Innovative power capacitor technologies for wide band-gap semiconductors

Advanced design features for high-frequency applications

Eduardo Drehmer
Aluminium & Film Capacitors Business Group
Málaga, Spain
March 14, 2020
Eduardo Drehmer
Director of Marketing
FILM Capacitors

Background:

- Over 20 years experience with knowledge on Manufacturing, Quality and Application of Electronic Components.
- Responsible for Technical Marketing for Film Capacitors

+1 732 319 1831

Eduardo.drehmer@tdk-electronics.tdk.com

www.tdk.com
Growing demands challenging power electronics

MOBILITY

INDUSTRIAL

- Low losses
- Miniaturization
- High energy density
- High robustness

MEDICAL

- EMC
- Integration

ENERGY
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)

New Si/SiC/GaN features

- 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

Demands on DC link

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

---

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
Improved performance at high temperatures (1)

**High mechanical stability**

- Shrinkage in transverse direction
- **High crystalline BOPP**
- COC-PP
- **NEW**

**Low specific leakage current**

- Specific Leakage Current – 250 V/μm
- **NEW**
- High crystalline BOPP
- CC-PP
Improved performance at high temperatures (2)

**Less derating**

PP+COC Blends – T-Derating curve

- **COC-PP**
- **High crystalline BOPP**

**Same ESR**

Frequency response of ESR

- **High crystalline BOPP**
- **COC-PP**

**Best of both worlds**

- Aging and failure mechanism similar to BOPP
- Similar self-healing properties
- Stable performance at up to 125 °C
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>50</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>150</td>
<td>5</td>
</tr>
<tr>
<td>200</td>
<td>9</td>
</tr>
<tr>
<td>250</td>
<td>12</td>
</tr>
<tr>
<td>300</td>
<td>15</td>
</tr>
</tbody>
</table>

**ESR rises sharply with rising frequency**

Standard capacitor
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>0.00</td>
</tr>
<tr>
<td>50</td>
<td>0.9</td>
</tr>
<tr>
<td>100</td>
<td>1.6</td>
</tr>
<tr>
<td>150</td>
<td>3.6</td>
</tr>
<tr>
<td>200</td>
<td>5.6</td>
</tr>
<tr>
<td>250</td>
<td>8.0</td>
</tr>
<tr>
<td>300</td>
<td>11.5</td>
</tr>
</tbody>
</table>

High ESR

- High power losses
  - 20 A @ 50 kHz: 1.6 W
  - 20 A @ 200 kHz: 3.6 W
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

Standard power capacitor

Effects of inhomogeneous impedance and internal resonances

Current sharing (%)

Frequency [kHz]

Top winding

Bottom winding

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

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

NEW

<table>
<thead>
<tr>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traction, industrial drives, renewable power</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 V / 2300uF to 2.2 kV / 370uF</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 up to 150A/mF@700V and 950A/mF@2200V</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 100mm</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_{rms}
- Frequency: 30 kHz
- Ambient temperature: 30 °C
- Power losses: 13.2 W

Homogenous temperature distribution
- Max temperature: 58.7°C
- Min temperature: 41.3°C

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
Selected development projects with new HF film capacitors

Infineon Technologies AG:
- Solar 1500V Demonstrator
- Easy 3B module: 1200V TRENCHSTOP™ IGBT7 + 1200V CoolSiC™ MOSFET

TDK Electronics:
- Hybrid DC-Link capacitor: 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

- **Continuous R&D**
  - New dielectrics for higher operation temperature

- **Further integration of busbar + capacitors**
  - Optimize entire DC link for high-frequency operation

- **PCB mounted high-frequency solutions**
  - Applying design rules to PCB mounted capacitors

- **Smart capacitors able to provide feedback to converter control systems**
  - Predict remaining lifetime according to real operation conditions
  - Improve reliability based on additional active and passive safety sensors…

© TDK Electronics • 2020

CC • 10/19 • 24