Metallized Hybrid Film for DC-Link Application

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Office of Electricity Delivery and Energy Reliability

Managed by
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Transportable Energy Storage Systems For Grid Applications

Transportable energy storage systems will be used to:
- Integrate renewable energy sources and mitigate intermittency
- Improve grid stability and reliability by providing new capacity that can be deployed quickly
- Offer a cost effective way to balance the load
Use of DC-Link Capacitors

Each energy storage unit includes one or more high power inverters to convert DC voltage to three phase AC.

A key component of the inverter circuit is the DC-link capacitor, used to minimize ripple current, voltage fluctuation and transient suppression.

The DC-link capacitor is one of the largest, costliest and most failure-prone components in today’s inverter systems.

This holds true for all inverters used in applications that range from residential to automotive (HEV and EV) and grid based systems.
Metallized Polypropylene (MPP) capacitors are used almost exclusively in all HV and automotive DC-Link capacitor applications.

PP films have low Dissipation Factor (DF) and high breakdown strength.

The dielectric constant $\kappa = 2.2$ limits the energy density of MPP capacitors to $<1\text{J/cc}$.

MPP capacitors are rated to $85^\circ\text{C}$ with a maximum operating temperature of $105^\circ\text{C}$ with 30% derating, or a drop in energy density of 50%.

The temperature limitation also impacts the ability of MPP capacitors to handle high ripple currents and high $dV/dt$ transients at high ambient temperatures.

High currents generate $I^2R$ heating ($R=\text{ESR}$), which lowers the mechanical strength of the film at the termination, which causes loss of contact between the termination spray and the electrode layer, increasing the ESR, which leads to higher $I^2R$ heating.
Solution to MPP Capacitor Limitations

EMERGING TECHNOLOGIES

Development of New High Temperature Films
- Polyphenylene Sulfide (PPS) already in use for some capacitor applications
  - lower energy density than PP poor self healing properties
- New high temperature films: for example PEI developed by GE and FEP and FPE films developed by 3M.
  - Not available in thin enough gages, very high cost, lower energy density than PP, some not self healing.

New high temperature capacitor films that match the dielectric properties and cost structure of polypropylene is at best a long-range endeavor
SIGMA TECHNOLOGIES APPROACH

Improve the properties of polypropylene films by “converting” or coating the base PP film with a polymer dielectric that has superior thermomechanical properties.

Converting is common practice in packaging films to improve strength, barrier, printability, heat sealability, etc.

Capacitor films have not been converted before due to the lack of a coating technology capable of thin, uniform polymer coatings, that are economical to apply, pinhole free, high temperature, and have capacitor quality dielectric properties.
SIGMA TECHNOLOGIES APPROACH

- Sigma has been working over 20 years in the development of an environmentally friendly nano-coating process using 100% solids
  - No solvents which require recovery
  - No water which requires energy to dry
  - No hazardous waste for disposal
  - No primers, surfactants and adhesion promoters

- Submicron thin, pinhole free coatings with surface leveling properties

- High temperature (>200°C)

- Excellent dielectric properties

- Amorphous cross linked polymers with breakdown strength >1000V/µm (higher than any polymer film)
DIELECTRIC MATERIALS

- Multifunctional acrylate based monomer materials that are electron beam cured

- $\text{H}_2\text{C}=\text{CHC(O)O R(X) OC(O)CH}=\text{CH}_2$

- $R = \text{aliphatic, aromatic, heterocyclic}$

- $X = \text{any functional group, eg}$
  - amino, cyano, fluoroalkyl, nitrile, halogen, glycolyl, organometallic, other.
Unique Polymer Dielectric Deposition Process

Metallized Hybrid Film Capacitor for DC-Link Applications

[Diagram of polymer dielectric deposition process]

- Plasma Treater
- Process Drum
- Coated Polymer Film Web to Wind Roll
- Curing Device
- Nozzle
- Atomizer
- Degas Vessel with Liquid Monomer
- Evaporator
- Pump
- Vacuum (Vac)
- Electron Beam Curtain
- Monomer Storage
- Monomer Evaporation System
Commercial Applications of the Acrylate Coating Process
Flexible Optically Variable Devices

Metallized Hybrid Film Capacitor for DC-Link Applications

Opaque Metal Layer

Transparent Metal layer

Dielectric layer
Commercial Applications of the Acrylate Coating Process
Ultra High Barrier Films Licensed For Use In New AMOLED Cell-Phones and OLED TVs

Metallized Hybrid Film Capacitor for DC-Link Applications
Commercial Applications of the Acrylate Coating Process
Radiant Barrier Materials For Heat Management
Sigma Technologies is a Leading US OEM

Metallized Hybrid Film Capacitor for DC-Link Applications

Polymer Film or Non Woven Fabric

Protective Polymer Layer with Low IR Absorption

95% Heat Reflection

Metallized Layer

reduce heating costs
reduce cooling costs
• Sigma dedicated more than 10 years developing the PML capacitor technology before licensing it to two multinational capacitor OEMs.

• Sigma developed the material and process technology and built production equipment for producing the Mother Capacitor material.

• Surface mount low voltage PML capacitors are now used in common consumer electronic devices such as digital cameras, LED and LCD TVs, audio amplifiers and others.
Process of Converting Capacitor Films to “Hybrid” Polymer Films
Objectives and Impact of Phase II Program

KEY OBJECTIVES OF PHASE II PROGRAM
• Optimize acrylate dielectric materials
• Scale up to a roll to roll pilot line
• Produce Full Size HV DC-link Capacitors
• Demonstrate performance using application specific capacitor tests
• Develop a Business Plan to Transition Into Production

IMPACT ON POWER CONTROL SYSTEMS
• Compact inverter modules that can operate at higher temperature
• Improvement in life and system reliability
• Increase competitiveness of US OEMs
PP Film was exposed to 20 passes of Low Voltage Electron Beam and UV radiation with no acrylate coating.

Low Voltage Electron Beam (<10KV) was selected. At this voltage level the electron penetration is <1µm.
Dielectric Properties of Hybrid PP Films

Dielectric constant and dissipation factor performance as a function of temperature of a base PP film and a hybrid film produced by coating the PP film with a high temperature acrylate polymer dielectric.
Breakdown Strength of Hybrid PP Films

Increase in Breakdown Strength
Breakdown Strength of Hybrid PP Films

Increase In Breakdown Strength

<table>
<thead>
<tr>
<th>Film</th>
<th>Breakdown Voltage (kV)</th>
<th>Total Thickness (µm)</th>
<th>Breakdown Strength (kV/µm)</th>
<th>% Increase in Breakdown Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9 µm PP</td>
<td>3.8</td>
<td>5.9</td>
<td>0.6154</td>
<td>-</td>
</tr>
<tr>
<td>5.9 µm PP + 0.3 µm Acrylate</td>
<td>4.5</td>
<td>5.9 + 0.3</td>
<td>0.6981</td>
<td>13.4</td>
</tr>
<tr>
<td>3.9 µm PP</td>
<td>2.8</td>
<td>3.9</td>
<td>0.6753</td>
<td>-</td>
</tr>
<tr>
<td>3.9 µm PP + 0.7 µm Acrylate</td>
<td>3.4</td>
<td>3.9 + 0.7</td>
<td>0.7221</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Using 0.5µm Acrylate 1000 layer PML capacitors was constructed and tested.

At 500VDC the 0.5µm dielectric capacitors are stressed at 1000V/µm.

This is higher than the intrinsic breakdown strength of polymer film dielectrics (which is in the range of 400V/µm to 700V/µm).
Thermal Properties of Hybrid PP Films

Increase in $I^2R$ thermal capacity generated by ripple currents

Heat Capacity of Metallized PP and Hybrid PP Films

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum Power Dissipation ($I^2R$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9µm PP</td>
<td>6.5”</td>
</tr>
<tr>
<td>5.9µm PP 0.8µm Acrylate</td>
<td>7.5”</td>
</tr>
<tr>
<td>3.9µm PP</td>
<td>8.5”</td>
</tr>
<tr>
<td>3.9µm PP 0.8µm Acrylate</td>
<td>9”</td>
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</table>
Impact on HV Capacitors Impregnated with a Dielectric Fluid

Metallized Hybrid Film Capacitor for DC-Link Applications

Microcracking Caused by Swelling

- Base PP film
- Hybrid Film

Active Electrode with Controlled Metallization to Simulate Self Healing Capacitor Electrodes

Heavy Metallization to Simulate Heavy Edge Electrodes and Facilitate Electrical Contact

Capacitor Film

Oil
Castor oil was chosen based on reduced swelling and higher breakdown voltage.
DC-link Hybrid Metallized Film Design

5.9μm and 3.9μm Control PP and Hybrid PP Metallized Films are Produced for Evaluation and Comparison of Key Capacitor Properties
Inverter Sales Market Forecast and Major Inverter Applications

Inverters Used in Storage Modules Tied to Renewable Energy Sources and the Grid
## Market Drivers

### Application Priorities by Market Drivers

*Priority ranking per application*

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Cost</th>
<th>Performance (efficiency)</th>
<th>Reliability Lifetime</th>
<th>Form factor</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PV inverters</strong></td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>+</td>
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<tr>
<td><strong>EV/HEV</strong></td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
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<tr>
<td><strong>Wind turbines</strong></td>
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<td><strong>Rail traction</strong></td>
<td>+</td>
<td>+</td>
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<tr>
<td><strong>UPS</strong></td>
<td>+++</td>
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<td>+++</td>
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<tr>
<td><strong>Grid Tied Storage</strong></td>
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<td>+++</td>
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DC-link Capacitor Market Forecast

Significant Market Size for Any Passive or Active Component
Summary

Hybrid PP films provide a low cost alternative to high temperature films with superior dielectric properties.

Higher thermal capacity to handle high amplitude ripple currents and high dV/dt transients.

Improved breakdown strength.

Excellent self healing properties.

Superior electrical contact of the arc-sprayed termination to the metallized electrodes.

Superior performance in the presence of dielectric impregnating fluids.
Thank You For Your Attention

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