Innovative power capacitor technologies for wide band-gap semiconductors

Advanced design features for high-frequency applications

Dr. Lucía Cabo
Fernando Rodríguez
Aluminium & Film Capacitors Business Group
Málaga, Spain
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Growing demands challenging power electronics

- INTEGRATION
- EMC
- MINIATURIZATION
- LOW LOSSES
- HIGH ENERGY DENSITY
- HIGH ROBUSTNESS

MOBILITY

ENERGY

INDUSTRIAL

MEDICAL
Advanced semiconductors put high demands on the DC link

- Lower switching losses
- Higher switching frequencies and faster on/off performance
- Higher junction temperature
- Lower thermal resistance (package improvement)

Demands on DC link
- Higher operation temperature
- Heat transferred to the capacitors via the busbar
- Higher current density
- Higher energy efficiency
- Miniaturization
- Suitable for fast transients (dV/dt) and ringing effects

Challenge for passive components: Not be the bottleneck in new power electronics designs
Design goals for high-frequency capacitors

High operating temperature
- High temperature dielectric
- Handle heat coming from the semiconductor busbar
- High current capability

Low ESR vs frequency
- Minimized losses
- Wider operation bandwidth up to the MHz range
- Good performance close and above the resonance frequency

Low ESL of <10 nH (<5 nH for special designs)
- Internal design for high dV/dt levels
- Make snubber capacitors unnecessary
## New dielectric for high temperature is needed

Polypropylene (PP) is a commonly used standard dielectric in film capacitors. PP is transformed into a **biaxially oriented PP (BOPP) film** in a sequential stretching process.

### Advantages of BOPP film
- State-of-the-art dielectric
- Excellent self-healing properties
- Low losses
- Low price

### Disadvantages of BOPP film
- Limited performance at high temperatures
- $T_{\text{max}} = 105 \, ^\circ\text{C}$ for high crystalline BOPP
- $T_{\text{max}} = 125 \, ^\circ\text{C}$ for some special BOPP grades – with derating

### Classic high temperature alternatives to PP
- Limited self-healing
- Difficult to process
- Expensive

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Polypropylene is reaching its limits due to the rising demands of new wide band-gap semiconductors, especially in high-temperature applications.
New material blend for high temperatures

Semi-crystalline PP

- Easy to process into films
- Temperature limitation

Amorphous cyclic olefin copolymer (COC)*

- High temperature operation
- Not processable into thin films

Blended film

- Improved temperature operation
- Processable into thin films down to 3 µm

* TOPAS® COC
Improved performance at high temperatures (1)

High mechanical stability

- High crystalline BOPP
- COC-PP

Low specific leakage current

- Specific Leakage Current – 250 V/μm
- High crystalline BOPP
- COC-PP

Graphs showing shrinkage in transverse direction and specific leakage current over temperature.
Improved performance at high temperatures (2)

Best of both worlds

- Aging and failure mechanism similar to BOPP
- Similar self-healing properties
- Stable performance at up to 125 °C

New PP+COC blends – T derating curve

- COC-PP
- High crystalline BOPP

Frequency response of ESR

- High crystalline BOPP
- COC-PP
Standard power capacitors have unfavorable ESR characteristics

ESR rises sharply with rising frequency

![Graph showing ESR rises sharply with rising frequency for a standard capacitor](image-url)
Standard power capacitors have unfavorable ESR characteristics

ESR rises sharply with rising frequency

<table>
<thead>
<tr>
<th>Frequency [kHz]</th>
<th>ESR [mΩ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>50</td>
<td>6</td>
</tr>
<tr>
<td>100</td>
<td>9</td>
</tr>
<tr>
<td>150</td>
<td>12</td>
</tr>
<tr>
<td>200</td>
<td>15</td>
</tr>
<tr>
<td>250</td>
<td>12</td>
</tr>
<tr>
<td>300</td>
<td>9</td>
</tr>
</tbody>
</table>

High ESR

- Standard capacitor
  - 20 A @ 50 kHz: 3.6 W
  - 20 A @ 200 kHz: 15 W

High power losses
Root causes of increasing ESR

- Inhomogenous impedance and internal resonances
- Negative electromagnetic interaction
- Winding geometry and metal profile
- Skin effect
Root causes of increasing ESR

- Inhomogeneous impedance and internal resonances
- Negative electromagnetic interaction
- Winding geometry and metal profile
- Skin effect

Factors offering most potential for improvement!

Power capacitors must be fundamentally redesigned in order to operate reliably at higher frequencies.
Standard capacitors are limited at high frequencies

Effects of inhomogeneous impedance and internal resonances

Standard capacitors are not ready for high frequencies
High ESR has thermal consequences

Hot spots in different windings with 20 K difference

Overall thermal map

Cross-section

Higher switching frequencies cause unbalanced thermal behavior
Design of high-frequency capacitors focused on low ESR

New design must deliver low and stable ESR across the critical frequency range.
Design rules for high-frequency capacitors

- **Same impedance** of all internal capacitive elements above, below and close to capacitor resonance frequency

- **Avoid negative electromagnetic interactions** between conductors (FEA electromagnetic software)

- **Overlapped busbar** from terminals to winding connection point is required in order to minimize the inductance

Current must be homogeneously distributed at all frequencies
Optimized design enables lowest ESL

- Balanced phase switching loops
- Same external dimensions and capacitance value
- Same metallized film and capacitive elements
- Lighter weight copper strips
- Significantly lower voltage overshoots

Makes snubber capacitors unnecessary in most cases
Introducing the new HF film capacitor series

**Fully compatible with SiC and advanced Si semiconductors**
- High power density
- Suitable for higher ambient temperatures
- Suitable for fast transients (dV/dt) and ringing effects
- Modular and suitable for parallel connection
- Snubber avoidance / low voltage overshoot
- Compact and lightweight, enables lighter cooling system

**Applications**
Traction, industrial drives, renewable power

<table>
<thead>
<tr>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 V / 2300 µF to 2.2 kV / 370 µF</td>
</tr>
<tr>
<td>Frequency operation range up to 2 MHz</td>
</tr>
<tr>
<td>ESL of 10 nH with 2 terminals</td>
</tr>
<tr>
<td>High current density of up to 150 A/mF @ 700 V and 950 A/mF @ 2200 V</td>
</tr>
<tr>
<td>Operating temperature (without voltage derating)</td>
</tr>
<tr>
<td>Standard polypropylene: +105 ºC</td>
</tr>
<tr>
<td>Advanced COC-PP dielectric: +125 ºC (in development)</td>
</tr>
<tr>
<td>Compact dimensions (4 sizes):</td>
</tr>
<tr>
<td>205 x 174 x 75 mm (l x h x w)</td>
</tr>
<tr>
<td>205 x 174 x 100 mm</td>
</tr>
<tr>
<td>210 x 126 x 70 mm</td>
</tr>
<tr>
<td>210 x 126 x 95 mm</td>
</tr>
<tr>
<td>Resin-filled plastic case</td>
</tr>
<tr>
<td>EN 45545 HL2 R23 (fire and smoke)</td>
</tr>
</tbody>
</table>
Advantages of new capacitor designs with a single winding

Boundary conditions
- Current: 130 A\textsubscript{rms}
- Frequency: 30 kHz
- Ambient temperature: 30 °C
- Power losses: 13.2 W

New capacitor designs enable stable thermal performance
New capacitor design enables linear ESR characteristics

New design features 80 percent lower AC losses at 100 kHz
Ready for hard switching

New HF film capacitor series with extremely low voltage overshoot and ringing

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Selected development projects with new HF film capacitors

- **Solar 1500 V power module (reference)**
  - Infineon Easy 3B: IGBT + SiC MOSFET
  - TDK DC link capacitors: HF film + aluminum electrolytic

- **ALSTOM traction converter**
  - 3.3-kV SiC MOSFET
  - New TDK HF film power capacitor

- **Traction power module (reference)**
  - Mitsubishi LV100 3.3kV SiC MOSFET
  - New TDK HF film power capacitor
  - Parallelization
  - Extension to Infineon XHP2 (1.7 kV and 3.3 kV): Ongoing
Future development focus

- New dielectrics for higher operation temperature
- Optimize entire DC link for high-frequency operation
- Applying design rules to PCB mounted capacitors
- Predict remaining lifetime according to real operation conditions
- Improve reliability based on additional active and passive safety sensors
- Smart capacitors able to provide feedback to converter control systems