

2013 Applied Power Electronics Conference  
 Advances in Capacitors and Ultracapacitors  
 for Power Electronics

## AC Capacitors 1000-7200 Vac, Film Capacitors With Aluminum-Foil Electrodes

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This presentation describes AC capacitors that are manufactured with film with aluminum foil, dielectric technology and applied in medium voltage systems. We are defining these medium voltage systems as those starting at about 1000 Vac and up to about 7200 Vac. Capacitors of this construction of polypropylene film with aluminum foil are often called “All Film” or “Power Capacitors.”

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## Film Capacitors By Construction

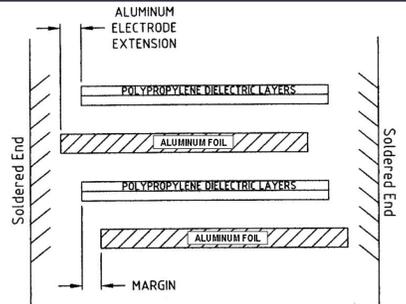
Film With Metal Foil- AC Capacitors	Film With Metal Foil- DC Capacitors
Typical at $\geq 800$ Vrms	Applicable to very high current densities only.
Metalized Film- AC Capacitors	Metalized Film- DC Capacitors
Typical at $< 800$ Vrms	The standard for most DC applications

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Film dielectric capacitors have two different types of electrodes. These are a discrete foil, which is typically aluminum or a very thin metallization that is vacuum deposited on the film. In addition to two different electrodes, we also can divide the capacitors into AC and DC applications. This produces a two by two matrix. We can see for AC capacitors, the film with metal foil construction is preferred at greater than or equal to 800 Vrms and the metallized film is typically employed at lower voltages.

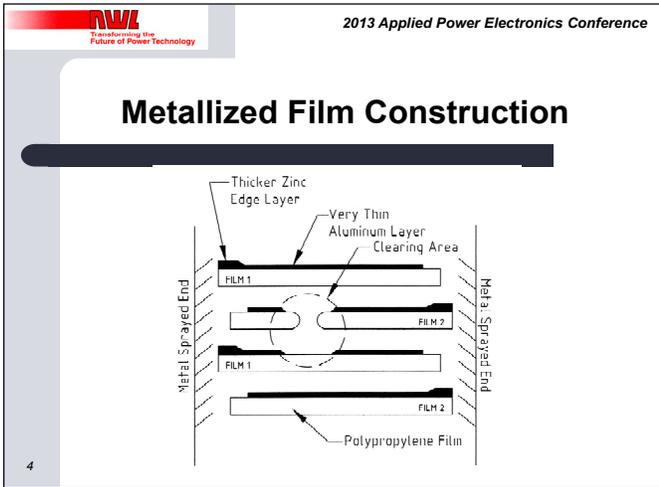
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## Film With Metal Foil Construction



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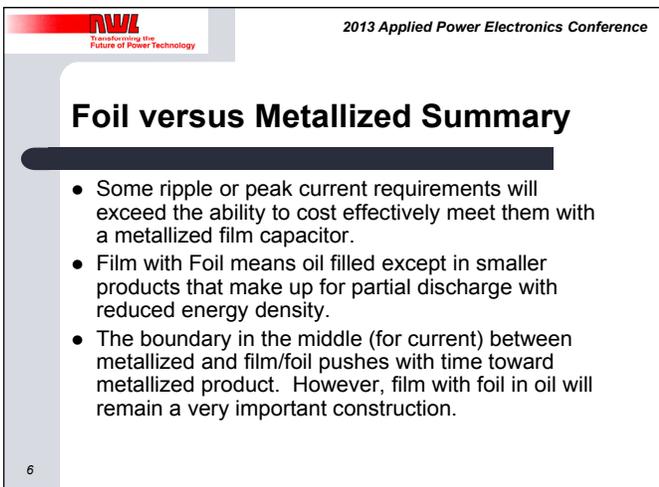
Here is a schematic of a film with metal foil construction. You can see the discrete foils independent from layers of polypropylene film. In this drawing, you can see the aluminum foil ends are soldered to make a connection. It is also common practice to attach to the foil ends with other mechanical connections if the currents are not too high.



Here is a schematic of a metallized film construction. In the most recent products, the metallization that is vacuum deposited on the films is profiled so it is thicker where it is attached to make an external connection and thinner in the inside of the capacitor body. The internal metallization being thinner allows for a more efficient self-healing process. Self-healing is a process where if a dielectric fault occurs, the area surrounding that fault is evaporated and electrically taken out of the capacitor. The “All Film” constructions do not self-heal and this is taken into account in designing with aluminum foil electrodes.



We can summarize on the film with metal foil and metallized constructions that are the building blocks of higher voltage film capacitors. The film with foil has the best ability to handle the highest ripple and peak currents. Metallized constructions can be designed to handle higher currents yet their ability is not as high as the discrete foil.



When using film with foil at higher voltages, the capacitor is almost always oil filled. It is possible to design a metallized film capacitor for most applications yet not most of the high voltage AC applications. The performance of the all film construction remains the best for the higher voltages due to its ability to handle high ac surge voltages. The “All Film” construction has the unique characteristic that the series losses improve with aging leading to lower self-heating.

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## Partial Discharge

- Partial discharge can have a dramatic effect on energy density and cost.
- Partial discharge makes limitations on voltage per capacitor element. This in turn leads to designing with capacitor elements in series.
- Capacitor elements in series increases volume, material usage and associated cost.

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Any discussion of a higher voltage system would be incomplete without discussing partial discharge. Partial discharge affects the size and cost of a capacitor. It often requires multiple capacitor elements to be wired in series in order to minimize it. This series wiring may be done externally by the user or internally to the capacitor. More series wiring increases size and cost.

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## Foil folding reduces partial discharge of AC Film/Foil products.

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For higher voltage capacitors with film dielectric and aluminum foil electrodes, there are techniques available to reduce partial discharge. One such technique is to fold the aluminum foil to produce a rounded edge. Here is a drawing of what this looks like.

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## High Speed Film Foil Winding

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Here is a photo of a piece of winding equipment that is used for making high voltage capacitors with film dielectric and aluminum foil electrodes. This allows a capacitor element to be made in an automatic repeatable fashion including the folded foil attributes for partial discharge elimination.

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### Advantages of High Voltage Oil Filled Film Capacitors

- Oil filled AC and DC film dielectric capacitors have certain advantages in life and thermal transfer over dry capacitors.
- Oil filled AC capacitors are still the industry accepted standard for most ratings. A smaller amount of AC ratings are available in constructions that are not oil filled.

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Oil filled high voltage capacitors do have some advantages in life and thermal transfer over non-oil filled versions. For AC capacitors, oil filled versions are still the industry standard.

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### The Losses of ALL Film Capacitors Improve With Age

Aging Hours (100 v/um)	100 Hz Tan delta	1 kHz Tan delta
0 Hrs	~0.0015	~0.0009
1000 hrs	~0.0005	~0.0004
2000 hrs	~0.00035	~0.0003

Test Details: 2 layers of 11 μm film at 2200 Vrms 60 Hz 70°C

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A very important reason why the thermal characteristics are favorable for the all film or power film construction is that the losses improve with age. This attribute is one of the reasons they are employed in high voltage applications. We know that the life of a device such as a capacitor is proportional to its hottest point or hot spot. However, if as a capacitor ages the amount of self-heating is reduced then the life is extended. This shows a test of a 1350 volt rated capacitor at 163% of its rated voltage and 70°C. Using 2L of 11-micrometer thick film, this translates to 100 volts/μm of film. It can be seen that the 100 Hz tan delta readings improved from about .0015 to about .00035 and the 1 kHz readings improved from about .0009 to .0003. In this case, we see a 3x or 5x improvement. The literature shows that 10x is often observed.

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### The oil is a strategic component

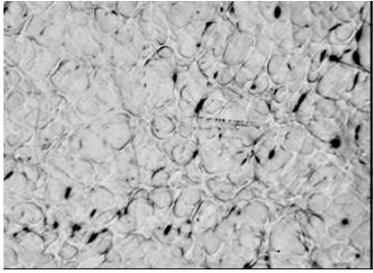
- Modern oil for power capacitors has an aromatic characteristic that penetrates and surrounds dielectric imperfections.
- The surrounding of the imperfections reduces partial discharge.
- The oil also has additives to trap some impurities that can damage the film.

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At one time, the oil used in power capacitors was known as Askerel or PCB. This was until the 1970's. It took about 10 years to develop suitable and safe alternatives yet the latest oil has outstanding characteristics. These characteristics include being aromatic with the ability to penetrate between the polypropylene film layers as well as into the layers. Any imperfections in the film become sites of partial discharge at a given voltage. By surrounding these sites, the inception voltage of partial discharge is substantially increased. There are certain ionic impurities that can damage the film and the oil has additives that trap these impurities to prevent damage. It is important that the capacitors be processed in clean room type facilities to prevent the introduction of unwanted impurities.

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**Polypropylene film has surface roughened to allow oil penetration**



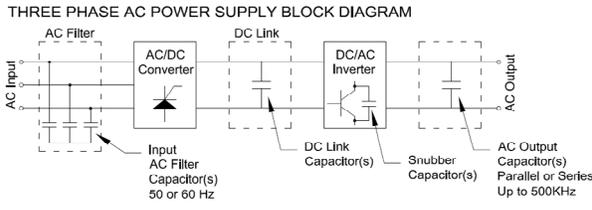
Films can be roughened as shown on one or both sides

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Here is a microscopic view of a sample of polypropylene film used for film with aluminum foil capacitor. The surface is purposely roughened. This is due to multiple layers of film being wound together. If there are two smooth surfaces next to each other, oil will not penetrate between them. The film can be roughened as shown on one or both sides. There are processes to make film with a naturally roughened surface and processes that require a subsequent roughening step after film manufacture.

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**Typical Circuit Locations for Medium Voltage AC capacitors**



THREE PHASE AC POWER SUPPLY BLOCK DIAGRAM

AC Input

AC Filter

AC/DC Converter

DC Link

DC/AC Inverter

AC Output

Input AC Filter Capacitor(s) 50 or 60 Hz

DC Link Capacitor(s)

Snubber Capacitor(s)

AC Output Capacitor(s) Parallel or Series Up to 500KHz

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Here is a schematic showing how some of these higher voltage, film dielectric capacitors can be applied in a medium voltage system. On the input, we may have a filter capacitor or capacitors seeing a 50 or 60 Hz voltage with superimposed harmonics. A system of this type may typically be used from up to 7200 Vac. The AC input voltage will be rectified in an AC/DC converter. The output will then be a DC waveform with a ripple voltage. Then we may be seeing a DC link or multiple DC link capacitors in the range of 600 to 10 kVdc. If this is an AC-to-AC system, the DC voltage will be converted in an inverter. On many designs, we may then have snubber capacitors. On the output, we may have parallel or series resonant capacitors. For film technology, typical frequencies for resonant capacitors may be up to 500 kHz.

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**Induction Furnaces use High Voltage AC oil filled Film Capacitors**



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An application where the system looks very much like the schematic that was shown is Induction Furnaces. They actually use most of the technologies of high voltage, film dielectric capacitors that was presented on the previous matrix. This includes AC capacitors with aluminum foil electrodes. The reactive power is so high that they are almost always water cooled. The DC Link capacitors are usually water cooled as well.

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**Typical Capacitor Resonant Voltages For Furnace Applications**

Resonant AC Voltage	Frequency Range (Hz)	Liquid Cooling
1250	250-10,000	Yes
1875	250-3000	Yes
2400	250-1200	Yes
3000	250-1200	Yes

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Some of the common AC resonant voltages are shown for Furnace Capacitors. It can be seen that all of these capacitors are used at much higher than line frequencies. Due to the severe combinations of frequency and voltage, all of these capacitors are liquid cooled.

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**Water cooled AC resonant capacitors**

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Here are some examples of water cooled AC resonant capacitors used in furnace applications. These capacitors may have a single or multiple water paths or circuits. Some of the designs have multiple terminals in order to tune a resonant circuit with the operating coil to achieve a high Q factor. The operating coil in the Furnace Application performs the operation of melting or heat-treating. It is known at resonance or the highest Q factor we need less current to power the melting or heat-treating operation.

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**Typical Input Voltages for Medium Voltage Motor Drives**

AC Input Voltage L-L	AC Input Voltage L-N	Typical Frequencies (Hz)
2400	1385.6	60
3300	1905.6	50
4160	2401.8	50 or 60
6600	3810.6	50 or 60
7200	4157.8	50 or 60

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AC capacitors for medium voltage drives typically have input voltages from 2300 to 7200 volts. We have seen requirements for both 2300 and 2400-volt capacitors, which we would consider the same class. These capacitors are usually employed in three phase systems. Therefore, single-phase capacitors may be used line to line or three phase capacitors. There are requirements for capacitors specified to operate at both 50 and 60 Hz.

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## Industry Criteria For Medium Voltage AC Capacitors

- Qualification standards Include IEC 60871, CSA 22.2 no 8 and IEEE 18.
- Terminal to terminal voltage withstand testing includes 2.0 or 2.15 x Rvac or DC alternative of 4.3 x RVac.
- Internal discharge resistors to achieve under 50 volts in less than 5 minutes.

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The capacitors for medium voltage AC systems such as motor drives have some industry standard criteria. The most common standards are the IEC, CSA and IEEE. One of the most important parts of these standards is the terminal-to-terminal dielectric withstand tests. If the preferred AC test is performed, the IEC 60871 and the IEEE 18 standards have a similar requirement for 2x RVac 10 seconds. The CSA 22.2 no 8 standard is more severe with a 2.15 x RVac 10 second criteria. All three of the standards have the same alternative DC test of 4.3xRVac. For example, with the DC test a 2000 Vac capacitor would be tested at 8600 Vdc. All three standards have the same criteria for internal discharge resistors. Since the use of internal discharge resistors is a safety device, it is common to apply them in the resonant capacitors for furnace applications also.

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## Three Phase Four Terminal Capacitor



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Here is an example of a 3 phase, four-terminal capacitor. This capacitor has a Wye connection with a fourth neutral terminal. It is common to employ a pressure switch in All Film capacitors including this capacitor type. The pressure switch is green and can be seen in the foreground of this photograph. This enables the user to recognize that a capacitor is failing due to an increase in internal pressure beyond a set point. The set point of the pressure switch is typically about 10 pounds per square inch.

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## Single Phase AC Capacitors



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Here are some single-phase AC capacitors with high voltage bushings designed for indoor or outdoor use. The industry standards have clear criteria for the ratings of these high voltage bushings. These are defined as short term AC withstand test and BIL or basic impulse level tests.

## Conclusion

- The polypropylene film with aluminum foil capacitor construction has low self-heating and high current capabilities.
- This construction can be tailored with liquid cooling if needed.
- Continuous improvements in assembly and material technologies are being made.