High Performance DC Bus Film Capacitor

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Imagination at work.
# Overview

## Timeline
- Project start: October 2013
- Project end: Sept. 2016
- Percent complete (50%)

## Barriers
- Temperature limit >140°C
- Volume down by 25-50%
- Cost reduction to $30

## Budget
- Total funding: $2646k
  - DOE share $1750k
  - Contractor share $896k
- Funding received in FY13/14 - $698k
- Funding for FY14/15 - $925k

## Partners
- Delphi / subcontractor for capacitor specification and testing
- Film processing and capacitor suppliers
Relevance

Objectives:
- Develop high temperature polymer film capacitors of >150ºC rating
  - Develop melt extrusion process for 3-5 μm thick polyetherimide (PEI) films to overcome volume and cost barrier
  - Develop nanocoating process for dielectric strength and self healing.
- Extrude 5 μm PEI films and demonstrate nanocoating process in Budget Period 1
- Validate roll-to-roll film coating process and capacitor manufacturers for inverter-specific capacitor in Budget Period 2

Largest component
<125ºC
Expensive
## Milestones

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Milestone or Go/No-go Decision</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 2014</td>
<td><strong>Go/No-go decision:</strong> Validate extrusion process for 5 µm PEI film. Is film thickness variation &lt;10% and wrinkles-free? Yes</td>
<td>Complete</td>
</tr>
<tr>
<td>Sept. 2014</td>
<td><strong>Go/No-go decision:</strong> Demonstrate 5 µm film rolls (500 meter). Check film properties, thickness variability and cost model.</td>
<td>Complete</td>
</tr>
<tr>
<td>Dec. 2014</td>
<td><strong>Milestone:</strong> - Identify nanocoating vendors and test R2R coating feasibility - Scale up 5 µm PEI film (2000 meter)</td>
<td>Complete</td>
</tr>
<tr>
<td>Mar. 2015</td>
<td><strong>Milestone:</strong> - Test mechanical and dielectric properties of 3-5 µm films - Develop 3 µm film with minimal defects (film with support)</td>
<td>Complete</td>
</tr>
<tr>
<td>June. 2015</td>
<td><strong>Milestone:</strong> - Scale up 3-5 µm PEI films and downselect thickness - Properties of nanocoating films</td>
<td>On track</td>
</tr>
<tr>
<td>Sept. 2015</td>
<td><strong>Milestone and Go/No go decision:</strong> - Scale-up nanocoating on 3-5 µm film - Build and test prototype capacitor</td>
<td>On track</td>
</tr>
</tbody>
</table>
Approach/Strategy

- Develop extruded high temperature PEI film to overcome the shortcomings of BOPP and cooling system.
- Leverage higher dielectric constant and thinner film for lower volume and cost than state-of-the-art.
- Enhance dielectric strength via inorganic coating of PEI films for operating voltage and smaller volume.

$$D = \varepsilon_0 K E_{BD}^2 / 2$$

High temperature extruded polymer film capacitor
Technical Accomplishments/Progress: PEI Film Extrusion Process

Barrier: Scaled-up extrusion process

High temp thinner PEI film successfully developed in production extruders. Two processes validated.
Developed working relationships, producing 4 µm films.

Supplier A
- Wrinkle-free film (3-7 µm)
- Uniform thickness (but higher roughness)
- DC dielectric strength (Weibull: 510-580V/µ)
- Good scalability (2000m x 530mm)
- Awaiting commercialization of 5 µm films

Supplier B
- Light crinkled film (5-7 µm)
- Uniform thickness (but some pits)
- DC dielectric strength (Weibull: 550-600 V/µ)
- Good scalability (2000m x 480mm)
- Awaiting production of 3 & 4 µm films
Properties of 5 µm PEI Films

Stable properties up to 180ºC, adequate for capacitor.
Breakdown Strength at High Temperatures

Weibull distribution, shape factor = 10

Temperature Dependence of Dielectric Strength of 6μm PEI

Breakdown Strength becomes lower at 150°C.
Optical Analyses of PEI Films

Defects on 5 µm extruded film (polarized optical microscopy)

Good thickness uniformity (+/-10% target), but a little wrinkle and defects
Development of 4 µm PEI Film

4 µm films with slip additives (5 wt%) for wrinkle elimination produced, but exhibit lower breakdown strength and broad distribution.

Breakdown strength defined at 63% probability and the shape factor $\beta$ measures the scatter.

4 µm - 520 kV/mm
5 µm - 552 kV/mm
7 µm - 577 kV/mm
Capacitor Winding Using 4 µm PEI Film

- Metallization off target due to low surface adhesion (excessive slip agent)
- High insulation resistance, but lower breakdown voltage
- New formulation and process underway.

<table>
<thead>
<tr>
<th>Unit #</th>
<th>600VDC Flash</th>
<th>DC current leakage (µA) @500VDC</th>
<th>IR @500VDC, MΩ</th>
<th>Capacitance (µF) at 1kHz</th>
<th>Dissipation Factor at 1kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pass</td>
<td>0.091</td>
<td>5500</td>
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<td>1.3</td>
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<td>4000</td>
<td>35.572</td>
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<tr>
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<td>35.934</td>
<td>1.36</td>
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<td>16</td>
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<td>0.09</td>
<td>5600</td>
<td>35.272</td>
<td>1.31</td>
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</table>
Development of 3 µm Films on a Carrier

- 6” wide uniform film roll produced at supplier C
- ~3 µm PEI produced on a carrier

Thickness uniformity was constrained by die-lip flatness. There are some good and thin areas.

http://commons.wikimedia.org/wiki/File:Extruder_section.jpg

12” web
Roll-to-Roll Oxide Nanocoating on PEI Film

Feasibility proved, but coating on free-standing films need to be studied.

TEM imaging

Sputter coating on free-standing film and faster e-beam coating feasibility underway

Feasibility proved, but coating on free-standing films need to be studied.

Box plot for 5μm PEI film with and without SiOx coating
(means are indicated by solid circles)

DC Breakdown Strength (kV/mm)

P<0.05

SiOx

TEM imaging

99.2 nm

2.50 μm

SiOx

5μm PEI

50nm SiOx on 5μm PEI
Technology-to-Market Development

GE design and coordinate capacitor manufacturing using high dielectric constant polymer films to achieve smaller volume units.

Extrusion of 3-5µm PEI films favorable for medium voltage and smaller capacitors.

Enhanced dielectric strength via nano-coating of PEI films to ensure voltage handling reliability.

Engaged Capacitor Mfgs early to align value chain

Kemet
ECI
DEI
NWL
SBE
Response to Reviewers Comments

AMR14 comments were generally positive with the reviewers posing three questions:

1. Be aware of the potential cost of the carrier film
   Yes, the team is aware of the cost of carrier and is working on minimizing carriers. Use of a carrier to support the very thin extruded film has the potential to improve the ease of handling and yield associated with various capacitor manufacturing steps, and the resulting process cost savings may help to offset the initial material cost of the carrier. The team will favor the free-standing film approach if high yield of 5, 4, and 3 µm films are gradually achievable.

2. Explain the approach from film to capacitors in more detail
   Taking into account both the film properties (e.g. dielectric constant, breakdown strength, and thickness) and capacitor design, 3-5 µm film was calculated to be able to meet DOE targets. The team is also considering the shape factor of different capacitor designs and packaging to minimize the volume, weight and cost (3 µm is ideal).

3. How much material production has contributed to achieving goals
   Decreasing the film thickness is critical to achieving the DOE goals as shown in the figure at right. Producing films below 4 µm with minimal wrinkles is necessary and will lead to achieve DOE’s unit volume target. High volume production of thin films may allow reduction of film manufacturing cost.
Collaboration and Coordination with Other Institutions

• Contract Collaborator
  – Capacitor specs definition and testing (Ralph Taylor / Delphi)

• Extruded Film Suppliers
  – Free-standing film process (A, B)
  – Carried film process (C)

• Other Service Suppliers
  – Materion, Amcor, FEP for inorganic coating (sputtering, e-beam)
  – Bollore, Steinerfilm for metallization
  – DEI, ECI, SBE, NWL, Kemet for capacitor winding, packaging and testing
Remaining Challenges

• Commercial scale 5 µm PEI films exhibit minor wrinkles to be minimized.
• Scale-up extrusion of 3-4 µm free-standing film without wrinkles remains challenging.
• Nanocoating processing method needs improving.
• Ultimate cost of extruded PEI film is difficult to control, and depends on film manufacturing process and market demand.
Future Work: Validate Films & Capacitors

FY2015
- Extrude 3-5 μm film with minimal wrinkles from production line (Q2).
- Test and validate scaled-up films thinner than 5 μm (Q2).
- Optimize R2R nanocoating using e-beam tool at commercial vendors (Q3)
- Prototype PEI capacitors using films of 5 μm or thinner (Q3)
- Down select PEI film and nanocoating process (Q4).
- Verify film processing cost model (Q4)

FY2016
- Scale up PEI film and nanocoating (Q1)
- Design, deposit and verify metallization (Q2)
- Build and test specified capacitors using thinner films (Q3)
Summary

• Scaled up production of PEI films of 3-5 µm in thickness, with minimal film wrinkling and thickness variability.
  • Melt extruded wrinkle free PEI films (5 µm).
  • Developed the second supplier for 3-5 µm film with minor wrinkles.
  • Produced 3 µm PEI film supported by a carrier.
• Developed nanocoating process on PEI films.
  • Demonstrated breakdown strength enhancement on nanocoated film.
  • Demonstrated R2R coating feasibility on free-standing film.
• Qualified film properties in terms of thermal, dielectric and mechanical characteristics.
• Developed a supply chain from film production to nanocoating to capacitor making.
  • Established collaborative relationships with various suppliers.
  • Demonstrated the feasibility of winding the extruded films through various process steps.
Acknowledgement

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Technical Back-Up Slides
### BP2 Tasks to Achieve & Key Deliverable

<table>
<thead>
<tr>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct</td>
<td>Nov</td>
</tr>
</tbody>
</table>

**Tasks**

1. Perform and evaluate nanocoating
2. Define capacitor specifications

**Key Deliverable**

- 3-micron film and nanocoating; Specified metallization design; 6 capacitors of specified requirements

**Go No/Go Decision Point**

Downselection of film thickness and coating process
Tear strength of nanocoating film

3 µm film, Capacitors

Build and test prototype capacitors

Scale up nanocoating on 3 µm film
Verify cost model for extruded films

Scale up extruded 3-5 µm PEI films with minimal thickness variation

Go No/Go Decision Point:
Capacitor Volume and Cost Reduction

Volume: 40% (50% higher permittivity, capacitor factor, component number, potting and casing free)

Weight: 40% (less connection, potting and casing free)

Cost: $30 (less film~$24, less package)

![Capacitor Image]

\[C/N = \varepsilon_0 \varepsilon \frac{\text{Area}}{\text{thickness}}\]

<table>
<thead>
<tr>
<th>Capacitor Volume and Cost Reduction</th>
<th>800 µF capacitor</th>
<th>3 µm PEI</th>
<th>2.5 µm PP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film volume (L)</td>
<td>0.254</td>
<td>0.257</td>
<td></td>
</tr>
<tr>
<td>Capacitor volume (L)</td>
<td>0.5</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Capacitor shape</td>
<td>Flat/16 parts</td>
<td>Round/48 parts</td>
<td></td>
</tr>
<tr>
<td>Space fill factor</td>
<td>0.05</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Potting casing (L)</td>
<td>No potting needed</td>
<td>Casing optional</td>
<td>0.15</td>
</tr>
<tr>
<td>Final Volume (L)</td>
<td>0.53</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Capacitor weight (g)</td>
<td>800-900</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>Overall weight (g)</td>
<td>≤1000</td>
<td>1800</td>
<td></td>
</tr>
</tbody>
</table>

Capacitor of $30 and 0.6L is possible.