IEEE PSMA Capacitor Committee Workshop 2020

Innovative film capacitor technologies for wide band-gap semiconductors

Advanced design features for high-frequency applications

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Growing demands challenging power electronics

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

MOBILITY

INDUSTRIAL

MEDICAL

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)

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
- 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.

<table>
<thead>
<tr>
<th>Advantages of BOPP film</th>
<th>Disadvantages of BOPP film</th>
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<tbody>
<tr>
<td>State-of-the-art dielectric</td>
<td>Limited performance at high temperatures</td>
</tr>
<tr>
<td>Excellent self-healing properties</td>
<td>$T_{\text{max}} = 105 , ^\circ\text{C}$ for high crystalline BOPP</td>
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<tr>
<td>Low losses</td>
<td>$T_{\text{max}} = 125 , ^\circ\text{C}$ for some special BOPP grades – with derating</td>
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<tr>
<td>Low price</td>
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<table>
<thead>
<tr>
<th>Classic high temperature alternatives to PP</th>
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<tbody>
<tr>
<td>Limited self-healing</td>
</tr>
<tr>
<td>Difficult to process</td>
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<td>Expensive</td>
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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 (+)
Improved performance at high temperatures

Less derating

PP+COC Blends – T-Derating curve

High crystalline BOPP

COC-PP

Same ESR

Frequency response of ESR

High crystalline BOPP

COC-PP

NEW

Best of both worlds

• Aging and failure mechanism similar to BOPP

• Similar self-healing properties

• Stable performance at up to 125 °C

Attracting Tomorrow

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Standard power capacitors have unfavorable ESR characteristics

ESR rises sharply with rising frequency

High ESR

High power losses

1.6 W

3.6 W
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

Hot spots in different windings with 20 K difference

Overall thermal map
Cross-section

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

New design must deliver low and stable ESR across the critical frequency range.
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 Modular film DCR series

Under development

Ready for standard DC-Link optimization

- High energy density
- Voltage range from 900V to 2400V:
  - Case 1: from 2100μF@900V to 340μF@2400V
  - Case 2: from 3700μF@900V to 600μF@2400V
- Modular concept for parallelization
- Operating temperature: +85°C
- Frequency operation range up to 100 kHz
- Low ESR vs frequency
- Snubber avoidance / low voltage overshoot
- Low ESL 14 nH
- Dimensions:
  - Case 1: 205 x 170 x 90 mm (l x h x w) 3.7kg
  - Case 2: 220 x 215 x 115 mm (l x h x w) 6.1kg
- Resin-filled plastic case
- EN 45545 HL3 R23 (fire and smoke)

Applications

Traction, industrial drives, renewable power

Expected release: 2020 Q2
Samples: available under request
Electromagnetic & thermal simulation
Standard Product – Customized solution

Electromagnetic PEEC simulation
- Thermal BC
- Electrical BC
- Capacitor design
- Electromagnetic simulation

Losses distribution
Current distribution
Electrical model

Electromagnetic interaction study @ 10 kHz

Capacitor electrical model

Ratings
- Rp
- ESL
- ESR(f)
- C

Electromagnetic & thermal simulation
- New Modular film DCR series
- 200 A_{RMS} @ spectrum fsw = 2kHz

Thermal FEM simulation
- Thermal simulation
- Thermal model
Introducing the new HF Modular film DCR series

Under development

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

Expected release: 2020 Q4
Samples: available under request

Operating temperature
- Standard polypropylene: +105 °C
- Advanced COC-PP dielectric: +125 °C (in development)

560 Vdc / 1520 µF to 2280Vdc/ 175 µF
- Frequency operation range up to 2 MHz
- Extremely low ESR vs frequency
- ESL of 16 nH with 1 pair of terminals
- High current density of up to 206 A/mF @ 560 Vdc and 1286 A/mF @ 2280Vdc
- Compact dimensions (2 sizes):
  - 210 x 130 x 70 mm (l x h x w) 2.8kg
  - 210 x 130 x 95 mm 3.1kg

- Resin-filled plastic case
- EN 45545 HL3 R23 / HL2 R22 (fire and smoke)

Applications
- Traction, industrial drives, renewable power
Selected development projects with new HF modular film capacitor series

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

**TDK Electronics:**
- Hybrid DC-Link capacitor: New HF film PCB+ aluminum electrolytic

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

**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
HF modular film capacitor series: Ready for hard switching

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