Understanding capacitors

Cyril Bateman looks at the second most widely used capacitor technology – namely plastic film – and reveals the features of all the different types in common use.

The modern plastic film capacitor offers a unique balance between pulse current handling, size and cost. Historically, ceramic capacitor development was driven by American technology. The plastic film capacitor on the other hand was a European, mostly German driven, development.

Today, ceramic and film capacitors are manufactured throughout the world, but evidence of these past differences remain. Being influenced by Europe and the USA, UK component makers became strong in both technologies.

Plastic film capacitors fall into two main application categories – those with metallised electrodes for conventional decoupling tasks and those with foil electrodes for improved pulse-current handling. All are manufactured using commercially available, flexible plastic dielectric films. These films need only the base metal electrodes to be added.

Film capacitors can be automatically wound and economically assembled. Choice of the film material and electrode type determines the capacitor's finished size and performance relative to temperature and frequency.

Plastic film background

The original plastic dielectric could not be produced as a thin self-supporting film. One method used in early plastic-film capacitors was described in British patent 587 935 of 1944. This involved soft metal-foil electrodes, onto which the plastic dielectric film was applied. Known as lacquered film capacitors, these types are now obsolete. The technique permitted polymer dielectric as thin as 1.5 microns to be cast directly onto foil electrodes.

Plastic material for use in modern capacitors must have the right electrical properties. It is essential that the material can be produced with sufficient strength and flexibility to withstand element winding at speed, and with a thickness providing the desired size and capacitance.

Development of plastic materials[1] escalated rapidly in the fifties, resulting in today's three most popular plastic capacitor dielectric materials – polyethylene-terephthalate, polycarbonate and polypropylene. Polystyrene is also used. Plastic film capacitors are now the second most widely used capacitor family, accounting for more than one quarter of all capacitor sales.

Note that polyethylene terephthalate is known by several names including Mylar PET, Melinex, Polyester and Hostaphan. For convenience I will use the term PET, except when referring to material produced by Du Pont de Nemours.

In 1951, Du Pont's Luxembourg plant developed a thin, bi-axially stretched, self supporting Mylar film for use in capacitors. By 1959 the Westermann Company of Mannheim in Germany, maker of Wima capacitors, had developed suitable electrode metallisation methods for 6 micron film. The first viable, mass produced, general purpose metallised film capacitor had arrived.[2]

Modern plastic-film capacitors

To improve resistance to soldering heat and cleaning solvents, the long established polystyrene dielectric is slowly being replaced by polypropylene – especially for small, very close tolerance, axial and radial leaded parts.

Recent developments using polyethylene-naphthalate and polyphenylene-sulphide have provided a surface mounting, uncased yet moisture-resistant chip film capacitor. Polyphenylene-sulphide chip capacitors can withstand flow soldering.

This article covers the main film-capacitor products in use today. Other types not mentioned here have been popular in the past but are now redundant and are therefore omitted.

Making film dielectric

All polymers have a very high molecular weight. They have extremely long, and frequently multi-branched, molecular chains made up mainly of hydrocarbons. These repeating molecular chains have a natural inclination to merge into a dense tangle of twisted and intertwined chains.[1]

Thin films of these plastics are made using one of two main methods – spreading from a molten state and casting from solution using a solvent.

Although inherently brittle when cold, polystyrene can be heated and extruded as a tube. The diameter can be mechanically expanded while the polymer is hot. Additionally, longitudinal stretching can be applied as the film cools.

Stretching is important not only in reducing film thickness. Due to the partial alignment of the molecular chains that occurs, brittleness is reduced, and the film is made stronger. At the final stage, the stretched tube is flattened by passing between rollers. By 1960, a consistent film thickness of 10 microns was achievable using these techniques.[3]

Polyolefine films – such as low and high-density polythene and polypropylene – can be produced in a similar way. Usually though, the initial diameter stretching is done by blowing air through the centre of the extrusion die into the still hot tube.

Using extrusion and stretching techniques Mylar capacitor film of 1.5 microns thickness – some 15-20 times thinner than human hair – was first introduced in 1978. This film had a tensile strength of 1000kg/cm^2 and a 500V dielectric breakdown strength. This exceedingly thin film was used in the production of Wima capacitors[2] in 1980.

In contrast, a 2 micron thick polycarbonate film was available in the late sixties. It was used by the A H Hunt Company in the production of their Metalac metallised polycarbonate capacitors. These had values up to 10μF at 100V in a tubular case measuring 14 by 33mm.

The polycarbonate film was produced by casting from solution in a suitable solvent. Solvent casting is expensive but can produce a more uniform thin film than extrusion and blowing. This cast film is stretched or drawn down to final thickness.

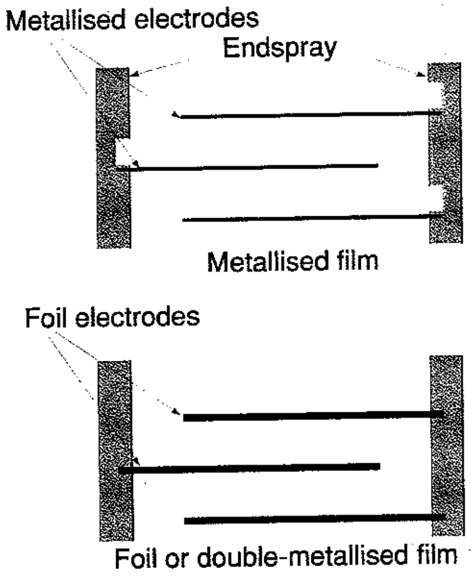


Fig. 1. Having no discrete electrodes, the metallised film capacitor maximises capacitance and voltage for a given size, but has limited current handling. Use of foil electrodes maximises current handling but reduces capacitance. Double metallised film electrodes, described in a German Patent, offer intermediate capacitance and current handling.

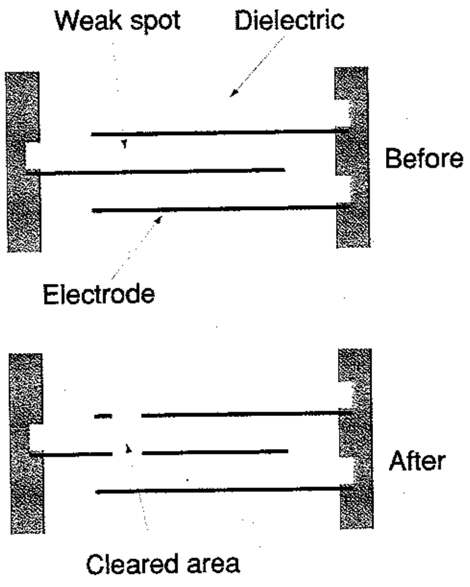


Fig. 2. Metallised film capacitor cross section, illustrating self-healing action. Before and after views show how electrodes and dielectric film are both involved when 'clearing' a fault.

Adding electrodes

As with paper capacitors, discussed in the February issue, either soft metal electrode foils or metallisation of the dielectric film's surface can be used.

Metallised-film electrodes, usually of aluminium evaporated under vacuum at high temperature, are extremely thin and optically transparent. Metallised film gives the best possible capacitance/voltage ratio for a given case size. But such thin electrodes are resistive, degrading power factor at high frequency and restricting capacitor current handling, **Fig. 1**.

The major benefit from using metallised electrodes is their ability to self heal, allowing much thinner dielectric films to be used relative to foil electrodes. When subjected to an excess voltage, during manufacture or service, this thin resistive metallised electrode easily evaporates away from any weak areas of dielectric. This evaporation isolates the weak areas and restores the capacitor's insulation resistance, **Fig. 2**. The same weak dielectric in a foil electrode capacitor becomes permanently short circuited and the capacitor fails.

The metallised film needs to have a non-metallised edge to insulate it from one or other of the two termination electrodes. The virgin polymer film is often masked down one edge during the metallising process. Alternatively, spark erosion can be used to produce an insulated edge on the film after the metallisation process.

Extended foil construction

Unlike paper capacitors, foil-with-film capacitor windings are almost invariably of 'extended-foil' construction. Inserted tab connections are sometimes used with buried foil electrodes in polystyrene capacitors, allowing heat sealing of the winding.

Due to their low resistance, metal-foil electrodes give better power factor and current handling. Their 5 to 6 micron foil thickness increases the capacitor's physical size though. Not being a self-healing construction, these metal-foil types need to have either a thicker dielectric or a reduced working voltage, compared to a capacitor with metallised electrodes, Fig. 1.

A good compromise

An alternative thinner electrode system has been developed which helps keep the size increase down. Its current handling is much better than metallised film, and it features self healing. Electrode resistance is intermediate between foil and conventional metallised dielectric. In this construction, electrodes of very thin film metallised on both sides, are used with non-metalised dielectric film.

These electrodes are made using PET or polycarbonate. Both materials are easy to metallise and are available as very thin films. Being used only as electrodes and not as part of the capacitor's dielectric, they can be more heavily metallised. The resulting electrodes are much thinner and softer than conventional metal foil electrodes and have a lower resistance than is possible with metallised dielectric film.

Being self-healing, these doubly metallised film electrodes can be used with very thin, un-metallised dielectric films. This results in a small capacitor with excellent current pulse capabilities. This construction was described[4] in German patent G.P.2151438.

Polypropylene film is difficult to metallise – even after corona surface treatment to improve adhesion. Resulting electrode resistance is generally 3 to 5Ω per square.

This doubly metallised film electrode system, used with untreated Polypropylene dielectric, optimises ac and pulse current performance. It provides a polypropylene capacitor that is physically small, self healing and has good pulse handling capability.

Putting it together

Having chosen the electrode and dielectric film system, how are film capacitors assembled? Two methods prevail – winding and stacking. Larger capacitors are invariably wound, but for common printed board sizes, Siemens favours the stacked-film approach. Westermann by contrast winds everything.

Strictly speaking, both types are wound. Westermann winds to the finished size whereas Siemens winds many metallised-film capacitors in one master capacitor on core wheels up to 60cm diameter. These capacitors[5] are metal sprayed at the ends, heat treated as needed, then diced to produce the finished capacitor elements, **Fig. 3**. A similar approach is used to make Panasonic's surface mounted chips, introduced in 1992.

Having used both stacked and wound miniature film capacitors interchangeably for many years, I find both styles satisfactory. If you are interested in exploring the wound versus stacked discussions, take a look at an article in *Elektronik*[5] and page 202 of the Siemens Film Capacitor Databook on cd rom.

Capacitor elements are usually wound in clean-room conditions using high speed, split mandrel, fully automatic winders. The split mandrels are part of the winding machine. They are arranged to withdraw from either side of the capacitor, releasing the completed winding. Increased diameter mandrels are used to facilitate capacitor flattening, **Fig. 4**.

Large tubular capacitor windings may use the so-called lost core or lost mandrel approach. Here, the winding mandrel is not part of the winding machine, but usually an injection moulded hollow spindle. The mandrel becomes part of the finished capacitor, ensuring mechanical stability during subsequent heat treatment and in service.

Various arrangements of foil or metallised electrodes can be provided – including extended foil and two-in-series constructions.[6]

All windings, whether round, stacked or flattened, are stabilised by heat treatment. This treatment allows the film's natural shrinkage to consolidate the winding and relieve stresses in the dielectric.

Terminations

Termination wires for extended-foil-electrode capacitors can be soldered or electrical resistance welded directly to the foil electrodes. With both foil and metallised electrodes though, metal-sprayed end connection are more common.[6] The metal spraying technique used is known as 'Schoop' end spraying.

Due to its low melting temperature, polystyrene dielectric is not end sprayed. Often, the foil is extended slightly to allow the lead wires to be connected directly. Alternatively, tabs connected to the lead wires are inserted into the foil electrodes.

Where metal spraying is concerned, after the initial spray, the end contact can be consolidated by spraying other metals and/or solder coating. Final lead-wire connection is made either by soldering or resistance welding.

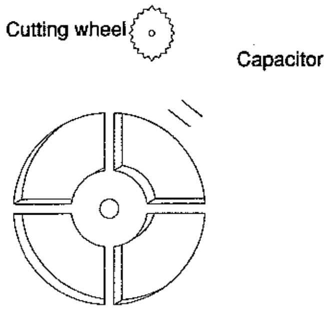


Fig. 3. Stacked film production technology. Large rings of metallised film, of width equal to the final capacitor body length, are wound on 'core' wheels. These rings are metal end sprayed, then sliced to make individual capacitors.

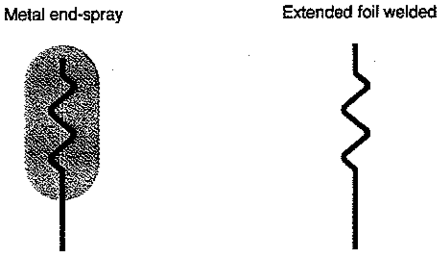


Fig. 4. Winding on a larger diameter mandrel allows the roll to be flattened to form the capacitor element. Both metallised and extended-foil electrode capacitors can take advantage of sprayed-metal end connections. Foil electrodes that extend beyond the dielectric roll allow resistance welded, directly attached lead wires. In the centre is the wound capacitor before compression.

Dielectric characteristics

All capacitor dielectrics described as polar or non-polar, depending on the symmetry of their molecular structure. Symmetrical, non-polar materials have electrical characteristics effectively constant with changing frequency. They also exhibit minimal dielectric absorption effects.

If the molecular structure is not symmetrical, it has a dipole moment resulting in increased dielectric constant, and is designated as polar. Electrical characteristics are strongly frequency dependent. As frequency rises, the capacitance decreases while tanδ losses increase. In addition, there are notable dielectric absorption effects.

These polar and non-polar terms are a function of the basic material used and should not be confused with the constructional terms polarised and non-polarised, as applied to electrolytic capacitors.[7]

Generally, the non-polar dielectric PTFE provides the best performance – especially at very high frequencies and temperatures. But PTFE capacitors are expensive and rare.

The polystyrene alternative

Polystyrene is a low-cost non-polar dielectric that *is* freely available. At low frequencies, it has better capacitance stability and lower losses than PTFE. It offers the best characteristics of any commercial film dielectric and exhibits a slightly negative temperature coefficient of –150ppm.

This material provides stable capacitance and extremely low tanδ losses with frequency. In addition it has very low dielectric absorption, negligible voltage coefficient, good long-term capacitance stability and a 'Q' approaching 1000 at 1MHz for small values.

applications. But two inhibiting factors emerged. Polypropylene has an extremely smooth surface finish that has to be corona treated to make the metallised electrode adhere properly. PET suppliers rapidly developed much thinner, more easily metallised and stronger capacitor films.

Consequently, polypropylene is currently replacing polystyrene in low value precision foil and film designs. It remains the benchmark dielectric for ac tasks and applications where high pulses are expected. These capacitors are made with foil and metallised film carrier electrodes and non metallised polypropylene dielectric films.

Recent developments

The drive to provide small low-cost surface mounted bare chip capacitors to compete with ceramic chip capacitors has resulted in the introduction of two new film dielectrics.

The general-purpose polyethylene-naphthalate, or PEN, has a +200ppm temperature coefficient and characteristics sim- to PET. It is strongly polar. At 1.2%, it has the highest dielectric absorption of any capacitor film.

Low-loss polyphenylene-sulphide, or PPS, is a non-polar dielectric with a 'K' of 3. Its capacitance value and $\tan\delta$ losses are stable over temperature. Its small negative temperature coefficient and other characteristics are similar to polypropylene, but it is available in thicknesses down to 2 microns. PPS has a much higher softening temperature and in sections thicker than 25 microns, it is recognised as a V-0 (UL94) flame retardant material.

Many older plastic dielectric films resulted from developments by UK or German engineers. But this bi-axially stretched PPS film was developed jointly by the Phillips Petroleum Company and Toray Industries of Japan. The basic PPS polymer may be familiar to many as the high temperature moulding compound Ryton.[11]

PPS has a melting point of 285° celsius a $\tan\delta$ and dielectric absorption second only to polystyrene and polypropylene. With a dielectric constant of 3, a 2 micron minimum thickness and a very high tensile strength similar to PET, you can expect to see PPS film finding use in many ac and pulsed-current applications in the future.

While more than ten different plastic-film dielectrics are rently used in capacitor manufacture, those mentioned above represent the most widely used.

Pulse and ac applications

Properly constructed plastic-film pulse capacitors provide a long service life while subjected to extremely severe conditions of voltage or current pulse and temperature. Presented with a pulse or ac application, how can a designer determine which capacitor can handle the task without overspecifying?

Figure 5 shows alternative constructions for high-voltage pulse-handling capacitors. With sinusoidal applications, determining the circuit voltage and current requirements is simple. Given the capacitor's $\tan\delta$ or equivalent series resistance at the relevant frequency, capacitor power dissipated is easily calculated, either manually or using Spice simulations.

With non-sinusoidal waveforms this is no longer the case since the equivalent series resistance for all capacitors varies with frequency. Using transient or time domain simulations, Spice can calculate capacitor currents over time. But it cannot then use the frequency-dependent resistance value needed to calculate the capacitor's actual power dissipation. Rules of thumb have been invented but they tend to be hit and miss.

For a low-loss component, capacitor current at any given harmonic relates to the harmonic's voltage multiplied by the harmonic number. Assume a simple square wave application at 10kHz repetition with the 0.056µF capacitor shown in **Fig. 6**. Equivalent series resistance, or esr, at the fundamental frequency is 0.0593Ω. For such a low loss, near ideal capacitor, the current at the fundamental and each harmonic will be almost equal. Since this capacitor's esr continues to reduce with frequency, then some 80% of its total RMS power is dissipated at the 10kHz fundamental.

At a certain frequency, a capacitor's esr reaches a minimum. Generally, this frequency is lower for larger capacitors. As frequency rises beyond this point, esr increases again, contradicting assumptions made in the last paragraph and much increasing power dissipation at harmonic frequencies.

Of course the square wave is only one possible waveform. With pulse waveforms, as duty cycle changes, the voltages for higher harmonics quickly increase compared to those of a square wave. Harmonic power then considerably exceeds that dissipated at the fundamental frequency, dominating the power dissipated by the capacitor.[12]

Dissipation with complex waveforms

The only useful way of determining power dissipation under these conditions requires a number of procedures. First, FFT conversion of the observed voltage waveform across the capacitor into the frequency domain is used to identify the voltages and relative phases of each harmonic component.

Calculation of capacitor current then needs to be carried out at each harmonic frequency. Identification of the capacitor's esr at each relevant harmonic frequency comes next. Finally, calculation of the total power dissipated by these harmonics in the capacitor can be determined.

Designers interested in a step-by-step method of calculating capacitor power dissipation due to pulse waveforms will find details in my April 1995 capacitor article.[12]

Every manufacturer of pulse capacitors provides guidance on how best to perform these calculations in their catalogues and application notes. They frequently use simplifications and approximations. Many offer to perform the above recommended FFT routines and more for you, on receipt of accurate voltage and current oscillograms.

Evox Rifa provides two additional aids. One is a booklet called *Pulse capacitors basic information*, written by Professor Bengt Alvsten of the University of Aolberg, Denmark. The other is a software package dedicated to calculations for their pulse capacitors, called *PCCAD*. This software can be downloaded from the company's web page or requested on floppy disk.[13]

The *PCCAD* software package includes an on disk catalogue of pulse capacitors together with a form of FFT program that allows a pulse waveform to be analysed. The catalogue can be accessed graphically to extract any needed capacitor parameter – esr, $\tan\delta$ or maximum permissible current or voltage – all versus frequency and ambient temperature. The slider bars and simple menu approach used are clearly visible in Fig. 6.

Capacitor self inductance

With the exception of the bare surface mount capacitor chip, all film capacitors use wire connecting leads between the external circuit board and the capacitor winding.

A long established rule of thumb assumes the self inductance of a wound, extended foil or Schoop end-sprayed capacitor element is similar to, or maybe slightly less than, its body length of lead wire. This low self inductance value results from each wound turn being effectively short circuited

For many years polystyrene remained the preferred dielectric for precision capacitors, but its low softening temperature required careful soldering. Polystyrene cannot be metallised and is attacked by board-washing solvents in unprotected. For these reasons it is slowly being replaced by polypropylene.

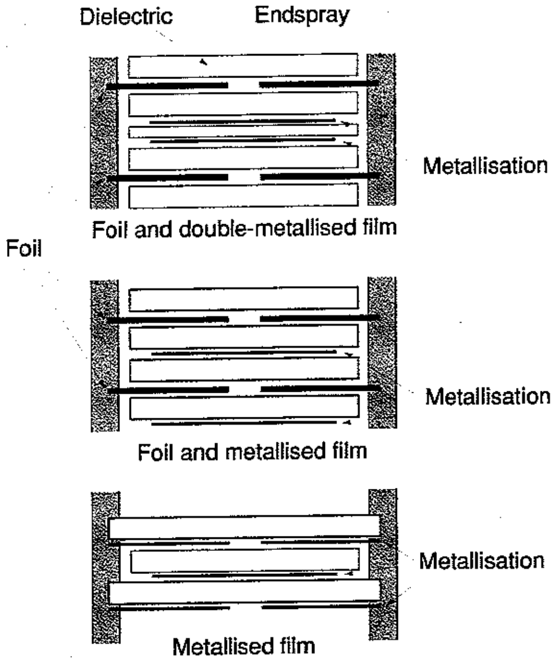
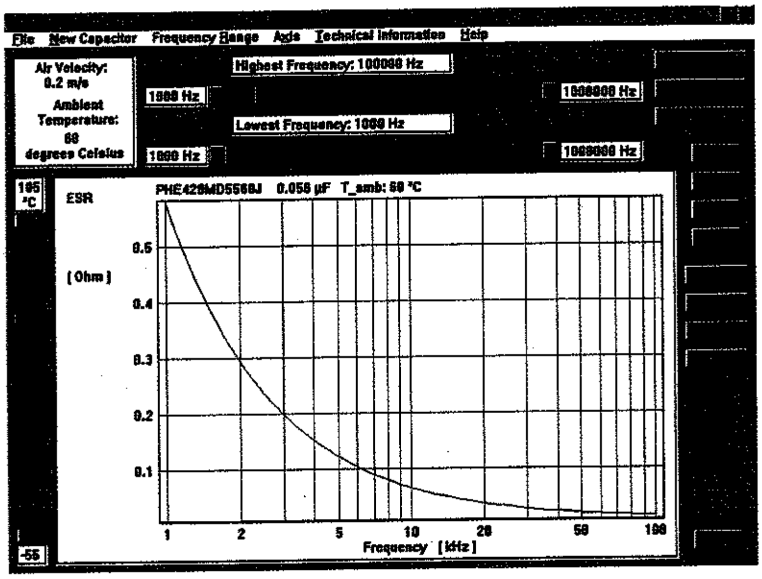


Fig. 5. Low-current, high-voltage, pulse capacitors are made using only metallised film electrodes. Increased current handling is provided by use of foil electrodes with a conventional series metallised film dielectric, or the doubly metallised non-dielectric film electrode, as used in the original Wima FKP1 samples. This represents a trade-off between capacitor size and current handling.



Air Velocity: 0.2 m/s
Ambient Temperature: 60 degrees Celsius
Highest Frequency: 100000 Hz
Lowest Frequency: 1000 Hz
1000 Hz
1000000 Hz
1000 Hz
1000000 Hz
PHE426MD5560J 0.056 µF T_amb: 60 °C

Fig. 6. The Evox-Rifa pulse capacitor on-screen catalogue, used to ascertain capacitor esr by frequency, at 60° ambient. Alternatively it can provide plots of tanδ by frequency, and rms current and voltage limits versus frequency and temperature.

PET dielectric is strongly polar, with a dielectric absorption figure of around 0.25%. It has a 'K' value of 3.3 and a typical temperature coefficient of +400ppm. PET's capacitance and tanδ characteristics are both frequency and temperature dependent.

Despite these poorer electrical characteristics though, PET metallised film provides significant size and cost reduction benefits. As a result, PET components are used in almost all general-purpose film-capacitor applications.

Polycarbonate and polypropylene

Polycarbonate is also polar, but less so than PET. Its dielectric absorption is around 0.2%. It has a 'K' value of 2.8 that remains nearly constant with temperature, but it is more expensive. Its use now is generally restricted to the higher temperature rated, or flatter temperature coefficient circuit needs.

Polypropylene is a non-polar dielectric, with a 'K' value of 2.2 and less than 0.1% dielectric absorption. It offers similar but slightly poorer electrical characteristics than polystyrene. It has a high softening temperature and is relatively inert to solvents. As a result, it is tending to replace small precision polystyrene and foil capacitors.

With a slightly negative temperature coefficient of –150ppm, polypropylene provides stable capacitance and extremely low tanδ losses with increasing frequency. It has a negligible voltage coefficient, a capacitance stable over time and a 'Q' approaching 1000 at 1MHz for small capacitance values. It has the highest voltage breakdown strength of these films, but cannot be used thinner than 4 microns to make capacitors.

When introduced as a capacitor dielectric in the early seventies, usable polypropylene film could not be produced any thinner than 9 microns. But its excellent ac characteristics, combined with the pressing market need for a good 250V ac mains capacitor, led to its first commercial introduction.

The Erie 54000 polypropylene film capacitor was wound on a lost core for long term mechanical stability.[8] It used two metallised-film windings in series to avoid internal ionisation. This technique is still used in modern designs.

High working stresses

A pressing design problem was presented by the introduction of the first generation all solid state 110° colour televisions. The high voltage transistorised line deflection systems required two extremely highly stressed capacitors.

The capacitor used to resonate the line output transformer to the fifth harmonic of the line scan frequency was subject to 1.5kV pulses. The 'S' or scan correction capacitor was required to pass 6A at line scan frequency. Initially, these tasks were carried out by using custom designed tubular windings of metallised polypropylene. A four-in-series winding was used for the 'Line-tuning' and a 'two-in-series' for the 'S' correction capacitors.[8]

Subsequently, Westermann introduced the first very high voltage and pulse capable capacitor ranges. Their MKP10 and FKP1 self healing, flattened designs also used polypropylene dielectric. The original FKP1 samples that I have were resin cast, but current production components[4] use a moulded 'E' case with resin filling, **Fig. 5**.

At that time in the early 70's, many capacitor designers[9,10] including me expected that polypropylene would become a near universal film capacitor dielectric for both ac and dc to every other turn, in effect a single turn winding.

Depending on wire gauge used, typical capacitor wire leads display some 7 to 8nH of self inductance per cm length. Printed circuit board tracks 0.5mm wide display some 8 to 9nH of self inductance per cm length, according to copper laminate thickness used.[14]

A small 7.5mm lead spacing boxed radial capacitor, pcb mounted, will thus exhibit some 5nH of self inductance due to its element winding length and a further 5nH due to its mounting lead wires – 10nH in total.

So the capacitor element has similar or less inductance than its body length of printed circuit track. When inserting or removing a leaded capacitor in an existing track length, only the capacitor lead wires affect the net inductance. The capacitor element's self inductance is pretty much offset in each case by change in the printed circuit track length used, hence track inductance.

Inserting a non-leaded chip capacitor with a body width similar to or wider than the track can be expected to slightly reduce a printed board track's net inductance.

In practice most pcb-mounted, leaded film capacitors of 1nF or above exhibit series resonance well below 100MHz. With many applications this is unimportant, but with faster logic and micro-processors, lead-wire contribution is unacceptable. Such applications force use of non-leaded, physically short, uncased capacitor elements.

To aid the designer's choice, most capacitor makers supply tables or graphs of self resonant frequencies. ■

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