CAPACITOR FUNDAMENTALS 301

HOW TO SELECT A CAPACITOR FOR POWER SUPPLIES
Capacitor Committee

Upcoming Events


Capacitor Workshop
“*How to choose and define capacitor usage for various applications, wideband trends, and new technologies*” The day before APEC, Saturday March 14 from 7:00AM to 6:00PM

Capacitor Industry Session as part of APEC
“*Capacitors That Stand Up to the Mission Profiles of the Future – eMobility, Broadband*” Tuesday March 17, 8:30AM to Noon in New Orleans

Capacitor Roadmap Webinar – Timing TBD – Latest in Research and Technology
Eduardo Drehmer
Director of Marketing
FILM Capacitors

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Background:
• Over 20 years experience with knowledge on Manufacturing, Quality and Application of Electronic Components.
• Responsible for Technical Marketing for Film Capacitors
Edward Lobo was born in Acushnet, MA in 1943 and graduated from the University of Massachusetts in Amherst in 1967 with a BS in Chemistry. Ed worked for Magnetek, Aerovox and CDE where he is currently Chief Engineer for New Product Development.

Ed has served for over 52 years in capacitor product development. He holds 14 US patents involving capacitors.

Ed Lobo
Chief Engineer, New Product
elobo@cde.com
This presentation will guide individuals selecting components for their Electronic Power Supplies. Capacitors come in a wide variety of technologies, and each offers specific benefits that should be considered when designing a Power Supply circuit.

The presenters will cover critical parameters that should be considered when selecting capacitors and comparing advantages and disadvantages of the various types of capacitors available in the market.
BASIC CONCEPTS / SYMBOLS

Basic Concept

Symbols

<table>
<thead>
<tr>
<th>Name</th>
<th>Abbreviation</th>
<th>Farads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Picofarad</td>
<td>pF</td>
<td>0.000000000001 F</td>
</tr>
<tr>
<td>Nanofarad</td>
<td>nF</td>
<td>0.000000001 F</td>
</tr>
<tr>
<td>Microfarad</td>
<td>uF</td>
<td>0.000001 F</td>
</tr>
<tr>
<td>Milifarad</td>
<td>mF</td>
<td>0.001 F</td>
</tr>
<tr>
<td>Kilofarad</td>
<td>kF</td>
<td>1000 F</td>
</tr>
</tbody>
</table>
MOST COMMON CAPACITOR TECHNOLOGIES

Ceramic (MLCC)

Film (Metalized Film)

Aluminum (Electrolytic)
OTHER CAPACITOR TECHNOLOGIES

Tantalum

Supercapacitors
## TECHNOLOGY COMPARISON

<table>
<thead>
<tr>
<th>Capacitor Type</th>
<th>Max. Possible Capacitance</th>
<th>Voltage Range</th>
<th>Max. Permissible Current</th>
<th>Max. Operating Temperature</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aluminum Electrolytic Capacitor</strong></td>
<td>&gt; 1F</td>
<td>ca. 650 V</td>
<td>ca. 0.05 A/µF</td>
<td>85°C up to 150°C</td>
<td>smoothing, buffering, DC Link</td>
</tr>
<tr>
<td><strong>Film Capacitors</strong></td>
<td>&gt; 8mF</td>
<td>ca. 3kV</td>
<td>ca. 3 A/µF</td>
<td>70°C up to 125°C</td>
<td>DC Link, EMI suppression, filtering</td>
</tr>
<tr>
<td><strong>MLCC’s</strong></td>
<td>&gt; 100 µF</td>
<td>ca. 10 kV</td>
<td>ca. 10 A/µF</td>
<td>85°C up to 200°C</td>
<td>EMI suppression, buffering, coupling</td>
</tr>
</tbody>
</table>
## Technology Comparison

<table>
<thead>
<tr>
<th>Items</th>
<th>Ceramic Capacitors</th>
<th>Aluminum Electrolytic Capacitors</th>
<th>Film Capacitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large capacitance</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Temperature characteristics</td>
<td>✓/1</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>DC bias characteristics</td>
<td>✓/1</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Lifespan</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture/Heat resistance</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Self-healing</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Compact size</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*1 Type1 (temperature compensating) only
Surface Mount

- Smaller Components
- Lower Power

Normally using reflow soldering process.
(~260°C peak body temperature)
TERMINATIONS / ASSEMBLY TYPE

PCB Mount / Through Hole

- Different Shapes/Sizes
- Medium Power

Normally using wave or selective soldering process. (~120°C peak body temperature)
TERMINATIONS / ASSEMBLY TYPE

BusBar / Screw Types

- Large Volume
- High Power

No soldering needed.
Mechanical assembly parameters are critical.
the equivalent circuit diagram is described like following:

beside the capacitance you have 3 major parameters:

- **ESR** – Equivalent Series Resistance
- **ESL** – Equivalent Series Inductance
- **R_{ISO} / R_{Leak}** – Isolation Resistance
the equivalent circuit diagram is described like following:

\[ ESR = \frac{\tan \delta}{2 \cdot \pi \cdot f \cdot C} = \tan \delta \cdot X_C \quad \text{mit} \quad X_C = \frac{1}{2 \cdot \pi \cdot f \cdot C} = \frac{1}{\omega \cdot C} \]
ESL – Equivalent Series Inductance

the equivalent circuit diagram is described like following:

Is mainly driven by inner construction of capacitor element and connections to it

New cap designs are optimized for low ESL to drop these parasitic effects

Can be calculated as following:

\[ ESL = \frac{X_L}{2 \pi f} \Rightarrow X_L = (2 \pi f \cdot ESL) = (\omega \cdot ESL) \]
the equivalent circuit diagram is described like following:

\[ R_{ISO} / R_{Leak} \]

- Is the ohmic resistance between the electrodes
- Will be given as \([M\Omega]\) or as \(\tau\) [s]

\[ \tau[s] = R_{ISO}[M\Omega \cdot \mu F] = R_{ISO}[M\Omega] \cdot C[\mu F] \]

Humidity can reduce the isolation resistance drastically.
Capacitor Characteristics

EQUIVALENT CIRCUIT: Z - IMPEDANCE

The equivalent circuit diagram is described like following:

- \( Z \) - Impedance
- Describes the AC mode characteristics
- Is based on 3 parameters: ESR, \( X_L \) and \( X_C \)
- Can be calculated as following:

\[
Z = \sqrt{ESR^2 + (X_L - X_C)^2}
\]
Ceramic Capacitor Temperature Classes:

- **Class 1** ceramic caps offer high stability and low losses for resonant circuit applications.
- **Class 2** ceramic capacitors offer high volumetric efficiency for smoothing, bypass, coupling and decoupling applications.
- **Class 3** ceramic capacitors are barrier layer capacitors which are not standardized anymore.
- **Class 4** (or written class 4) ceramic capacitors are barrier layer capacitors which are not standardized anymore.

With class definitions understood you can look how the temperature coefficients break down.

Ceramic caps might show significant variations in their characteristics due to Amb Temp.
TEMPERATURE RATINGS

Aluminum Electrolythtic Typical Curves

Metalized Film Typical Curves

- ALU caps might change significantly their life expectation by temperature.
- FILM caps are very sensitive to high temperatures.
<table>
<thead>
<tr>
<th>Operating temperature range</th>
<th>Max. operating temperature $T_{\text{op, max}}$</th>
<th>$+125 , ^\circ\text{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper category temperature $T_{\text{max}}$</td>
<td>$+125 , ^\circ\text{C}$</td>
</tr>
<tr>
<td></td>
<td>Lower category temperature $T_{\text{min}}$</td>
<td>$-55 , ^\circ\text{C}$</td>
</tr>
<tr>
<td></td>
<td>Rated temperature $T_{R}$</td>
<td>$+85 , ^\circ\text{C}$</td>
</tr>
</tbody>
</table>

**Amb + Self Heating!**

Temperature used for other ratings listed
Thermal Analyses can be very useful!!
Case Temperature: (Amb + Self Heat @ Max Load)

Search for your component Hot Spot
COMMON FAILURE MECHANISMS

- Over Temperature
- Over Current
- Over Voltage
- Humidity
- Mechanical Stress
Check with your supplier for these details. Have a clear mission profile of your application.
WHAT IS AN INVERTER

- Direct Current DC is converted to Alternating Current AC
  - Solar
    - DC from solar panels
  - UPS
    - DC from batteries
- AC converted to DC then back to AC
  - Wind turbine
  - Variable Frequency Drive (VFD)
    - Motor control
  - Induction heating
  - HVDC power transmission
CAPACITORS FOR INVERTERS

High capacitance and very high ripple current capability needed for today's inverter designs for wind, solar, fuel cells, UPS systems, medical power and more.

- Power Film DC Link
  - High capacitance and very high ripple current capability needed for critical power electronics applications.

- Screw Terminal and Snap-in Capacitors
  - High ripple current screw terminals and snap-in capacitors for critical power electronics applications.

- IGBT Snubber Modules
  - Board-mount or direct-mount styles for maximum protection.

- AC Harmonic Filter Capacitors
  - Oil filled types contain an environmentally friendly fluid and their built-in safety pressure interrupter ensures open circuit failure mode at end of life. Use axial type ACF for the same high-performance filtering where dry construction is preferred.
PRODUCTS FOR THE INVERTER

DC Link Capacitors:
Used for bulk storage and ripple filtering

Aluminum Electrolytic

OR

Power Film
WIND TURBINE INVERTERS

CONTROL CIRCUIT

INPUT FILTER

AC TO DC CONVERSION

DC LINK

DC TO AC CONVERSION

L/C OUTPUT HARMONIC FILTER

LOAD

AC IN

~

AC

~

AC

~

BATTERIES / SUPERCAPS

CONTROL CIRCUIT

AC

SF, PC, PFCH, & ACF

DC

SNUBBER

DC

SCREW TERMINAL, POWER FILM, & PLUG IN

AC

SF, PC, PFCH, & ACF
UNINTERRUPTIBLE POWER SUPPLY - UPS

LINE

INPUT FILTER

AC TO DC RECTIFIER

DC LINK

DC TO AC CONVERSION

L/C OUTPUT HARMONIC FILTER

LOAD

AC

AC

CHARGE

BATTERIES / SUPERCAPS

CONTROL CIRCUIT

SF, PC, PFCH, & ACF

SF, PC, PFCH, & ACF

SNUBBER

SCREW TERMINAL, POWER FILM, & PLUG IN
## DC LINK CAPACITORS

### DC LINK CAPACITORS: Film Versus Aluminum

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>ALUMINUM</th>
<th>FILM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance</td>
<td>High (3X Film)</td>
<td>Medium</td>
</tr>
<tr>
<td>ESR</td>
<td>30 mΩ Typical</td>
<td>2.0 mΩ Typical</td>
</tr>
<tr>
<td>Operating Temp Rating (with full ripple)</td>
<td>105°C Max</td>
<td>85°C Max</td>
</tr>
<tr>
<td>Ripple Current (1000 µF, 500 Vdc) @ 85°C</td>
<td>6.3 A</td>
<td>Up to 1500 Vdc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eliminates the need for capacitors in series and balancing resistors.</td>
</tr>
<tr>
<td>Voltage</td>
<td>550 Vdc</td>
<td>1.5 X rated for 10 s</td>
</tr>
<tr>
<td>Resistance to Overvoltage</td>
<td>50 V surge</td>
<td>fail open mode</td>
</tr>
<tr>
<td>Failure Mode</td>
<td>rupture</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>Liquid Electrolyte</td>
<td>Dry, no liquid electrolyte</td>
</tr>
<tr>
<td>Polarity</td>
<td>Must observe polarity</td>
<td>Non-Polar</td>
</tr>
</tbody>
</table>
INVERTER DC LINK APPLICATION

- 60 Hz AC is rectified to "lumpy" DC (120 Hz)
- A smoothing - DC Link capacitor is placed between the rectifier and the inverter switch to smooth the voltage
- DC Link decouples the input from the output
- DC Link must also handle high frequency ripple resulting from inverter switching
ALUMINUM ELECTROLYTIC CAPACITORS

More Capacitance for the Buck
ALUMINUM ELECTROLYTIC ADVANTAGE

• The high value capacitor choice
• Typically last more than 10 years
• Lower cost dielectric for high capacitance and energy storage
• 4 to 10 times the capacitance per dollar of film capacitors
• Great for power electronics bus capacitors up to 550 Vdc
POWER FILM: DC LINK CAPACITORS

More Ripple Current for the Buck
POWER DC FILM ADVANTAGE

• The high ripple current capacitor choice
• Higher voltage than aluminum electrolytics - up to 1500 Vdc
• No need to place capacitors in series
  • Eliminates need for balancing resistors
• Dry construction – no electrolyte
• Non-Polar
• Self healing – open circuit failure mode
IGBT SNUBBERS

Discrete Axial Leaded Snubbers
High dV/dt – 940C, 941C PPA, PPS
Very High dV/dt: 942C, 943C

Radial Leaded Box Snubbers
High dV/dt: PSB

Direct Mount Snubbers
Capacitor Type: SCD, PMB, PMC
Clamp Type w diode: SCM
Dual Clamp Type: SCC
WHAT’S AN IGBT

• IGBT – Insulated Gate Bipolar Transistor
• Power switch of choice for most inverter applications
WHAT’S AN IGBT SNUBBER

The word **snub** means to rebuff, spurn, repulse, give someone the cold shoulder, shortened at the end.

IGBT Snubber: A device used to protect IGBT switches from overvoltage during turnoff.

During turn off, a voltage transient appears across the IGBT that may exceed its voltage rating. The voltage transient is proportional to the amount of stray inductance \( L \) and the rate in change in current with time.

\[
V_{\text{transient}} = -L\frac{di}{dt}
\]
WHAT’S AN IGBT SNUBBER

IGBT snubbers are designed to protect IGBTs by reducing the voltage spike across the IGBT during turn-off.

A conservative rule of thumb is to use $1\mu F$ of capacitance for every 100A of IGBT.
AC Film Capacitors
WHY IS HARMONIC FILTERING NECESSARY

- Clean power required for electrical equipment to function properly
- Inverter switching schemes cause harmonic distortion of the input / output power
- Filters required to “clean” the power
Inverter IGBT switching result in harmonics that are odd numbered multiples of the fundamental switching frequency (3rd, 5th, 7th, etc.). These harmonics combine with the fundamental frequency and cause distortion of the waveform.
Grid tie inverters require filter components in two key areas: The DC bus and AC output.

The AC output filter is a low pass filter (LPF) that blocks high frequency PWM currents generated by the inverter. Three phase inductors and capacitors form the low pass filters. Resonant filters are specifically designed (inductance and capacitance) to “tune” out the harmonic frequencies.
EXAMPLE OF CUSTOMER SUPPLIED WAVEFORM AND FFT

- Voltage waveform
- Harmonic content can increase peak voltages
- Peak voltages are typically higher than the fundamental voltage
- Dielectric thickness determined by peak voltage including harmonics
- FFT Harmonic current distribution
  - Fast Fourier Transform
  - Each harmonic current contributes to capacitor heating
  - Required to calculate power losses
  - Harmonic frequencies can develop higher currents than fundamental frequency

This information required for capacitor design
The safety pressure interrupter is designed to disconnect the capacitor section as the cover expands upwards due to internal gas build up. Care must be taken at installation to provide a minimum of 0.5 inch clearance to allow for this expansion.
Thank you

• www.psma.com