High Performance DC Bus Film Capacitor

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GE Global Research
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Project ID: #APE060
Overview

Timeline
• Project start: October 2013
• Project end: Sept. 2016
• Percent complete (16%)

Barriers
• Temperature limit >140ºC
• Volume down by 25-50%
• Cost reduction to $30

Budget
• Total funding: $2646k
  – DOE share $1750k
  – Contractor share $896k
• Funding received in FY13 - $698k
• Funding for FY14 - $925k

Partners
• Delphi / subcontractor
• US film and capacitor manufacturers
Relevance of Capacitors

DC bus capacitor

- The largest component
- <125°C use temperature
- Expensive

Objectives: High temperature benign capacitors made of thin polymer films to target at capacitors of 180°C, less volume, lower cost, and self healing.

Uniqueness and impacts:
High-Tg Polyetherimide (PEI) thin films to meet DOE requirements and broader application.

<table>
<thead>
<tr>
<th>DC Bus Capacitor Targets</th>
<th>DOE Metrics</th>
<th>GE technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature range of ambient air, ºC</td>
<td>-40 to +140</td>
<td>PEI (-40 to +180)</td>
</tr>
<tr>
<td>Volume requirement, L</td>
<td>≤ 0.6</td>
<td>3-5 µm film (0.3-0.5)</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>≤ 30</td>
<td>≤ 30</td>
</tr>
<tr>
<td>Failure mode</td>
<td>Benign</td>
<td>Self-clearing (Benign)</td>
</tr>
<tr>
<td>Life @operating condition, hr</td>
<td>&gt;13,000</td>
<td>200,000</td>
</tr>
</tbody>
</table>
## Milestones

<table>
<thead>
<tr>
<th>Month /Year</th>
<th>Milestone or Go/No-go Decision</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 2013</td>
<td>Milestone</td>
<td>Set-up program and establish working relationship with film manufacturers to develop extruded films</td>
<td>Complete</td>
</tr>
<tr>
<td>January 2014</td>
<td>Milestone</td>
<td>Demonstrate extrusion feasibility for 5µm film</td>
<td>Complete</td>
</tr>
<tr>
<td>February 2014</td>
<td>Milestone</td>
<td>Test dielectric properties and surface morphology of 5 µm PEI film</td>
<td>Complete</td>
</tr>
<tr>
<td>March 2014</td>
<td>Go/No-go decision</td>
<td>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>May – Dec. 2014</td>
<td>Milestone</td>
<td>Identify inorganic coating vendors and test coating feasibility</td>
<td>On schedule</td>
</tr>
<tr>
<td>May - Dec. 2014</td>
<td>Milestone</td>
<td>Test mechanical and dielectric properties. Develop 3 µm film with minimal defects</td>
<td>On schedule</td>
</tr>
<tr>
<td>June - Sept. 2014</td>
<td>Go/No-go decision</td>
<td>Demonstrate 5 µm film rolls (500 meter). Check film properties, thickness variability and cost model.</td>
<td>On schedule</td>
</tr>
</tbody>
</table>
Approach/Strategy

- Develop high temperature PEI film to overcome the shortcomings of BOPP and cooling system.
- Higher dielectric constant and thinner film for higher capacitance density and smaller volume than state-of-the-art.
- Enhanced dielectric strength via inorganic coating of PEI films for smaller volume.

High temperature extruded polymer film capacitor
Accomplishments/Progresses: Extruding Thinner Polymer Film

Wrinkle free thinner films with high dielectric strength were being extruded.

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

High dielectric strength and thinner films are desirable allowing more design space and maximization of film properties.

Capacitance density increases with decreasing film thickness, leading to smaller capacitor volume.
Traditional Extrusion of Free-Standing Film (7 µm)

Min-6.9; Max-7.6
Thickness variation of 10% achieved
Traditional Extrusion of Free-standing Film (5-µm)

Films with thickness variation of 6% achieved.
Surface Profilometry of 5µm Film

Sensor: 300-µm
Detection speed: 1000Hz
Scan size: 5mm x 5mm
Step size: 5µm
Data processing: segmentation, plane fit

This dip is only ~0.6µm deep

Films surface morphology and roughness is acceptable.
Dielectric Constant and Loss

Dielectric constant remains 3.16-3.2 in the range of temperature and frequency of measurements.

Extruded film exhibits low dielectric loss and stable dielectric constant.
New Extrusion Mechanism-Carried Films

Controlling screw speed, film take-up speed of carrier, die lip gap and temperature, carrier, etc.

Film wrinkle issues avoided by using a carrier.
Carrier Treatment and Performance

Carrier #1

Carrier #2

Two carriers developed for good adhesion and delamination.
Slitting and Delamination Feasibility: 5 µm Film

After slitting

After delamination

All film processing appears to be feasible
Properties of PEI Films Released from Carrier

Thinner film shows lower breakdown strength (458.2 kV/mm for 5 µm, 574.1 kV/mm for 10 µm, beta~9)
Collaboration and Coordination with Other Institutions

• Film extrusion
  – Japan film manufacturer (e.g. MPI)
  – US film manufacturer

• Capacitor specs definition and testing
  – Ralph Taylor / Delphi

• Coordination of services
  – Materion for inorganic coating
  – Bolloré for metallization service
  – DEI and ECI for capacitor winding service
Feasibility of Metallization and Capacitor Fabrication for 5-7 µm Films

Disregard the challenges for thinner PEI films at metallization and capacitor winding, capacitors were produced. Yield is to be improved.
Remaining Challenges

• Procurement of scale-up rolls of 5 µm film takes longer time due to certain limitation of film vendors.
• Extrusion and thickness variation for 3 µm films need improvement.
• Nanocoating on thin films requires high tear strength of polymer films. Process optimization is required.
Proposed Future Work

• Optimize extrusion parameters in film scale-up processes for both extrusion mechanisms. Confirm film delamination and windability on wider rolls (Q3FW14).

• Fully evaluate scale-up films to understand dielectric strength, mechanical strength, thermal stability and rewinding issue (Q2FY14).

• Demonstrate nanocoating effect on PEI films. Experiments will be performed in GE labs (Q3FY14) and using pilot equipment at commercial vendors (Q1FY15).

• Key milestones will be the downselection of film thickness and nanocoating recipes (Q4FY14).

• Verify film processing cost model (Q4FY14).
Summary

• **Project relevant to DOE capacitor and inverter development**
  • GE team established to develop polymer film capacitors meeting DOE’s goals
  • Scale-up of 3 µm PEI films are desirable to meet all capacitor requirements.

• **Year 1 focused on polymer film extrusion and scale-up**
  • Developed wrinkle free PEI films (5-7 µm) using melt extrusion
  • Demonstrated satisfactory performance 5-7 µm PEI films
  • Developed a carrier-supported film extrusion method in US

• **Collaboration expanded to different film and capacitor vendors**
  • Established collaborative relationships with subcontractors, film processing vendors
  • Plan to explore different metallization schemes and capacitor winding at vendors
Technical Back-Up Slides
Progressive Effects in PEI Film Development

- wrinkle minimized
- thickness consistency improved

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)

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

<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.
Acknowledgement

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