High Temperature DC-Bus Capacitor Cost Reduction and Performance Improvements

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Sigma Technologies International

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Project ID #: **EDT059**

Overview

Timeline

- Start date – October 1, 2013
- End date – March 31, 2017
- Percent complete – 100% as of 3/31/2017

Budget

- Total funding: $3,510,897
  - DOE share: $2,288,559
  - Contractor share: $1,222,338
- Expenditure of funds in
  - FY13: $129,484
  - FY14: $1,239,821
  - FY15: $996,153
  - FY16: $1,089,990
  - FY17: $55,447
  - Total: $3,510,897

Barriers addressed

- A & C (Cost & Weight): Overall size and cost of inverters, as well as thermal management system
- D (Performance and Lifetime): High-temperature operation
  - The performance and lifetime of capacitors available today degrade rapidly with increasing temperature (ripple current capability decreases with temperature increase from 85˚C to 105˚C)

Partners

- Interactions / collaborations
  - Delphi Automotive Systems
  - Oak Ridge National Laboratory
  - Project lead: Sigma Technologies

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Relevance/Objectives

- Overall Objectives
  - Reduce the cost, size and weight of the DC-link capacitor by >50%
  - Increase durability in high temperature environments
- Objectives this period
  - Produce full size parts
  - Develop an encapsulation package
  - Test PML capacitors in an inverter circuit
  - Continue long term testing
- Impact
  - Accelerate the manufacturing capability and mass production adoption of energy-efficient and cost-effective APEEM capacitor technologies into electric drive vehicles, such as electric vehicles (EVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs)

Project Milestones

Month/ Year	Milestone or Go /No-Go Decision	Description	Status
March 2017	Milestone	Produce Gen2 Parts meeting or exceeding DOE requirments	Completed

Approach – Overcome Limitations of Polypropylene (PP) DC-Link Capacitors

- Current baseline PP DC-link capacitors are large (~1 liter), heavy (~1 kg), temperature limited (105˚C) and costly
- Metallized PP capacitors must be derated from 85˚C to 105˚C by at least 30%, which is >50% drop in energy density
- PP DC-link capacitor supply chain: Today's PP DC-link capacitors utilize extruded and biaxially oriented film produced and metallized by just a handful of film OEMs worldwide, as a result most capacitor OEMs produce similar products and there is limited opportunity for innovation

- Sigma has developed a solid state Polymer-Multi-Layer (PML) Having a prismatic shape with
- low ESL and ESR
- Operating temperature (T_{op}) range of -40^{o}C < T_{op} < 140^{o}C
- Dielectric constants in the range of 3.2, Dissipation factor DF < 0.01 through out the temperature range
- Submicron polymer dielectric
- Benign failure mode
- Transformational and potentially disruptive technology: Liquid monomer and Al wire are converted in a single step into Mother Capacitor material

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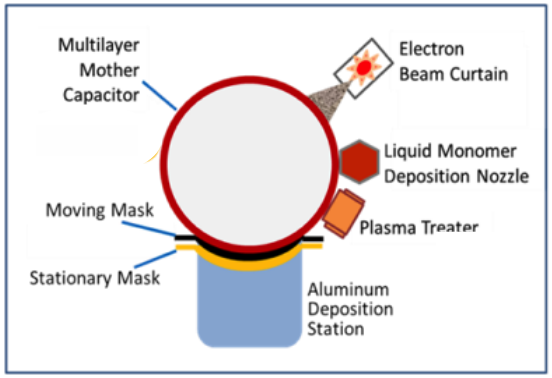
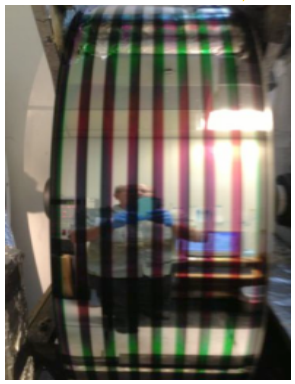
Approach – High Temperature, High energy density Polymer Multi-Layer (PML) DC-Link Capacitors

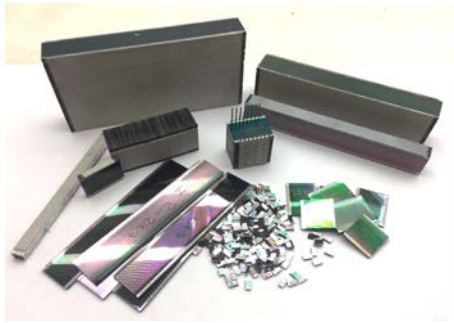


PML Capacitor Process Schematic

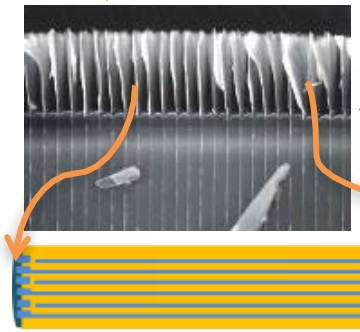


10ft long Mother Capacitor Material On Process Drum

12" x 12" Card Segmented from the Mother Capacitor

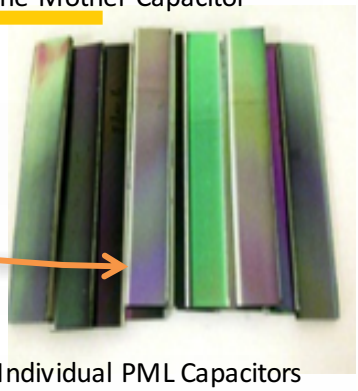


Capacitor Chips and Chip Stacks to Form Larger Capacitors



Plasma Ashed Termination Heavy Edge

Arc Sprayed Termination



Individual PML Capacitors

All aspects of capacitor manufacturing are controlled by the capacitor OEM

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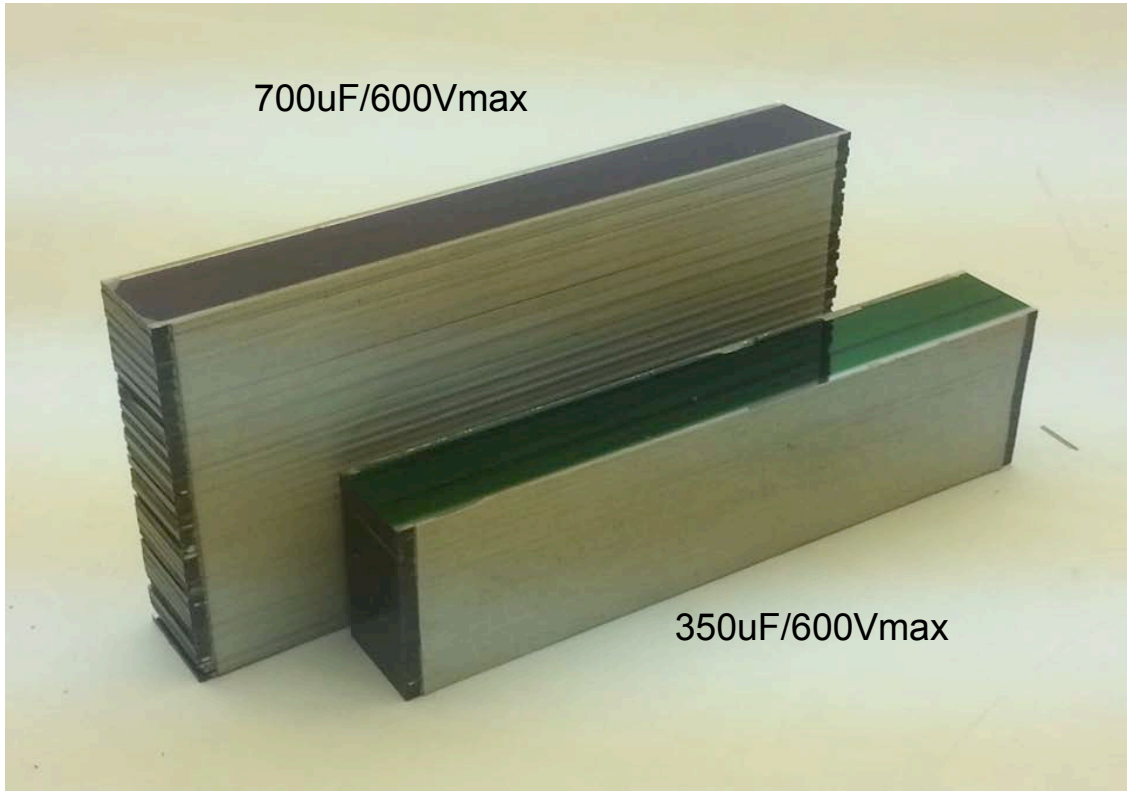
Technical Accomplishment - Simple Prismatic Construction



All Applications Regardless of Voltage and Capacitance
Are Served By A single Solid State Part With Low ESR and ESL

Technical Accomplishment - Packaging

Overmolding (Transfer Molding)

Epoxy Potting in a High Temperature Box

Two Different packaging Designs Have been Pursued
Overmolding and Epoxy Potting

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Technical Accomplishment – Evaluation of the PML capacitors

- Over the course of this development various forms of the new capacitor have been tested
  - Strips, stacks, packaged DC-link capacitors
  - Initial strips and stacks were not packaged
- When capacitors are received they are characterized for capacitance, ESR, ESL, dissipation factor, impedance, breakdown strength and the resonant frequency is measured
  - Evaluated using various AEC Q200D tests
  - Thermal storage, thermal shock, thermal cycle, bias humidity
- With a temperature range of -40° C to 140° C
- Test results show that PML capacitors are as good or better than PP capacitor with equal capacitance and voltage rating

Technical Accomplishment – Dyne Testing

Tested Configuration

- A 500µF unpackaged Sigma capacitor was instrumented with nine thermocouples
  - Three on the bottom surface equally spaced across the length
  - Three in center equally spaced across the length
  - Three on top surface equally spaced across the length
- Three additional thermocouples placed of the top surface of a packaged capacitor, equally spaced across the length
- This arrangement of thermocouples allows the measurement of temperature thru the cap in the vertical direction and the measurement of temperature across the cap in the horizontal direction
- The capacitor was mounted in the inverter proud, not in contact with the heat sink

Technical Accomplishment – Dyne Testing (cont'd)

- The heat sink coolant temperature is 75° C with the internal ambient inverter temperature stabilized at 105° C at which time the thermocouples start recording temperatures

Dyne Test Setup

- The inverter profile is set to run at its max continuous rating, creating a capacitor current of 82Arms
- This profile continues until the thermocouples temperatures stabilize
- Motor speed is set to zero and the inverter is turned off while the recording of thermocouple data continues till the thermocouples temperatures stabilize
- The purpose of the testing was to confirm that during the dyne test the Sigma capacitor does not exceed its temperature limits or fail
- **The capacitor was well within it tested thermal limits and no problems were incurred during testing**

Technical Accomplishment – 500µF/600V Volume Comparison

- Sigma's capacitor is 1/3 the volume and weight of an equivalent polypropylene (PP) capacitor

- PP capacitors Cannot exceed 105ºC
- Sigma's capacitors have been tested between -40ºC to 140ºC with results comparable to or better than PP

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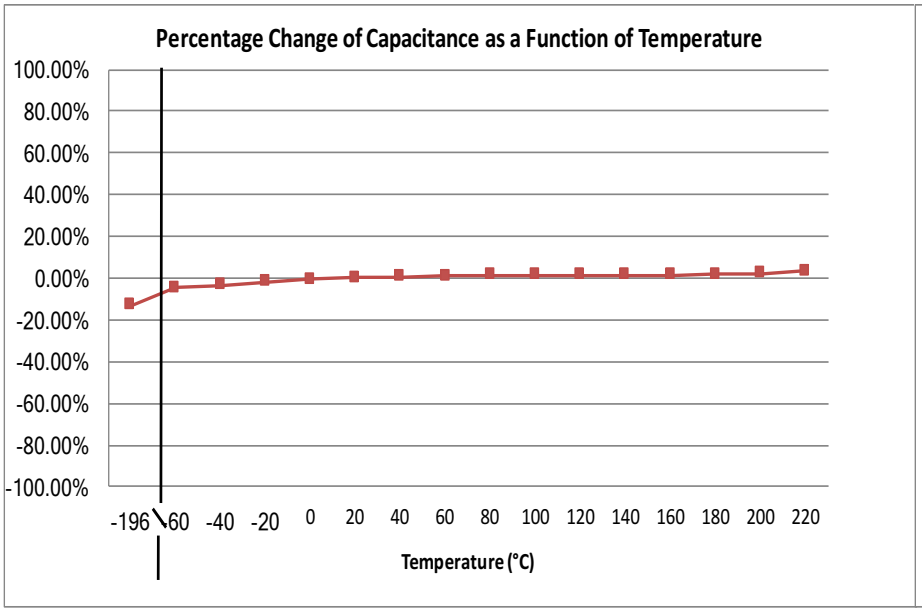
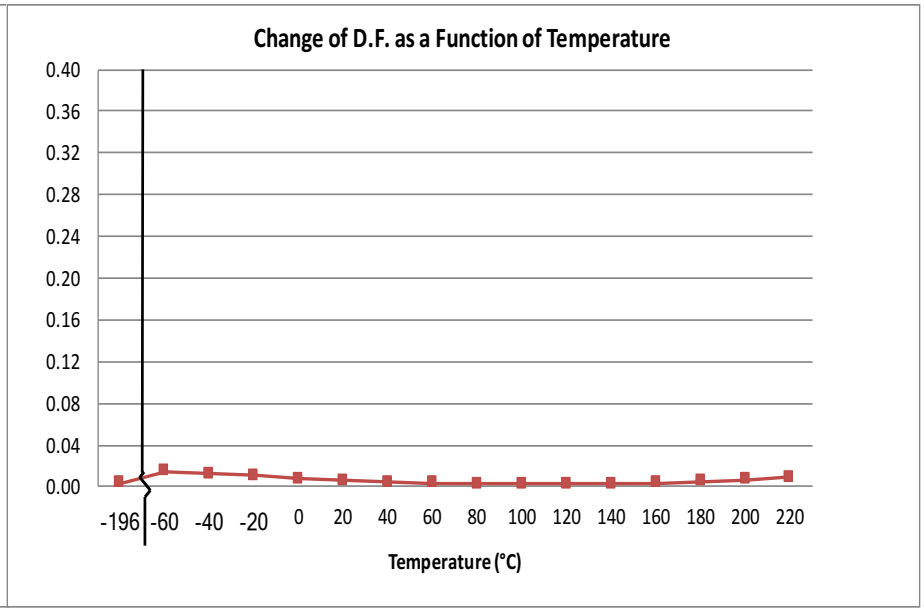
Technical Accomplishment – Stability of the PML Capacitor Dielectric as a Function of Temperature





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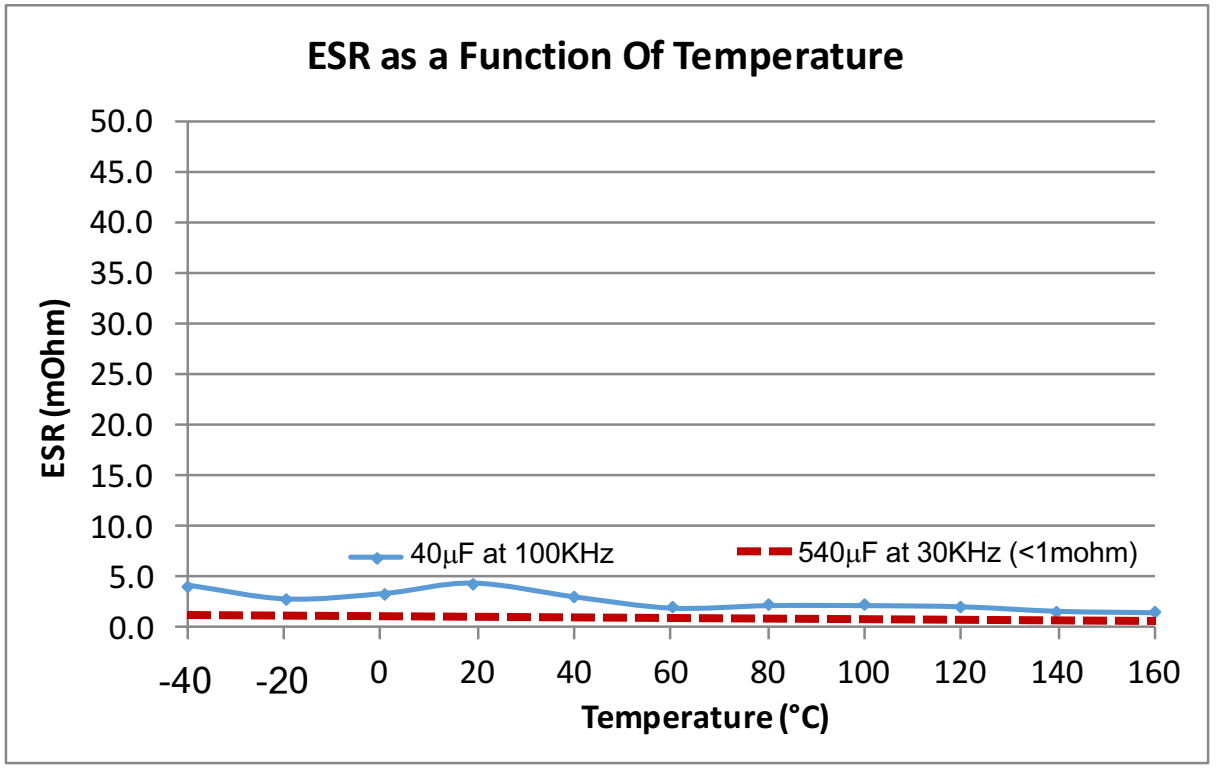
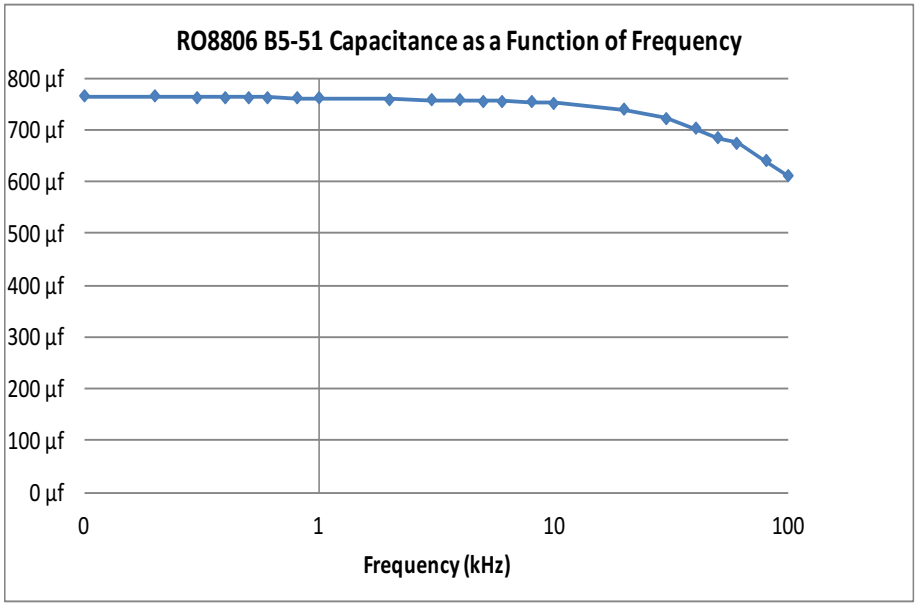
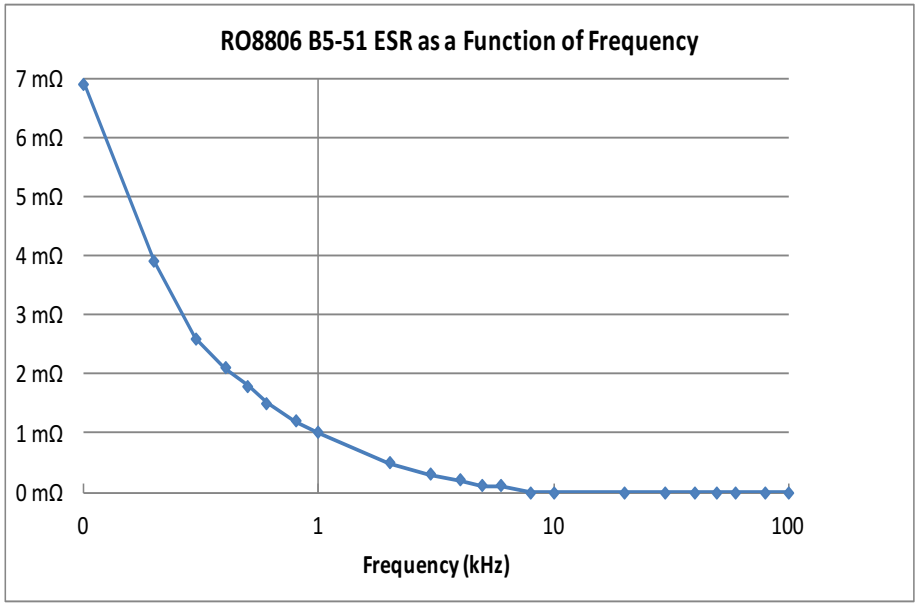
Technical Accomplishment – ESR as a Function of Temperature

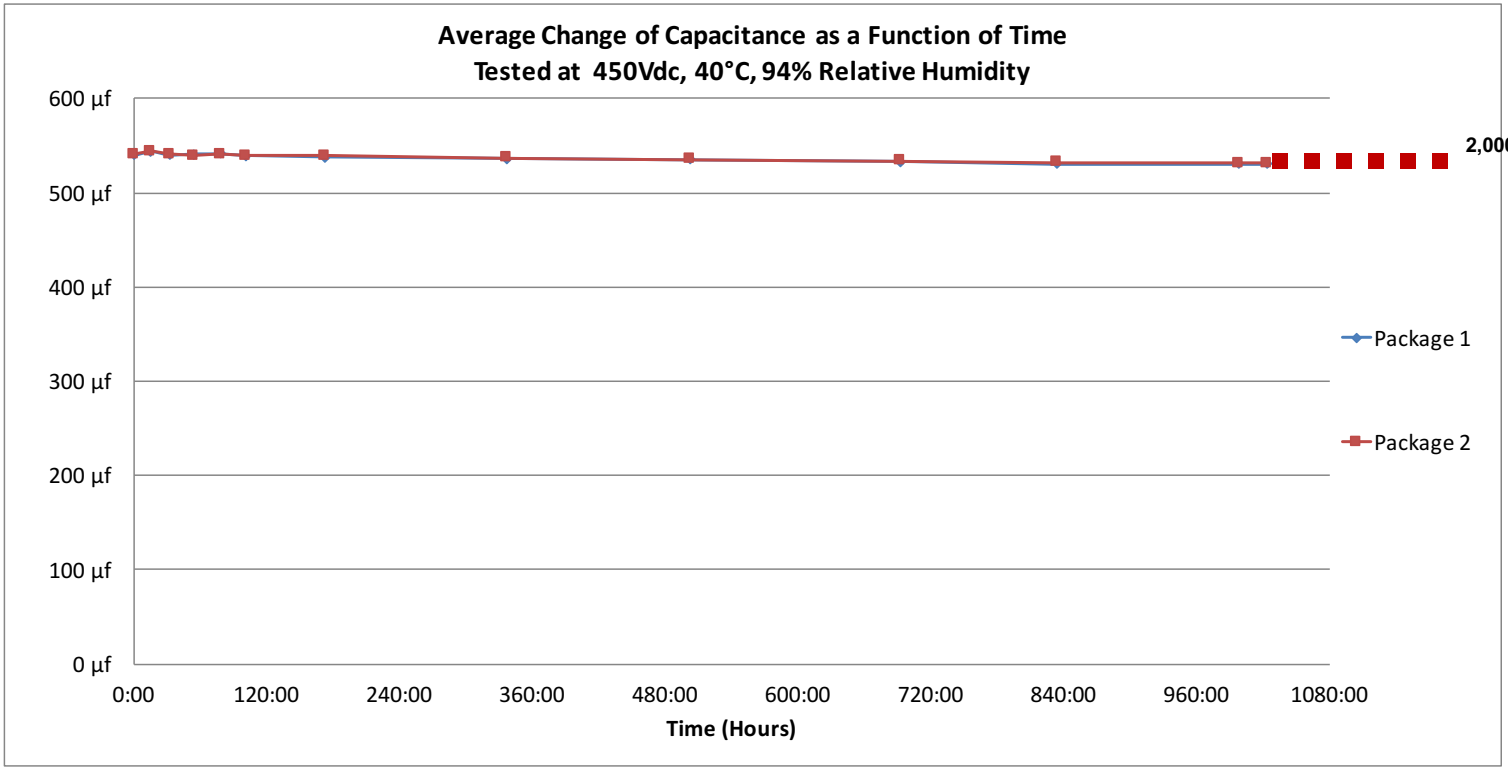


Technical Accomplishment – Capacitance and ESR as a Function of Frequency 770mF/600V Part Tested At Room Temperature





Technical Accomplishment – Life Test of 500mF/600V PML Capacitor Packaged Using An Epoxy Potting Process



Potted in Air – Production Parts Will be Vacuum Potted

Technical Accomplishment – Higher Voltage Parts Ratings

During this development period Sigma demonstrated that PML parts can be produced to service higher voltage with even higher ripple current per microfarad capacity

A number of parts have been produced with a rating of 240μF/700V/900V_{max}, for a Formula-e car inverter

Preliminary data indicates that PML capacitors with a voltage rating >1000V can be produced that can handle high ripple currents to service higher frequency SiC MOSFET based inverter circuits

Technical Accomplishment – Lower Voltage Ratings

Low voltage inverters (12 and 48V) are used in a variety of applications that - include: Electric steering, Start and Stop Systems (compressor, water pump) - Electric turbos wipers, window motors, blower, other -

- Aluminum electrolytic capacitors rated 25V to 63V are used for such applications
- PP capacitors are not available for such low voltages
- PML capacitors can have dielectrics with a thickness as low as 0.1μm, and can address low voltage applications
- When compared to electrolytics, PML Capacitor have
  - Lower ESR
  - Lower ESL
  - Both Lower and Higher Operating Temperatures
  - Higher Resonant frequency
  - Higher Current Carrying Capacity
- A single PML capacitor can replace multiple electrolytics

Low voltage PML capacitor to replace electrolytics in high frequency switching circuits - 18,000 layer part
Resonance = 300KHz
ESR = 1mohm

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Response to reviewers comments

- 2016 review showed only positive comments and no questions from reviewers

Collaboration / Coordination with Other Institutions

- Delphi Automotive Systems, LLC
  - U.S.-based Tier 1 supplier to many U.S. and non-U.S. automotive OEMs
  - Delphi has been actively developing inverters and other power electronics products, including battery energy storage systems, for these OEM customers for over 30 years

- Oak Ridge National Laboratory
  - Power Electronics and Electric Machinery Research Center (PEEMRC) is the U.S. Department of Energy's (DOE) premiere broad-based research center for power electronics and electric machinery development
  - The PEEPSRC facilities include state-of-the-art laboratory equipment, and the engineers are versant in a multitude of component and system level modeling programs

Remaining Challenges and Barriers

Can PML capacitors pass the stringent AEC-Q200 Rev D Test Plan?

Preliminary Tests show that

- PML capacitors have low ESR which will minimize I^2R heating
- Current parts perform well under various thermal cycle tests. Performance will improve when parts are packaged
- Parts perform well on DC voltage, dV/dt and current tests
- Preliminary performance on bias/temp/humidity test suggests that packaged passivated PML capacitors will pass this test

At this stage there is not indication that PML capacitors will fail the qualification test plan used to qualify PP capacitors

Future Work

- Select one or both of the epoxy potting and/or overmolding packaging methods
- Continue to sample potential customers, using the pilot line
- Make further improvements to increase the capacity of the pilot line
- Finalize the design of production equipment and start to place orders
- Continue to contact potential customers and define new market opportunities

Any proposed future work is subject to change based on funding levels

Summary

The project has met and exceeded all DOE target requirements for the development of a new high temperature DC-Link Capacitor

DC-Link Capacitor Characteristic	DOE Target Requirement	PML Capacitor Property
Capacitor Rating	-	400VDC, 600VDC max 700μF, 165A, 295A max
Temperature Range	-40°C to 140°C	-40°C to 140°C
Volume Requirement (liters)	<0.6	<0.3
Direct Cost	<$30	<$20
Failure Mechanism	Safe – Self Healing	Safe – Self Healing
Energy Density	Best Effort	1/3 the Size of State of the Art Metallized PP Capacitors

Publications and Presentations

Publications

None at this time

A new patent has been issued by the US patent office that addresses both the PML capacitor properties as well as the use of PML capacitors for dc-link applications

Presentations

April 2017 – Project Presentation to DOE and Team Members