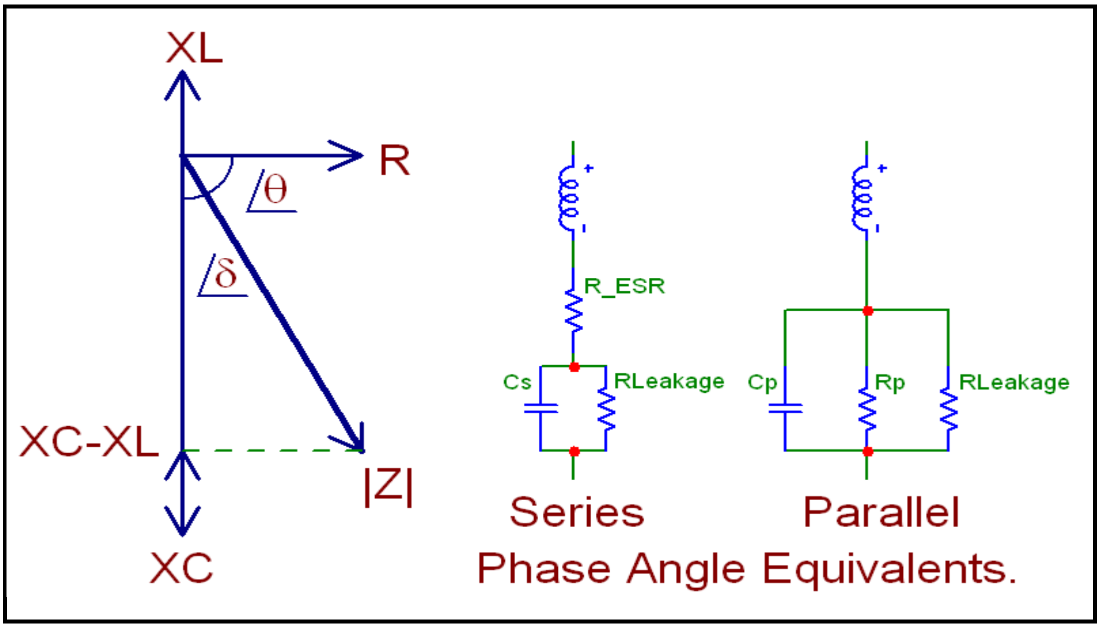

Figure 1. Many bridges default to the series equivalent measurement, but exactly the same tanδ loss angle can be translated or measured using the parallel loss components, as shown by the equivalent phase angle equations.

Even the most perfect capacitor dielectric insulator, having near constant losses with frequency, results in an ESR, shown as R_ESR in the figure, which must halve for each doubling of frequency. In practise this ideal halving is never possible because of the inevitable resistances which must be incurred in the capacitor end connections, metallic electrodes and any leadwires used. These effects are seen in these measured values of a very high quality Philips, near perfect, 1%, foil and polystyrene capacitor, which I measured at 1v AC, using a Wayne Kerr 6425 four terminal, digital, precision component analyser.

Frequency.	Capacitance, nF.	Tanδ	Phase ∠	Q	ESR Ohms.	Rp
1 kHz	9.9988	0.00005	89.997°	20,000	0.80	316.704MΩ
10 kHz	9.9986	0.00015	89.991°	6,500	0.26	9.745MΩ
100 kHz	10.0000	0.0005	89.971°	2,000	0.05	506.605kΩ

Subjected to an AC voltage or current, with or without any bias voltage, this ESR equivalent resistance dissipates power and the capacitor self heats above the local ambient temperature. A typical equipment local ambient temperature, may be say 50°C. The maximum permissible capacitor internal hotspot temperature for polystyrene dielectric should be less than 70°C at which temperature the capacitor might survive perhaps 2-3000 operating hours. In equipment terms that is unacceptably short so either this local ambient temperature or the capacitor self heating must be reduced.

Aluminium electrolytic capacitors housed in aluminium cases are supplied with a plastic oversleeve, which serves two purposes, it is easily printed with capacitance and voltage etc., but more important this sleeve actually dissipates heat more rapidly than does the bare aluminium can, so must never be removed. When I first worked designing electrolytics, like many people I queried this fact, so performed several practical test measurements of capacitors specially assembled with thermocouples to measure internal temperatures. Subjected to 50Hz test current, I measured the internal hot spot temperature of each capacitor after 3 hours, initially complete with its plastic sleeving then having removed this sleeve, retested each capacitor. In every case the sleeved version was several degrees cooler. Researching my reference books I found the answer, the low temperature infra-red radiation from the semi-polished aluminium cans was significantly lower than that from the near mat surfaced thin plastic sleeving.

Capacitor distortions.

My original series titled "Capacitor Sounds" published in the Electronics World magazine, now available for download from my web page, demonstrated the different levels of distortion produced by differing capacitor dielectrics and capacitor assembly methods, both with and without DC bias voltages. I first became aware of this from two quite different sources. I was then technically responsible for capacitor applications, at that time the company produced more than fifty quite different ceramic capacitor formulations, from N1500 through C0G up to K10,000, all having differing characteristics. One of my more interesting customers was Acoustical Engineering, who carefully researched how differing capacitors affected the sound from their pre-amplifier. As a result Quad decided to not use any ceramic capacitor with a "K" value higher than our K120051 material, a fairly low "K" material, which from their tests audibly degraded this pre-amp compared to lower "K" materials.

The second case was when one of our sales managers sold the then new X7R multilayer ceramic capacitors, for use in the trigger circuit of a triac lamp dimmer, because that maker wanted to size reduce his assembly. Some months later many thousands of these dimmers were returned under warranty for making an intrusive buzz, clearly audible in a quiet lounge. This noise was generated by the X7R multilayer capacitor body itself vibrating. This was long before invention of the ceramic tweeter speaker. Hence we have two ways a capacitor can affect our listening. Later when tasked to design new ranges of audio optimised aluminium electrolytic capacitors, I found these capacitors also generated clearly audible sounds, when stressed.

But why should even the very best capacitor assemblies generate measurable distortion ?
Capacitor dielectrics resolve into two main categories, polar and non-polar. I'm not talking here about the different aluminium electrolytic capacitor constructions, but characteristics of the actual base dielectric materials, especially for the various plastic film capacitors we use. This difference depends on the symmetry or otherwise of the dielectric's basic molecular structure.

An insulator having a symmetrical molecular structure is defined as being "non-polar" and is characterised as having electrical characteristics effectively constant with frequency, minimal sound distortion and negligible dielectric absorption effects. Such dielectrics also have small dielectric constants, or "K" values, e.g. C0G/NP0 ceramic also Polystyrene, PTFE and Polysulphone films.

When the molecular structure is asymmetrical, it has a dipole moment which results in a much higher dielectric constant "K" value, it is called a polar dielectric, e.g. high K value ceramics such as BX, X7R, U2J, W5R, X5V and the notorious Z5U also Aluminium, Tantalum electrolytics, PET and Polycarbonate plastic films. Polar dielectrics are characterised by electrical parameters which change notably with increasing frequency and exhibit significant dielectric absorption. Capacitance values reduce and dielectric losses increase, with increase in frequency.

These polar and non-polar terms are a function of the basic materials used and should not be confused with the constructional terms polar and non-polar or bi-polar, as used for electrolytic capacitors.

For many designers, the non-polar PTFE dielectric, especially at high temperature and high frequencies provides the best plastic film dielectric performance possible but it is expensive and difficult to assemble so such capacitors are less readily available, especially in Europe.

At normal temperatures its performance is closely matched by the very low cost Polystyrene capacitors, for many years the material of choice for "Standard", close tolerance, laboratory capacitors. Today the inexpensive polysulphone and polypropylene capacitors provide excellent, very low distortion, extremely stable and low cost alternatives. Both films are among the very best of the non-polar film dielectrics.

With the near disappearance of the polystyrene capacitor, many standard laboratories now use NP0, C0G ceramic capacitors, one of the very best non-polar, non-distorting, stable, dielectrics of all, as low cost transferable standards, paralleling multiple capacitors as needed to attain larger values. In recent years, makers have introduced values of 10μF and above as direct factory orders, but these are not usually distributor stocked items. Long term stability of C0G/NP0 ceramic is described as not measurable, being more stable long term than even the best commercial digital LCR meters are able to measure.

Polar dielectrics include ceramic capacitors with the "K" label, e.g. K120051 and higher dielectric constants, especially BX, X7R, U2J, W5R, X5V and the notorious Z5U. As to common plastic film types, polycarbonate and notably PET are both strongly polar dielectrics. However both films share the ability to be extruded or stretched to produce exceptionally thin plastic films, having sufficient strength to allow manufacture of low voltage capacitors having exceptionally small dimensions for their capacitance value. However their basic polar nature ensures increased distortions, especially for second harmonic when DC biased and parameter changes both with frequency and temperature.

DC bias voltage effect.
Measured using AC stress only, a few, unusually well manufactured polar dielectric capacitors are able to produce little distortion, almost comparable with the best non-polar types. However when stressed with a D C bias voltage, the asymmetric polar dielectric molecular structure rotation becomes notably extended, resulting in the much increased second harmonic distortion being measured. However usually intermodulation distortion and third harmonic levels are little changed. Measuring the very best PET dielectric 100nF capacitor, of the very large numbers of PET capacitors I tested, using 4v at 1kHz I found its second harmonic distortion increased six fold when biased with 18v DC, total distortion now measured 0.00027%, more than four times greater distortion than measured with a good non-polar capacitor. Most other PET capacitors tested measured at least ten times greater distortion.

Measuring a non-polar dielectric capacitor with or without DC bias voltage, second harmonic distortion levels remain almost unchanged and immeasurable, because bias voltage does not affect its symmetric molecular structure's rotation. Using the above test levels, the 100nF C0G ceramic second harmonic distortion was less than -125dB and its total distortion measured just 0.00006%.

For capacitor values larger than a few microfarads, to reduce cost and space we are forced to use either Aluminium or Tantalum electrolytic types. These are available both as the traditional "polarised" style and non-polarised or "Bi-polar" types. The "Bi-polar", non-polarised construction uses two anode assemblies connected electrically "back-to-back", while physically larger they produce significantly less distortion, both with and without DC bias voltage, than any of the traditional "polar" types.

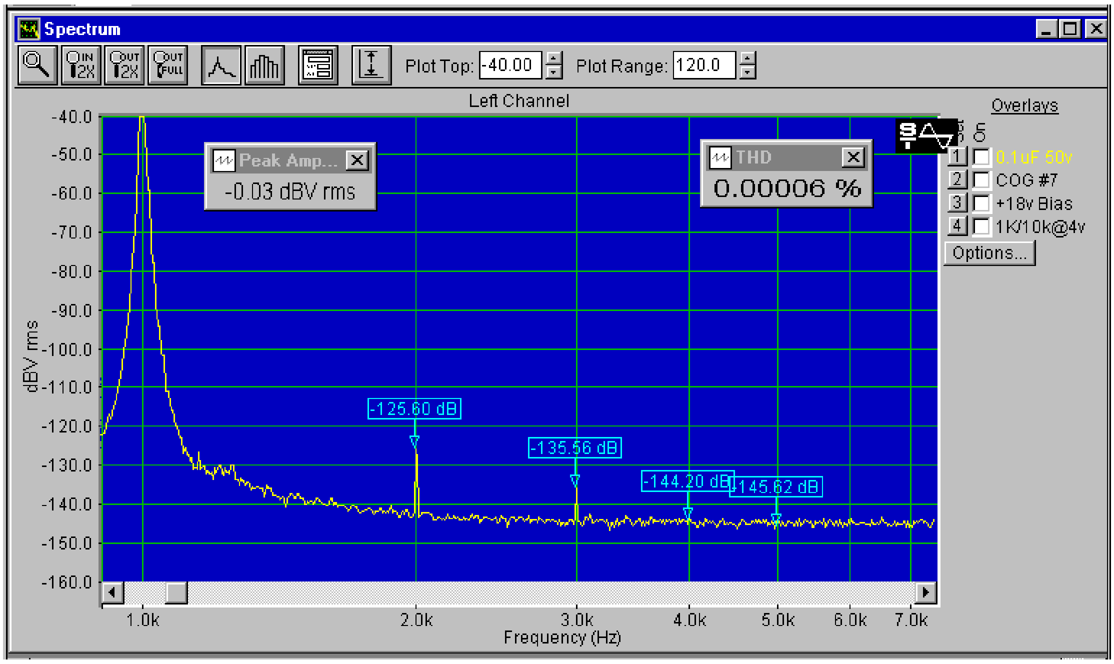

Figure.2. Tested with 4v at 1kHz and 100Hz, with 18v DC bias, this figure demonstrates the very low distortions possible using a C0G ceramic capacitor. This 50v rated 1% 100nF C0G multilayer was just 0.00004%, with 0v bias.

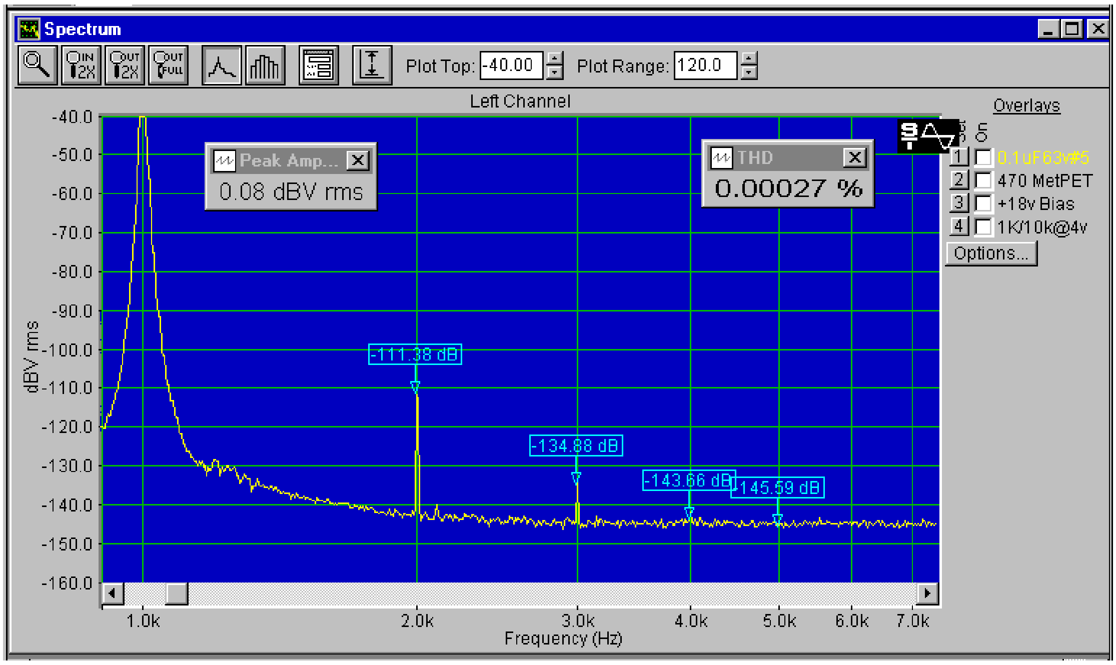

Figure. 3. Tested also with 1kHz and 100Hz and 18v DC bias, exactly as figure 2, above, this was the best sample of the many metallised PET capacitors I tested. Notice the much increased second harmonic.

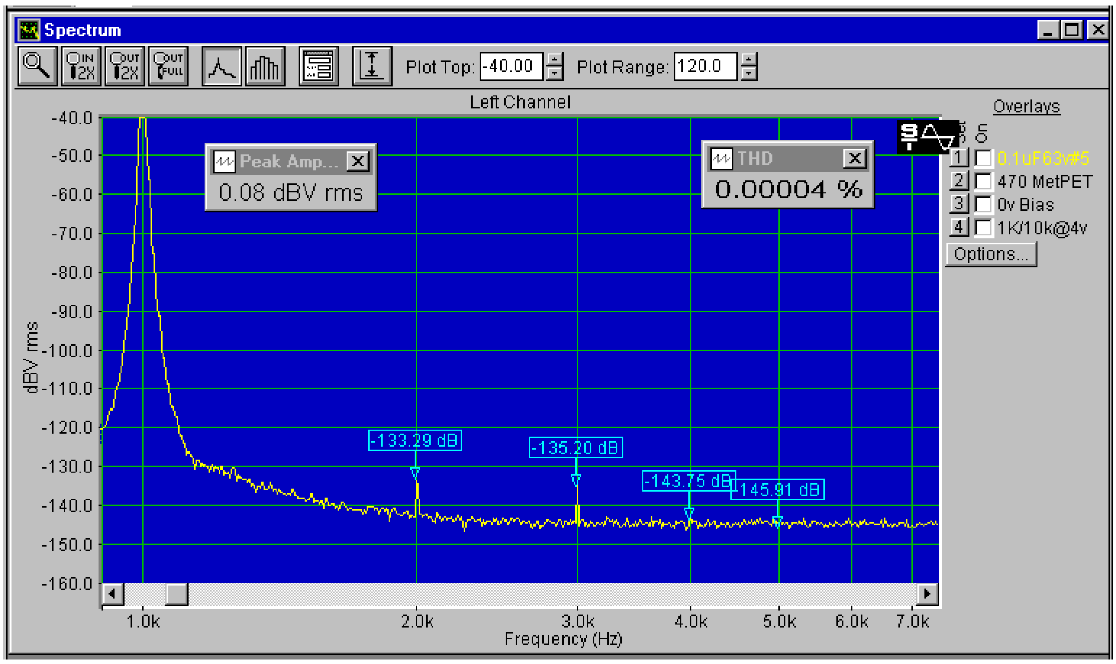

Figure. 4. The figure 3 capacitor but now tested with 0v DC bias, exhibits exceptionally low distortion, but as seen in figure 3, using a polar, PET metallised dielectric, any DC bias voltage causes second harmonic distortion.

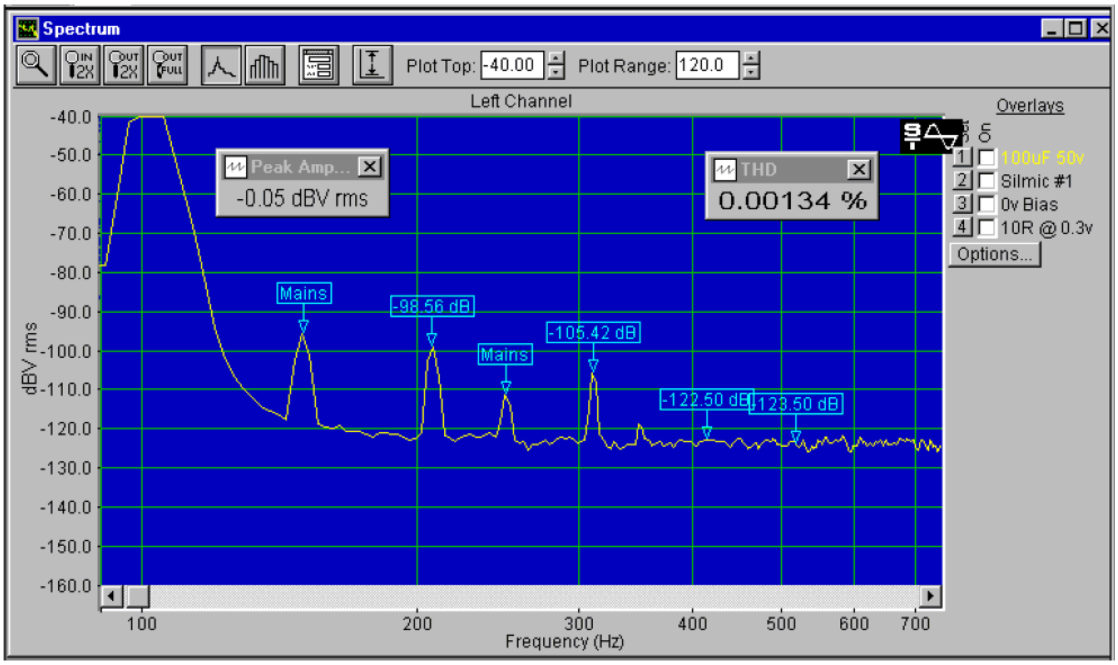

Figure.5. 100µF electrolytic capacitor is often used to DC decouple the negative feedback loop, but that can directly feed any distortion produced by this capacitor into the output. This capacitor was one of the best I tested at 0.3v AC.

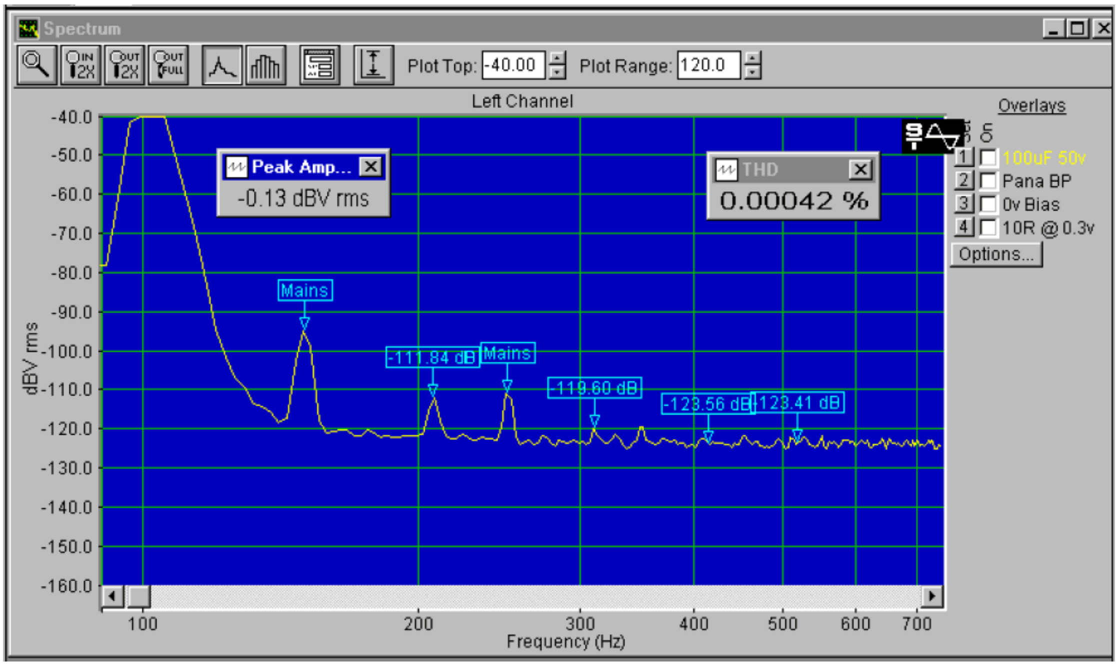

Figure.6. Replacing a conventional Polar Aluminium Electrolytic by a Non-polar (Bi-polar) type requires little extra board space or cost but reduces this distortion input by more than 300%.

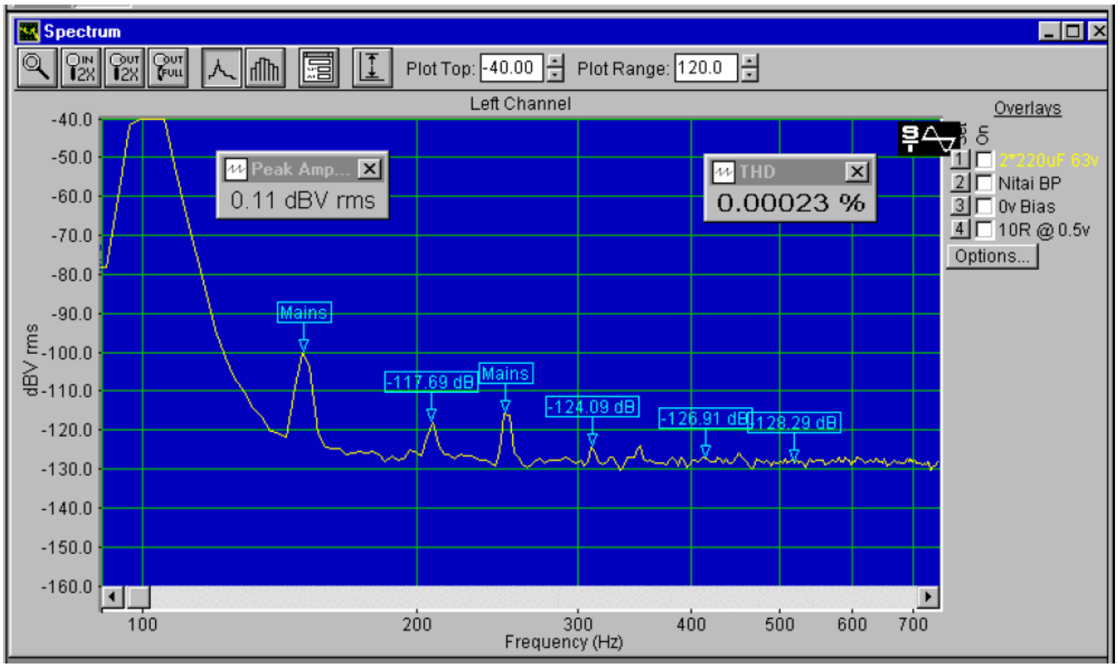

Figure.7. Perhaps you need low distortion but with voltages greater than the 0.3vac used for figs,5,6. By connecting two Non-polar types in series, distortion similar to that from metallised film capacitors can be assured.

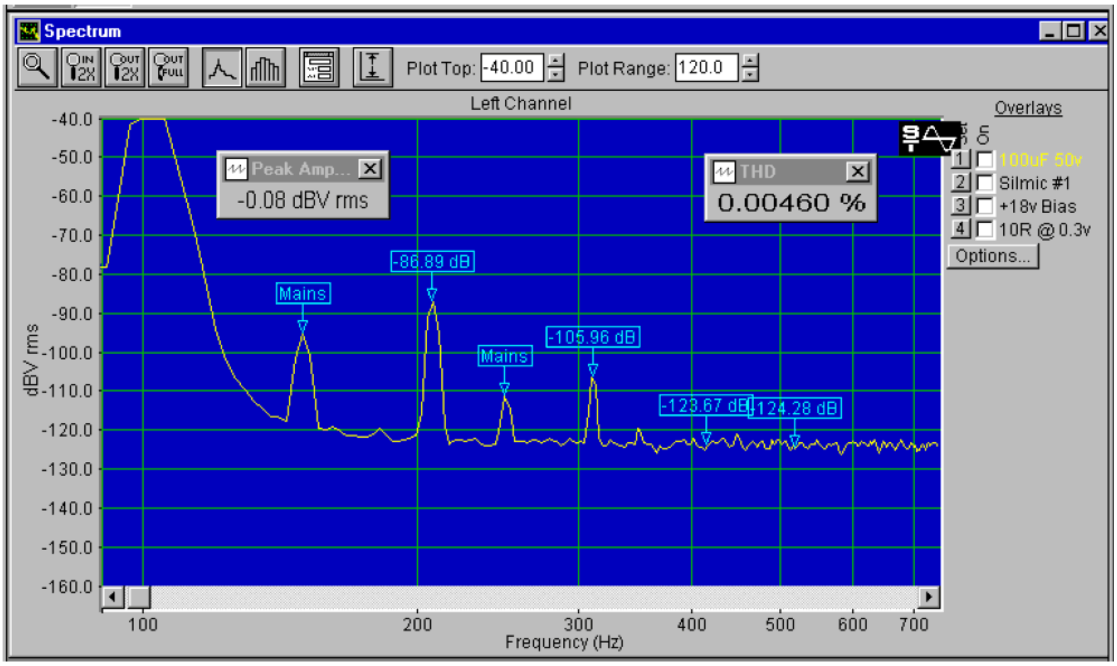

Figure.8. Any application of DC bias (polarisation) voltage to all aluminium electrolytic capacitors results in significant distortion, even with small AC voltages, 0.3v as used here. Distortions increase with AC and DC.

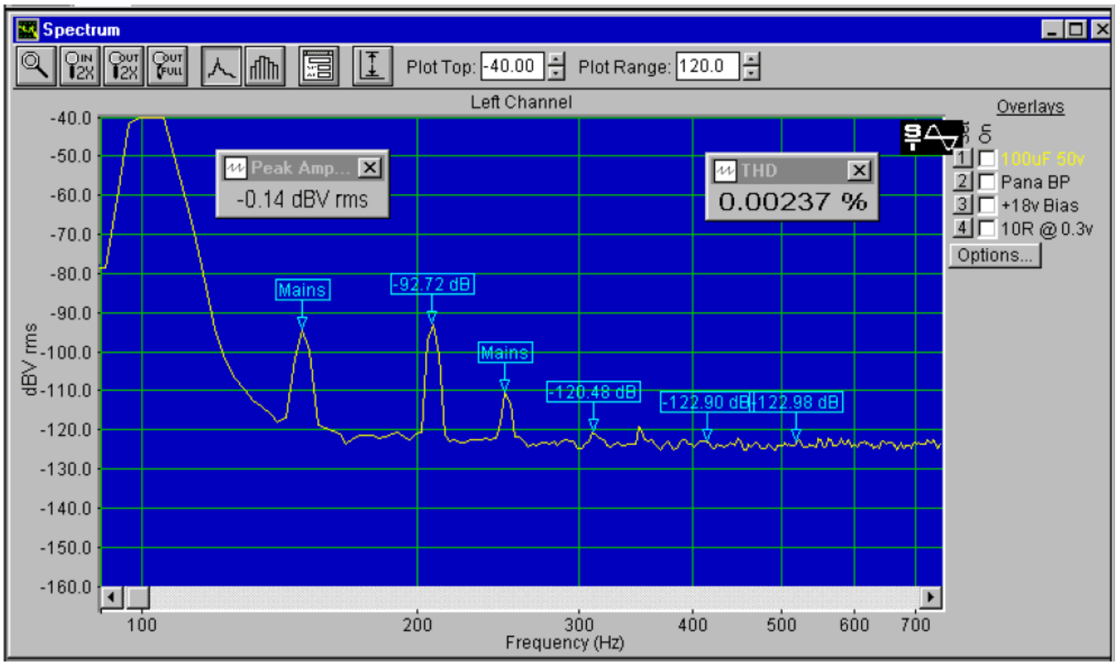

Figure.9. Using a Bi-polar Aluminium Electrolytic to replace even the best possible conventional Polar type, easily results in halving of distortions, and can be much less expensive. Both above capacitors are 100µF 50v parts.

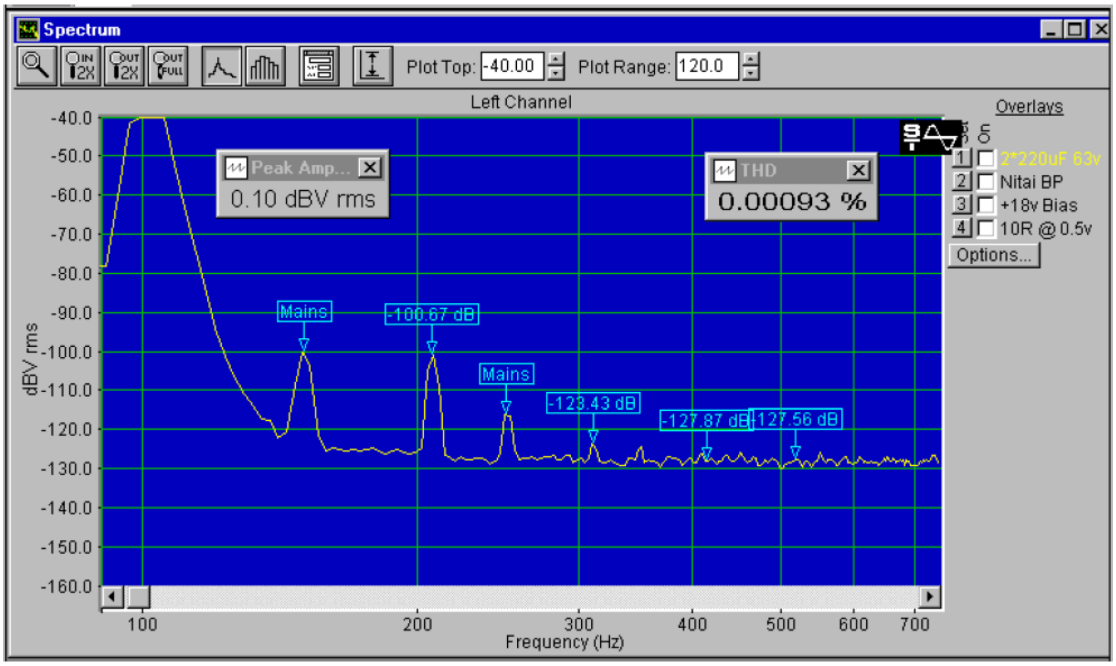

Figure.10. Using two Non-polar capacitors in series again dramatically further reduces distortions and allows use with increased levels of bias voltage and 0.5v AC signal voltages, providing acceptably low distortions even with 1v AC signal levels.

AC working versus DC rated capacitor applications.
Many years ago when impregnated metallised paper capacitors were the standard workhorse, it was considered that a capacitor rated for 400 v DC or above, could be used on 250 v AC mains. Since these capacitors were impregnated, depending on the impregnant used, this was just about feasible. Unfortunately this old saw tends to continue even today.

When the then new low cost, un-impregnated metallised PET capacitors became commonly available some forty years ago, the more expensive impregnated metallised paper capacitors were largely superseded. The best AC capable impregnant, based on chlorinated bi-phenols (PCB), was outlawed and to fill this gap the 400 v DC un-impregnated, usually flattened, metallised PET capacitors parts became adopted for many of these 250 v AC mains requirements. A great many of these capacitors dramatically failed. If you were lucky the end terminations eroded, effectively disconnecting the capacitor, but if unlucky the capacitor caught fire, as happened in a notable Bond Street, London, shopwindow.

Even today I have vivid recollections of this unhappy time when my task was to withdraw from all such 250 v AC mains applications and de-rate these capacitors to 160 v AC, on behalf of my employer, for this particular flat metallised PET capacitor construction.

Why should this problem arise ?
Given an impregnated or otherwise solid, void free, capacitor construction, 250 v AC and above, causes no insuperable problems. However un-impregnated capacitors inevitably contain many minute pockets of air, trapped inside the windings. The lower “K” value of the air dielectric void is then subjected to increased voltage stress, so may become liable to internal ionisation leading to “partial discharges” which can release nascent hydrogen, which then quickly degrades the plastic film dielectric.

According to Paschens curve of ionisation, an air filled void having optimum size and air pressure, with aluminium electrodes, can exhibit ionisation inception at voltages as low as 185 v AC. Hence my adoption of 160 v AC, to ensure some small safety margin for voltage spikes.

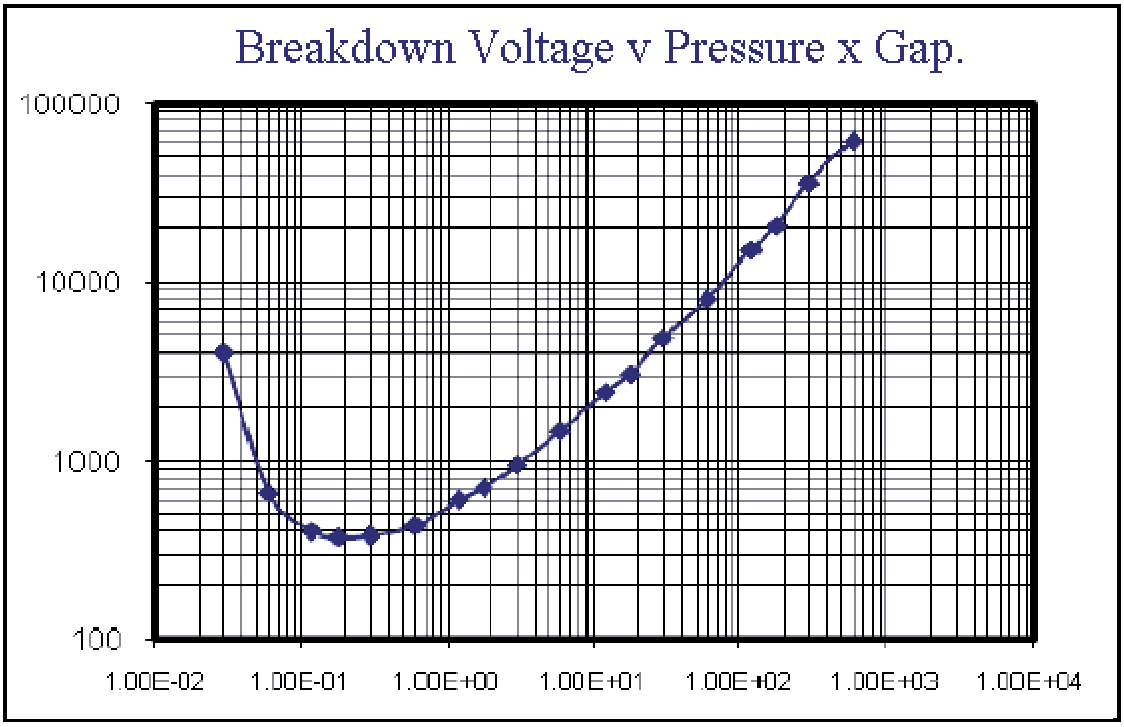

Figure. 11. In 1889, Friedrich Paschen investigated discharge inception voltage by air pressure, using two parallel 3/8” spaced electrodes.

Subsequent work found these voltages varied up/down with different gases and metal electrodes.

This ionisation discharge current once triggered, is self sustaining at lower voltages, almost down to zero volts. Thus once triggered, the resulting discharge continues for almost 50% of the alternating waveform. This ionisation discharge is damaging to almost all dielectric materials, resulting ultimately in a short circuited capacitor. Aluminium electrodes inception commences at much lower voltages than above.

From these unhappy experiences, International and National safety rules for class X capacitors, used across the 250 v AC domestic mains, together with a re-evaluation of the levels of mains born spikes which must be withstood, were developed. Two main capacitor class X styles then emerged, a much updated resin impregnated metallised paper capacitor from Sweden and the two-in-series metallised Polypropylene style originated by Erie Electronics UK in 1970, the world's first, approved, 250 v AC mains rated metallised capacitor. This two-in-series construction, wound using the "lost core" technique, worked well since with two capacitor elements in series, each shared around half of the applied voltage and the lost core winding technique maintained a tight, well controlled, element winding.

These ionising discharges damage capacitors by two methods. The insulating property of the dielectric becomes reduced and any metallised electrodes slowly disappear. In most cases the capacitor is totally destroyed, but I was fortunate to retrieve some development two-in-series motorstart/run capacitors which had been on AC endurance trials, by a world renowned washing machine maker based at Halifax in UK. Having been stressed for many hundreds of hours, these capacitors had been badly damaged, now have less than 50% of their initial value, but were not totally destroyed.

When I opened their hermetically sealed cases, the characteristic smell of polypropylene dielectric which had been ionised was un-mistakable. When unwound, the metallised electrodes were "moth eaten" with more than 50% of their original electrode area missing, it had simply been burnt away.

One final comment about the latest, sub-miniature electrolytics.
With any normal aluminium electrolytic capacitor, its small leakage current ensures the capacitor becomes discharged unless deliberately powered.

With small, low voltage electrolytics, the aluminium oxide which forms naturally on the cathode foil when exposed to air, acts as a second capacitor in series with that of the anode foil, reducing the net capacitance, increasing costs and physical size. Recent work by some foil suppliers coating the cathode foil with a thin coating of another metal which does not form an insulating oxide, has reduced this effect, thus reducing both cost and size of some low voltage, miniature, polar capacitors.

Provided the capacitor is used in a reasonably low impedance circuit, all seems well, however used in high impedance circuits these capacitors can exhibit a "battery" effect, generating a small DC voltage which depending on the metals used, can approach 1 volt. Test capacitors loaded with a 10MΩ resistance have been observed generating a steady DC voltage over a twenty four hour period. Loaded with an additional 4M7Ω this voltage reduced but again recovered when this second resistor was removed to leave the original 10MΩ.

In many, perhaps most circuits, this may not matter, but when used to de-couple the negative feedback arm in a conventional power amplifier, these capacitors have created problems. My suggested remedy is to use a non-polarised, Bi-polar electrolytic capacitor for this position, which has the added bonus of reduced distortions.