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Film capacitors: The versatility and stability you need for your applications

Sponsored by: TTI, Inc.

Film capacitors are versatile components that can be designed into power electronics for industries ranging from consumer and renewables to automotive, aerospace and military. These capacitors come with very specific advantages including non-polarity, a high insulation resistance, low dielectric losses and self-healing capability. Film capacitors can be optimized through different materials and manufacturing methods.

Capacitors are all unique; their fundamentals, the manufacturing processes, advantages and even technology trends are worth highlighting. There are different grades and applications critical to considering before choosing the best option.

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Exploring film capacitor varieties

Safety capacitors

There are various types of film capacitors designed to serve different aspects of electric design. The X (Table 1) and Y (Table 2) types of capacitors are safety, or EMI, capacitors that are generally found in power supply inputs. These capacitors are used to suppress EMI where each type is further divided in subcategories based on working voltage and peak voltage levels.

X Type	Peak Pulse Voltage	Peak Test Voltage
X1	2.5kV ≤ 4.0kV	C ≤ 1µF, 4.0kV C > 1µF, 4.0kV/√C
X2	≤ 2.5kV	C ≤ 1µF, 2.5kV C > 1µF, 2.5kV/√C
X3	≤ 1.2kV	Undefined

Table 1: Peak pulse voltage and peak test voltage of X-type capacitors. Source: TTI

Y Type	Rated Voltage	Peak Test Voltage
Y1	$\leq 500V_{AC}$	8kV
Y2	$150V_{AC} \leq 300V_{AC}$	5kV
Y3	$150V_{AC} \leq 250V_{AC}$	Undefined
Y4	$\leq 150V_{AC}$	2.5kV

Table 2: Rated voltage and peak test voltage of Y-type capacitors. Source: TTI

The most commonly used are the X1, X2 and Y1, Y2 types. X capacitors are placed between the line and the neutral inputs of the system (Figure 1). These eliminate differential mode interference and are designed to fail short. The result of this short triggers the fuse, or circuit breaker, to open in the event of an electrical shock hazard. Y capacitors are placed between the line and ground, or neutral and ground, and are used to filter out the common-mode noise. These capacitors are designed to fail open.

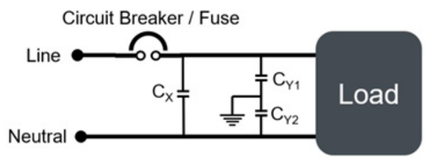

Figure 1: Placement of X and Y capacitors to suppress common-mode and differential noise. Source: TTI

Other types of film capacitors

Along with safety film capacitors, others include:

- DC link: Used for ripple reduction and line filtering
- AC filter: Used for noise and harmonic filtering
- Pulse or snubber: Used for absorbing voltage spikes, mitigating voltage overshoots, and eliminating transients and ringing

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   * Also often used for IGBT protection as well and to commutate the silicon-controlled rectifier (SCR) from an ON to OFF state
- DC: General purpose capacitors that are used in power supplies and various consumer electronics

Each of these film capacitor types will have a different construction to better serve its end application.

Exploring film capacitor varieties

The film capacitor manufacturing process for three products including plastic box, aluminum can or a customized solution (seen in Figure 2). Within this process, there are key steps to further analyze.

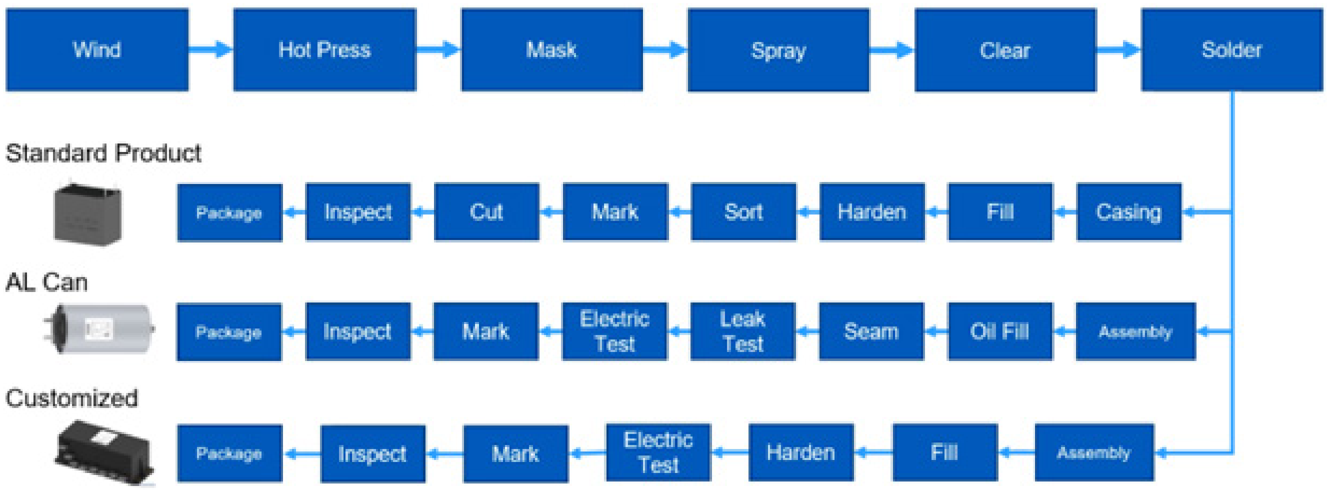

Figure 2: Film capacitor manufacturing process. Source: TTI

Extruding, metallizing and cutting rolls

The step shown in Figure 3 is the very start of the film manufacturing process where the plastic granules are converted into film in a tightly controlled and carefully monitored process. The thickness of the film has to be even to a nanometer scale (5 to 8 µm) throughout the roll, and from roll to roll. Then, aluminum or zinc is carefully deposited onto the base film in a high vacuum environment with a thickness of 0.03 µm to keep the surface even.

Figure 3: The extrude and stretch process. Source: TTI

The metallized film roll then must be cut to specification to create a given capacitor value. Figure 4 shows four different types of slitting. The shaded areas are the metal deposit on the plastic film where each rectangle represents a section of the continuous area. Straight slitting is the most common, however, wave slitting has advantages. It gives more surface area to work with, and provides mechanical strength for lead attachment, leading to lower ESR and better surge current capability.

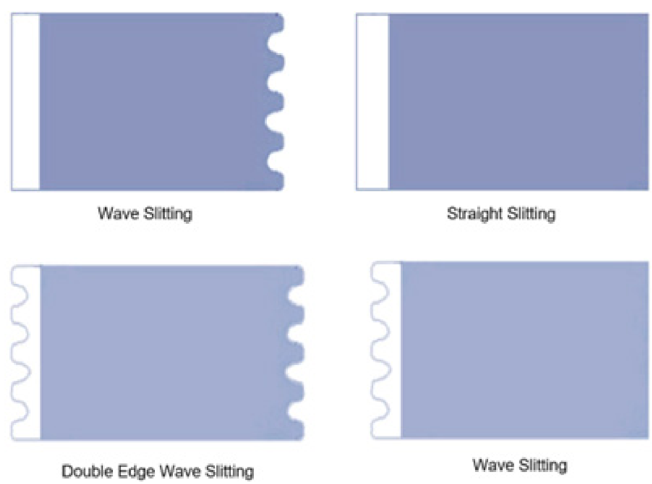

Figure 4: The techniques used to cut a metallized film roll to create a given capacitance. Source: TTI

Self-healing

The images in Figure 5 portray the self-healing process. When a weak or compromised spot encounters a high current flow that can cause dielectric breakdown, extremely localized heat (#5 and #6 in Figure 5a) transforms the affected spot into a tiny hole (#8) and clears out the metal around it (#4). This process keeps the remaining dielectric layer intact and re-insulates the electrodes to maintain the integrity of the capacitor where only an extremely small loss in capacitance takes place. The black and white SEM image shows the film after self-healing where a portion of the metal later has been removed.

Continuous metallization is commonly used; however, manufacturers have come up with other techniques to improve the performance by keeping the self-healing process isolated. One way is to divide the metallized area into many segments, or squares, where each square is connected with other thin metallized strips. The red circle in Figure 6 highlights the tiny strips that act as a fuse where, during the self-healing process, will isolate the damaged area.

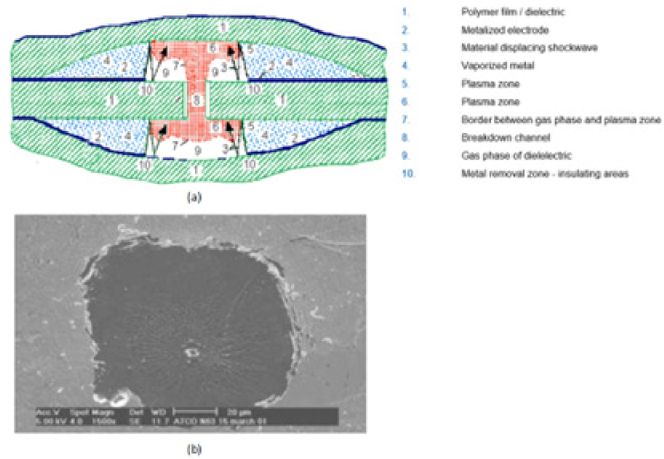

Figure 5: (a) Diagram of the self-healing process and (b) magnified image of self-healing where a portion of the metal layer has been cleared. Source: TTI

Winding

Once the film is metallized and cut in wave or straight slitting configurations for a specified capacitor value, two or more layers are bound together as shown in Figure 7. The two plastic strips are rolled on top of each other to make a capacitor. Then metal is sprayed on either side of the roll and finally leads are soldered for an external connection.

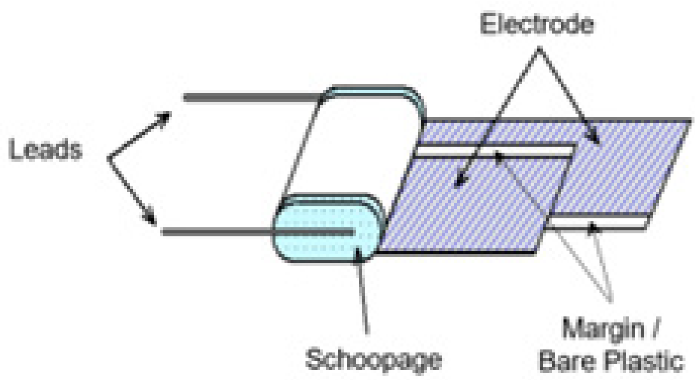

Figure 7: Illustration of capacitor assembly. Source: TTI

Manufacturers use other techniques to incorporate more than one capacitor into a single die. By offsetting metal layers, two, three or four capacitors in series can be cased in a single housing. Putting capacitors in series will result in a lower capacitance; however, working voltage is higher as these values are inversely proportional as shown in the equation below.

$$E = \frac{1}{2} CV^2$$

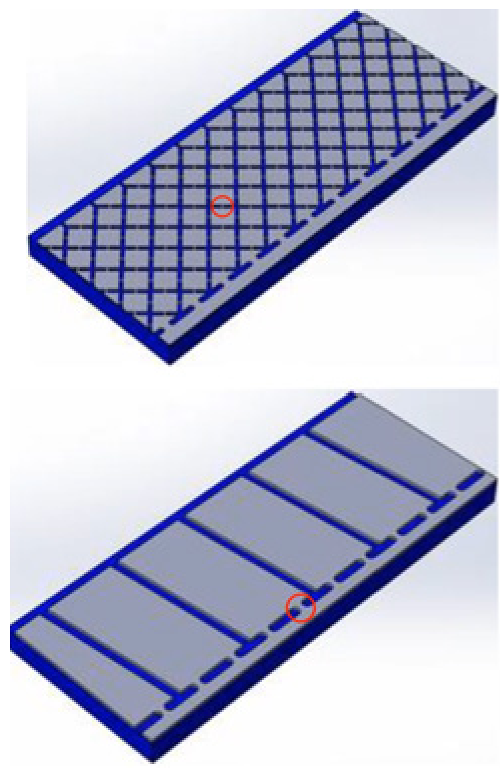

Figure 6: Isolating the self-healing process by using (top) thin metallized trips to create squares or (bottom) t-shaped segmentation of the metallized layer. Source: TTI

Hot-pressing, masking and schoopage

The capacitor's circular shape has the disadvantage of taking up more space on a PCB, so capacitors are hot-pressed to a flattened elliptical shape. The temperature, pressure and time must be controlled precisely so as not to cause any damage to the film or the metallized layer. After hot-pressing, each capacitor is masked with paper tape for the next step: schoopage.

Figure 8 shows a group of capacitors individually masked, except the two ends where the lead wires will eventually be placed (Figure 8a). The schoopage processes involves a metal wire passed in between two electrodes that are connected to a high-powered source so that the metal wire vaporizes and deposits on the exposed surface of the capacitor to form metal contact layers (Figure 8b); this process is repeated on both ends of the capacitors (Figure 8c).

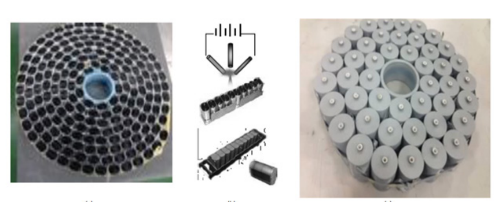

Figure 8: Schoopage process. Source: TTI

Final steps

The final few steps are clearing, welding, housing and filling (Figure 9). For clearing, each capacitor is charged 250% the working voltage. The process helps remove any humidity that might have been trapped during the previous steps and self heal the layer. Welding or soldering places two or more lead wires on each end of the capacitor. Finally, the capacitor is placed in the plastic housing, filled and sealed with polymer resin.

The finished capacitor can be seen in Figure 10 where each individual section is outlined.

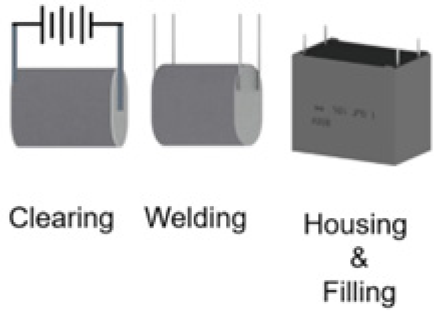

Figure 9: The clearing, welding, and housing/filling steps of capacitor manufacturing. Source: TTI

Aluminum can film capacitor

The process of making an aluminum (Al) can film capacitor is similar except the round capacitor is not hard pressed; instead it is left round (Figure 11). Then, depending on whether the Al can is oil-filled or dry-filled, the capacitor goes through a process to place the bound capacitor inside the Al shell and fill with oil or resin. The capacitor, whether resin-filled or dry-filled , must be cured before it is capped off. Oil-filled capacitors do not require this.

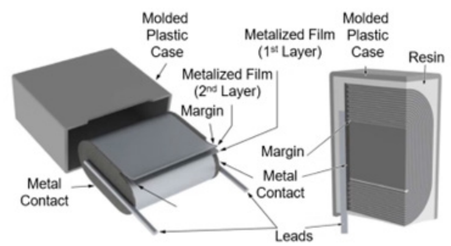

Figure 10: Diagram and description of film capacitor. Source: TTI

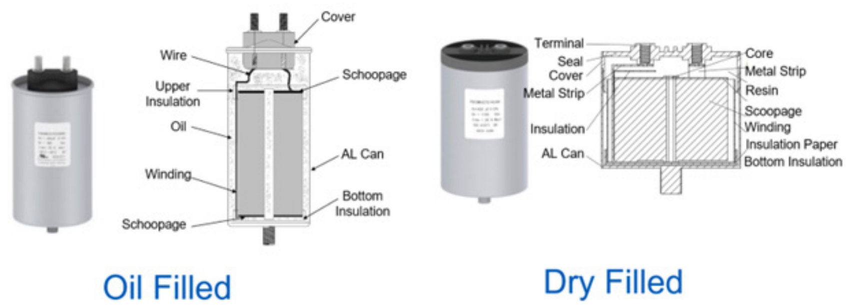

Figure 11: Oil-filled and dry-filled AL can film capacitors. Source: TTI

Industrial and material trends

Film capacitors come with a number of advantages including a high capacitance stability over temperature as well as frequency and voltage stability. They also come with a low dissipation factor, low ESR, low inductance (very short current path compared to other wound types), a high insulation resistance and high ripple current. The excellent reliability of film capacitors make them a desirable option in aviation, military and automotive industries where components experience harsh environmental conditions.

Various materials and construction techniques can be employed to optimize different parameters of the film capacitor (Table 3), for example, using new dielectric film materials such as polyetherimide (PEI) can increase the high temperature rating up to 150° C. Other films will ensure a high resistance to humidity, a high ripple current or low ESR.

Improvements	Potential modifications
High temperature rating (125° C to 150° C)	• New dielectric film (e.g., Polyetherimide)
High humidity (85° C/85% at rated voltage)	• Type zinc-aluminum metallized film (plasma treatment + anti-oxidation oil) • Acid anhydride epoxy resin with high moisture resistance
High ripple current, Low ESR/ESL	• Special film design • Advanced metallization technologies
Miniaturization	• Thinner film
High dV/dt	• Special wave cut film to improve welding performance • Better solder heat resistance • High frequency and low loss
Low noise	• Enhanced film adhesive by film metallization process • Simulated noise testing per customer's demand
Low power loss	• Metallized film with special resistivity structure (improved self-healing properties) • High performance low resistivity design
High surge voltage (greater than 4 kV)	• Segmented fuse metallized film • Improved explosion-proof epoxy resin • High endurance PBT plastic case

Table 3: Modifications to film capacitors to improve various performance parameters. Source: TTI

Higher temperature resistance, lesser water absorption rate and higher surface resistivity are all favorable attributes that help the product last longer. New plastic material for housing is being introduced to achieve such goals. Table 4 shows, for example, the surface resistivity of the polybutylene terephthalate (PBT) material is 100 trillion ohms, and the resistivity of polyphenylene sulfide (PPS) is 10 quadrillion ohms — an improvement of 100 times. This high resistivity helps to improve the leakage current. Similarly, the distortion temperature is 250° C for PPS, while PBT is deformed at 190° C. Ultimately, PPS is the material of choice for higher grade temperature, humidity, bias (THB) film capacitors.

After the housing, epoxy is the second line of defense to protect the capacitor. Similar to plastic housing — which faces an environmental beating — epoxy resin is another necessary component for a long-lasting product. As shown in Table 5, a polyurethane resin is used in dry-type Al film capacitors. For a higher reliability capacitor, anhydride epoxy resin is preferred for both standard and THB products.

Standard vs THB-grade

THB is a reliability test designed to accelerate the aging process of the capacitor at a given temperature, relative humidity and nominal voltage. Standard capacitors generally cannot withstand an extreme test environment. THB-grade products must be designed using special materials and processes that show no sign of deterioration and compromise to the product at the end of the test period. Table 6 highlights some of these differences.

The higher the grade, the more stringent the test requirements. THB grade III is the toughest test, but manufacturers often go even further and test the product for an even longer period of time; this will typically be denoted on the manufacturer's datasheet (e.g., 85° C, 85% RH, 2000 hours). The passing criterion for this test is to have less than 10% capacitance loss, very little change in dissipation factor, and no degradation in isolation resistance. This leads to a component with stable performance over its service life and is generally the go-to for more demanding applications.

Material	PBT	PBT (Glow Wire)	PBT (THB Type)	PPS
Density	1.55	1.55	1.55+	1.65
Water Absorbtion	0.1%	0.1%	0.08%	0.03%
Elongation	5%	5%	5%	2.5%
Dielectric Constant	5.2	5.2	5.2	3.9
Surface Resistivity	$1x10^{14}\,\Omega$	$1x10^{14}\,\Omega$	$1x10^{14}\,\Omega$	$1x10^{16}\,\Omega$
Dissipation Factor	0.0055	0.0055	0.0055	0.002
Distortion Temperature	180 °C	180 °C	180 °C	250 °C
Application	THB GRADE IB	THB GRADE IIB	THB GRADE IIIB	THB GRADE IIIB THB 2000H

Table 4: Plastic casing materials and their respective parameters. Source: TTI

Material	PU Resin	Anhydride Epoxy Resin (STD)	Anhydride Epoxy Resin (THB)
Dielectric Constant	3.6	3.3	3.2
Water Absorption (%)	0.30	0.15	0.02 to 0.06
Strength kV/mm	>18	>18	>20
Glass Transition Temperature (°C)	50	85	90
Coefficient of Liner Expansion (ppm/k)	$(6 - 10)x10^{-5}$	$(4 - 6)x10^{-5}$	$(3 - 5)x10^{-5}$
Bending Strength (MPa)	>20	>50	>60
Hardness	83	85	85
Volume Resistivity (Ωm)	$11x10^{5}$	$1x10^{5}$	$2x10^{5}$
Application	AL Can Dry Type	THB Grade IB THB Grade IIB	THB Grade IIB THB 2000H

Table 5: Epoxy resins used in film capacitors. Source: TTI

Film capacitors in the real world

Due to its robust design, the film capacitor is used in various industries (Figure 12). Automotive applications often require them in xEV subsystems such as the powertrain, onboard chargers , DC-DC converters and high voltage positive temperature coefficient (HVCH/PTC) heat pumps. Renewable energy systems such as solar inverters, windmill systems and various energy storage systems (ESSs) will incorporate film capacitors. Industrial uninterruptible power supplies (UPSs), inverters, motor controllers, charging systems and power supplies require many film capacitors. These components are also found in consumer electronics and applications such as ACs, refrigerators, microwave ovens, inductor cookers, power adapters and TVs.

Description	THB Product	Standard Product
Film & Metallization	THB film design THB metallization technology Special silicon oil	Standard film design & metallization
Metal Spray	Special metal	Standard metal spray
Plastic Case	PPS	PBT
Epoxy	High moisture resistance epoxy (Vacuum Epoxy Filling)	Standard
Process	THB	Standard
THB Performance	1000 hours 2000 hours	<500 hours

Table 6: Differences between a standard and THB-grade film capacitor. Source: TTI

Figure 12: Film capacitor applications. Source: TTI

Conclusion

Film capacitors are a critical component in power electronics design. In order to better select the best film capacitor for a specific application, it is important to understand the various types of film capacitors, their ratings and how they are manufactured.

Eaton offers a wide selection of DC link and safety film capacitors of type X1, X2 and Y2 in both standard and automotive grades for suitability in a wide range of applications. Learn more about Eaton and the extensive portfolio of products and services available today.

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