New Inverter Layout and DC Link Capacitor Integration for Increased System Density and Performance

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IECON 2008 Orlando, FL

Who is SBE?

- Formerly a Division of Sprague Capacitors
- The Barre, Vermont plant has been building film capacitors since 1946
- Polypropylene (PP) Film Capacitors built in Vermont since introduction of the Orange Drop® in 1959
- Recipient of a 2008 DoE SBIR Phase II award
  - High Temperature PP DC Link Capacitor using 105°C Cooling methods

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Statement of the Problem

- Nearly all PHEV, HEV, and EV applications use an inverter to convert DC from the battery/fuel cell to clean AC power for the Electric Motor
- Reliability is a major concern
- Engineering trade-offs
  - power density
  - cost
  - packaging flexibility
  - reliability

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Engineering Trade-Offs Driven by Temperature

- Temperature - Components inside the inverter must be kept within the material limitations for each component to insure good reliability
- This dictates low temperature cooling fluid for most inverters today
  - Typically 50 - 70°C liquid cooling in many applications
  - Air Convection Cooling common in Bus/Heavy Vehicle applications where sufficient surface area is available
- Cooling needs of the inverter are driven by the requirements of the semiconductor switching devices **and** that of the DC Link (Ripple) Capacitor(s).

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Engineering Trade-Offs Driven by Temperature

- Maximum reliable current density of the Inverter dependent on the Temperature Management Strategy
- The designer has four knobs to turn:
  1) coolant temperature
  2) coolant efficiency
  3) sizing of components/selection of material
  4) decrease current
- IT'S ALL ABOUT COMPONENT TEMPERATURE RISE IN THE INTENDED USE

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US Department of Energy's Take on it

"Hybrid Electric Vehicles (HEVs) and plug-in hybrids (PHEVs) require advanced technology in the areas of Energy Storage and **Ripple Current Capacitors**. These technology areas represent some of the most critical barriers to the development and marketing of cost competitive HEVs and PHEVs."

Emphasis added

U.S. Department of Energy, October 2006

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US Department of Energy's Take on it

"Currently, inverter technology used in hybrid electric vehicles uses 70°C coolant that is supplied via a separate cooling loop in the automobile. It is desirable to eliminate the need for an additional cooling loop to reduce cost and complexity in the vehicle."

U.S. Department of Energy, Freedom Car Program
Advanced Technology Solicitation, December 2006

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HEV/PHEV/EV Advanced Systems

- Battery/Fuel Cell Voltages:
  - 325V – 500V (388V typical)
- Ripple Currents of 100 – 250Arms are the typical demands of a 50 – 90kW Electric Traction Motor
- 10 – 15 year reliability
- Smallest size, weight, and cost
- Capacitors are approximately 40% of the volume

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HEV/PHEV/EV Advanced Systems

- Aluminum Electrolytic Capacitors
  - Typical current of 25 – 50Arms per capacitor
  - Require coolant of 50 - 60°C
  - Dense Packaging not possible
  - Long Term Reliability is fragile
  - Heavy
  - Lowest Cost

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HEV/PHEV/EV Advanced Systems

- Typical Film Solution
  - 50 – 75Arms per capacitor in cans or 5 – 10Arms per section
  - Require coolant of 50 - 80°C
  - Denser Packaging possible but still very thermally sensitive
    - Especially in the area of heat transfer efficiency
  - Long Term Reliability well known when operated within limits
  - Higher Component Cost

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Film Capacitor Design Limits

- SBE has performed extensive modeling and testing to prove exactly where the hot spot or hot region is in a film capacitor
- The farthest location from the terminals will have the highest temperature rise
  - Film resistive losses
  - Longest heat path to the “convection medium” (the terminals and end spray).

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An Annular Form Factor Solution

- Shortest distance between electrodes provides for lowest losses (resistive losses)
  - Capacitance and current handling are not reduced
- Shortest distance between electrodes provides the most efficient release of the generated heat
- Polypropylene (PP) film is a terrible thermal conductor

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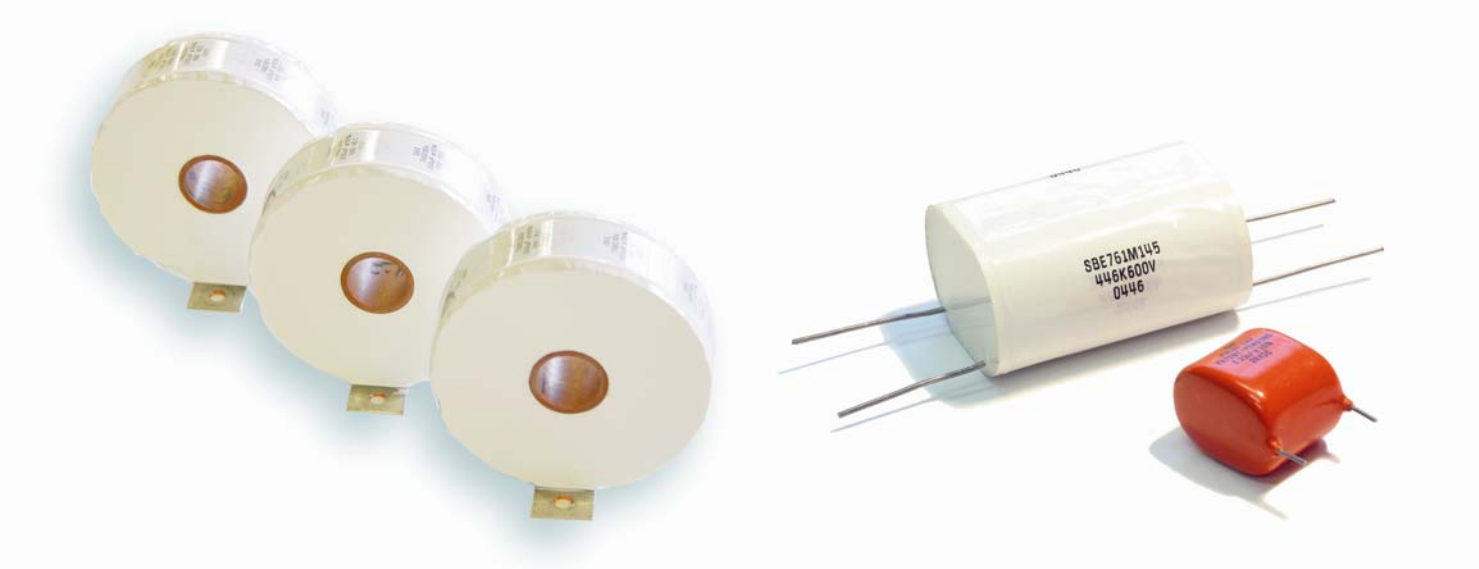
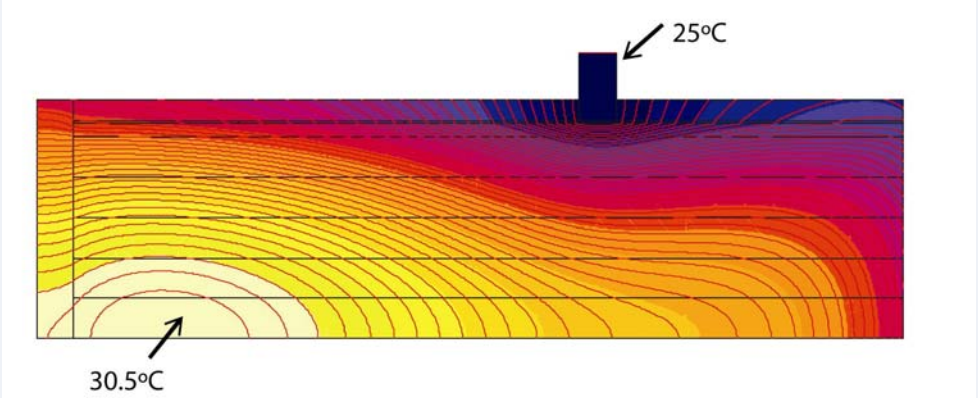
Film Capacitor Limits





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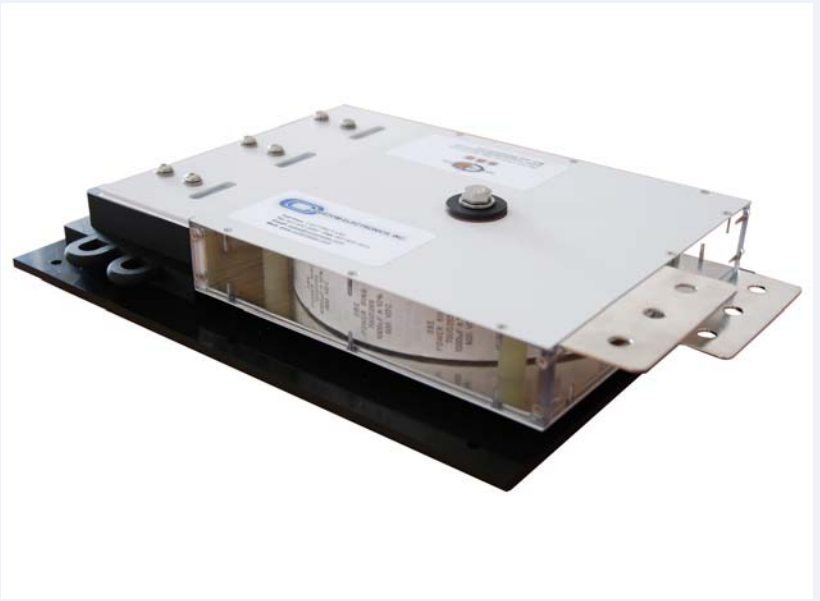
Film Capacitor Limits



Conventional Inverter
vs. Power Ring

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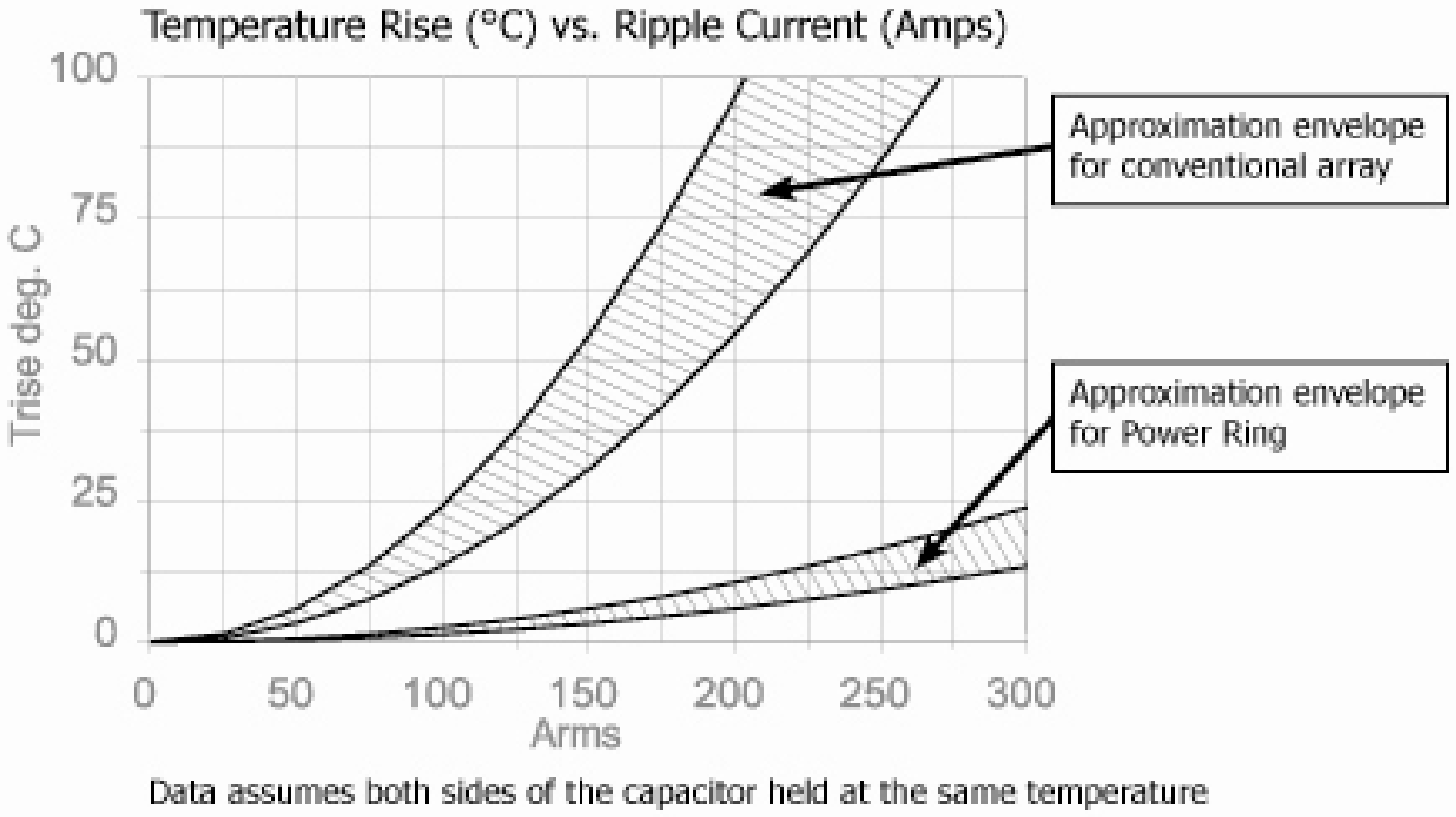
PP Capacitor Limitations



DoE SBIR Phase I Results

- In the DoE SBIR phase I, SBE performed material analysis and characterization on the base PP film material
- The PP Film was found to be stable into the 115 - 120°C region. This implies that 105°C cooling reliable operation is feasible as long as the hot spot temperature rise does not exceed 10 - 15°C.
- The PP Film exhibits voltage breakdown degradation as hot spot temperature increases however is usable to 700V+.
- More data on our website www.sbelectronics.com

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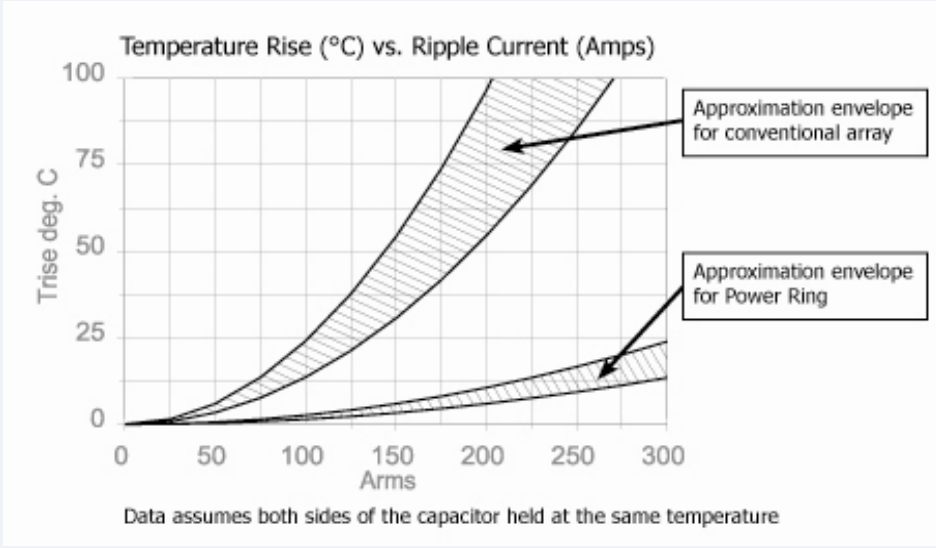
Method 1: Increasing Density of the Inverter

- Traditional Layout, higher performance/power density



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Method 1: Increasing Density of the Inverter

- Unprecedentedly low inductance connection between IGBT switch and DC Link
  - Already demonstrated to eliminate snubber requirements in many applications
- A 50% reduction in volume usage vs. traditional layout
- Cooled via a plate below die and capacitor
  - Allows for 105°C Coolant (DoE grant is funding the answer to the question: “At what current rating for automotive requirements?”)
- Cooled with air convection
  - Capacitor thermal efficiency allows an amount of heat transfer inefficiency

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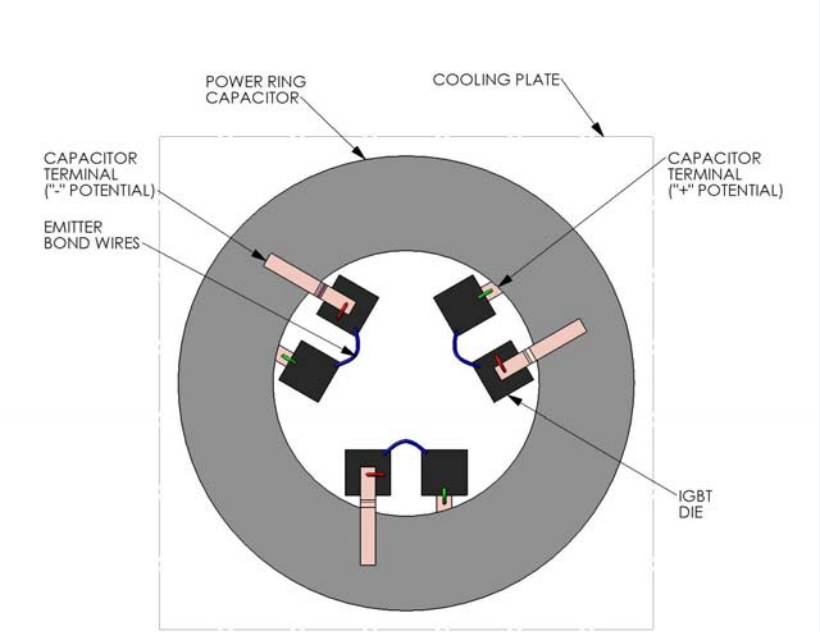
Method 2: Integrate Switch Module Inside the Ring

- The required volume is dictated by $\pi r^2 w$
  - R = radius W = width
- A 50% of radius hole only consumes 30% of the capacitor volume available
  - Typically, 1 inch of additional outside radius accommodates the use of the inner hole for this purpose



PROPOSED INVERTER/CAPACITOR ON COOLING PLATE TOP VIEW

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Method 3: Distribute Switch Modules around the Ring

- Uses conventional switch modules
- Efficient use of space
- Uniform distribution of current load

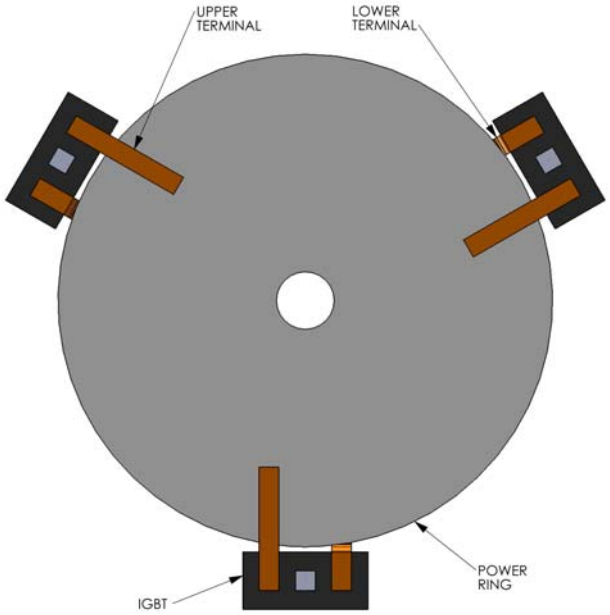
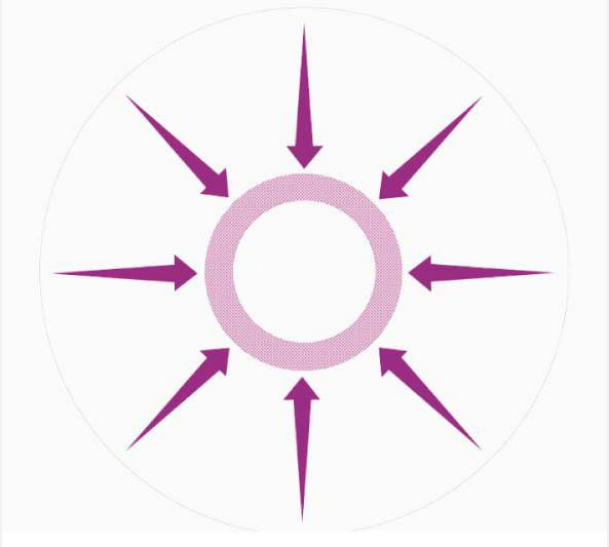


FIG 3-1

TOP-VIEW

Uniform Distribution of Current

- Uniform current insures that the “hot spot” will be the lowest absolute number for the capacitor
- That ultimate number will dictate reliability and “current rating” of the inverter
- Non-uniform connections result in hotter sections of the capacitors grouped in the area of the connections



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Thank You

SBE is seeking industry partners to take the integrated switch module/DC Link inverter to market.

Some DoE funding may be available.

For more information on any of these topics, please contact Ed Sawyer at EdSawyer@sbelectronics.com

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