Capacitor Technologies: A Comparison of Competing Options

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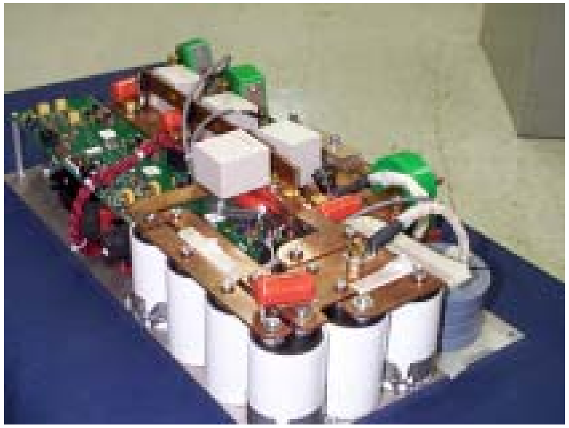

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The Optimum Capacitor for an Inverter is Application Dependent

- Different Inverter Applications
- Description of Different Capacitor Technologies
- Trade-offs of Capacitor Technologies
- Capacitor – Inverter Pairs

Types of Inverters and Prioritized Needs

Photovoltaic Inverters:

1kW to 10 kW residential

100kW to 300 kW commercial

Needs: reliability, cost, size, temperature

Vehicle Inverters:

50 kW to 150 kW;

Needs: temperature, size, cost, reliability (fail safe)

Utility Inverters:

10 kW to 500 kW (now)

2 MW to 20 MW (future)

Needs: reliability, cost, temperature, size

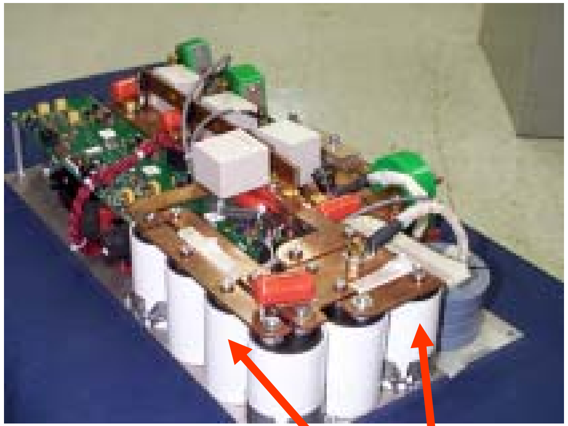
Reduction of DC bus Capacitor Size – Big Impact for Power Electronic Modules

<u>Goal:</u> Develop an improved capacitor technology for power electronic systems in next generation hybrid electric vehicles

<u>Capacitors in power electronic modules:</u>

DC bus capacitors:	0.3 - 1 mF
snubber capacitors:	0.1-1.0 μF
filter capacitors:	1-10 μF

ORNL 150 kW Inverter



Al Electrolytic Capacitors

Big Payoff: A technology for DC bus capacitors

- replace Al electrolytics
- tech advance applicable to snubber/filter caps

Electrolytic capacitors cannot meet the 110°C requirement for DC Bus Capacitors for 2004 Electric Hybrid Vehicles:

- **Al electrolytics - T_{max} ~ 70°C**
- **Ta electrolytics - V_{max}~125V, high loss at elevated temperatures**

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Different Capacitor Technologies:

Greatest Impact: DC Bus Capacitors: Largest Reliability concern

- Electrolytic Capacitors: Al and Ta
  - Temperature limitations, reliability
- Polymer Film Capacitors
- Multilayer Ceramic Capacitors
- Ultra capacitors or supercapacitors
- Solid Tantalum Capacitors
  - Low voltage, good ESR, expensive
- Ceramic Thin Film Capacitors
  - Not highly commercialized yet
  - Motorola mobile phones
  - 20 J/cm^3!!

Prius Inverter Polymer Film Capacitors

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Strengths of High Voltage Capacitor Families

- Reliability:
  - Multilayer Ceramic (temperature);
  - Polymer film multilayer (soft breakdown behavior)
- Size:
  - Electrolytics
  - Ceramic capacitors
  - Polymer film
- Cost
  - Electrolytic
  - Polymer film (3X less than ceramic)
  - Multilayer ceramic

DOE/EE Tech Team DC BUS CAPACITOR SPECIFICATIONS

Property	Now	2010 Tech Team Requirements
• CAPACITANCE	240 µF +/-10%	2000 µF+/-10%
• VOLTAGE RATING	525 VDC	600 VDC
• TRANSIENT VOLTAGE	600 V PEAK 50ms	700 V Peak for 50 ms
• LEAKAGE CURRENT		1 mA at rated voltage
• DISSIPATION FACTOR	<2%	<1%
• ESR, ESL	<3 milliohms	< 3 mohms, <20 nH
• RIPPLE CURRENT	90 Amps RMS	250 Amps RMS
• **TEMPERATURE**	**-40°C to +85°C**	**-40°C to 140°C**
• **SIZE; WEIGHT**	170cc **(1.4 µF/cm³)**	**400 cc (5 µF/cm³), 10.8 kg; 27 g/cm³**
		Semikron 1500 µF/1687cm³ = 0.9 µF/cm³
• **COST**		**$30**
• FAILURE MODE	Benign	Benign
• Life @80% rated Voltage		>10,000 hr, 200 A rms, +85°C

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Capacitor Ripple Current / Temperature Capacity

Ripple current is a function of temperature

Capacitor Type	Capacitance (F) Tolerance(%)	Rated Voltage (Volts DC)	Energy Density (J/m^3)	Ripple Current (A rms)	Temperature Range (°C)
Wound Polymer	230 ± 10%	500	8.01×10^4	48 (25°C) 20.7 (75°C)	-55 to +85
Multilayer Ceramic	225 ± 10% (5 @ 45μF)	500	1.40×10^5	87.91* (25°C) 120 (105°C)	-55 to +125
Electrolytic Alumina	220	450	2.66×10^5	2.7 (+85°C)	-40 to +105

Courtesy of S. Cygan, AVX
And M. Lanagan, PSU

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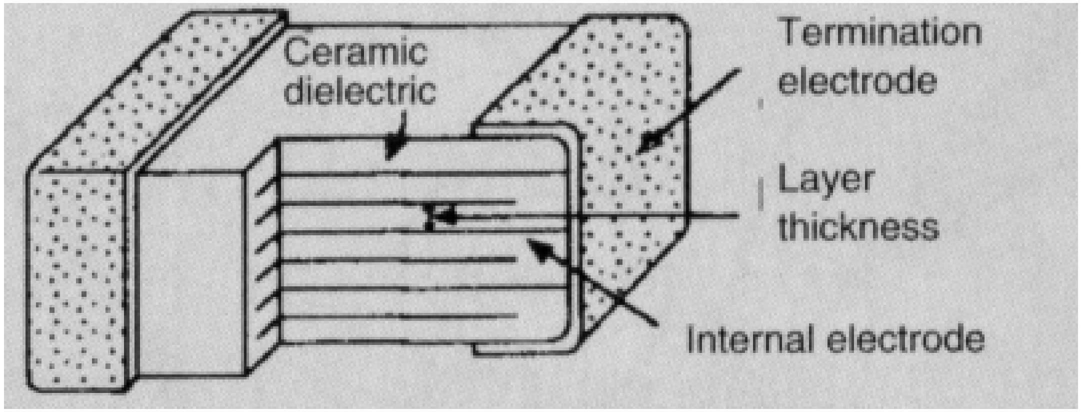
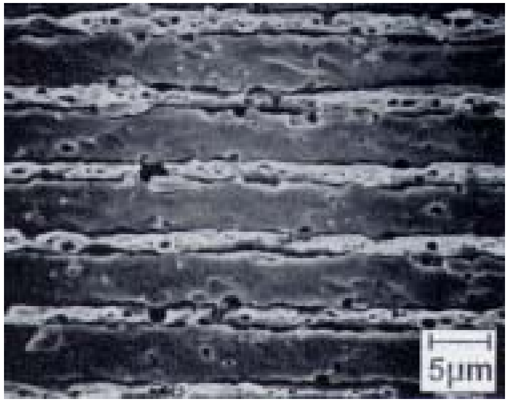
Multilayer Ceramic Capacitors

MLCCs





Fabrication: Tape cast layers w/ screen printed electrodes

Large value (> 0.1 mF), high voltage capacitors are available commercially on a limited basis

Costly: ~$100/capacitor (1 mF)

Reliability in Inverter environments needs more evaluation

Technical Challenges - multilayer ceramic capacitors

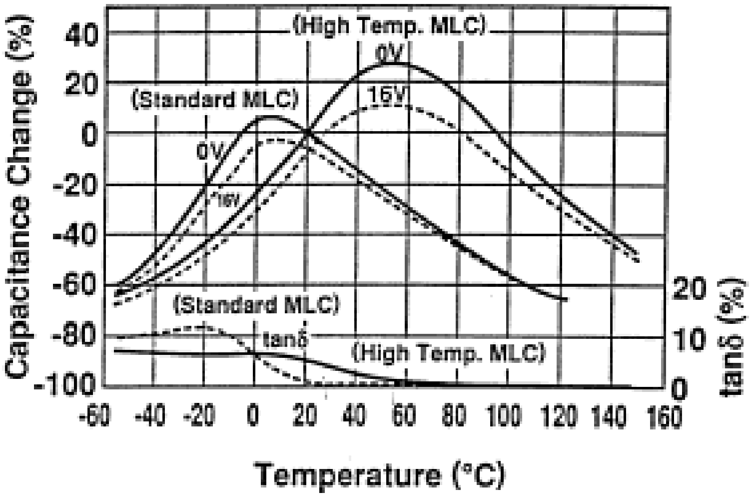
- To minimize cost, dielectrics must be compatible with base metal electrodes (e.g., Cu, Ni) or low Pd content Ag/Pd electrodes:

  low T processing

  resistance to reduction (base metal) ⇒ controlled doping
- Relatively thick dielectric layers:

  ~100 kV/cm operation ⇒ t~30-60 μm (cost - # layers)
- Minimize temperature coefficient of capacitance (TCC)

  X7R: <±15% variation from -55° to 125°C



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Polymer capacitors - a lower cost, lower performance alternative to MLCCs

Materials:

- PPS (polyphenylene sulfide) ε~3
- PET (polyester) ε~3.2
- Polyimide ε~3.5
- Teflon ε~ 2.0

Toyota Prius Capacitor Bank

Dielectric Strength (typical): 2.5-3 MV/cm

Dielectric loss (typical): < 0.3%

Insulation resistance (typical): > 10^{13} Ω/cm

Problems:

- Degradation at elevated temperatures (125°-150°C max)
- Commercial capacitors small values (~ 1μF)
  1mF, 4"x4"area ~ 5000 layers

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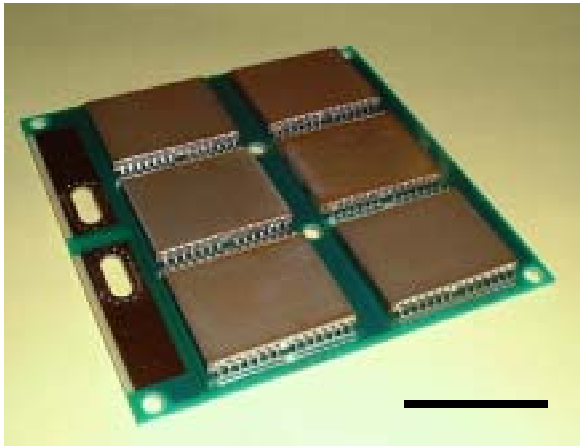
Monolithic Multilayer Ceramic Capacitors Have Reduced Size Compared to Polymer Caps

Prius Inverter:
Panasonic Polymer Film Capacitor
600 volt rating:
138 μF in 163 cm^3 = 0.85 μF/cm^3

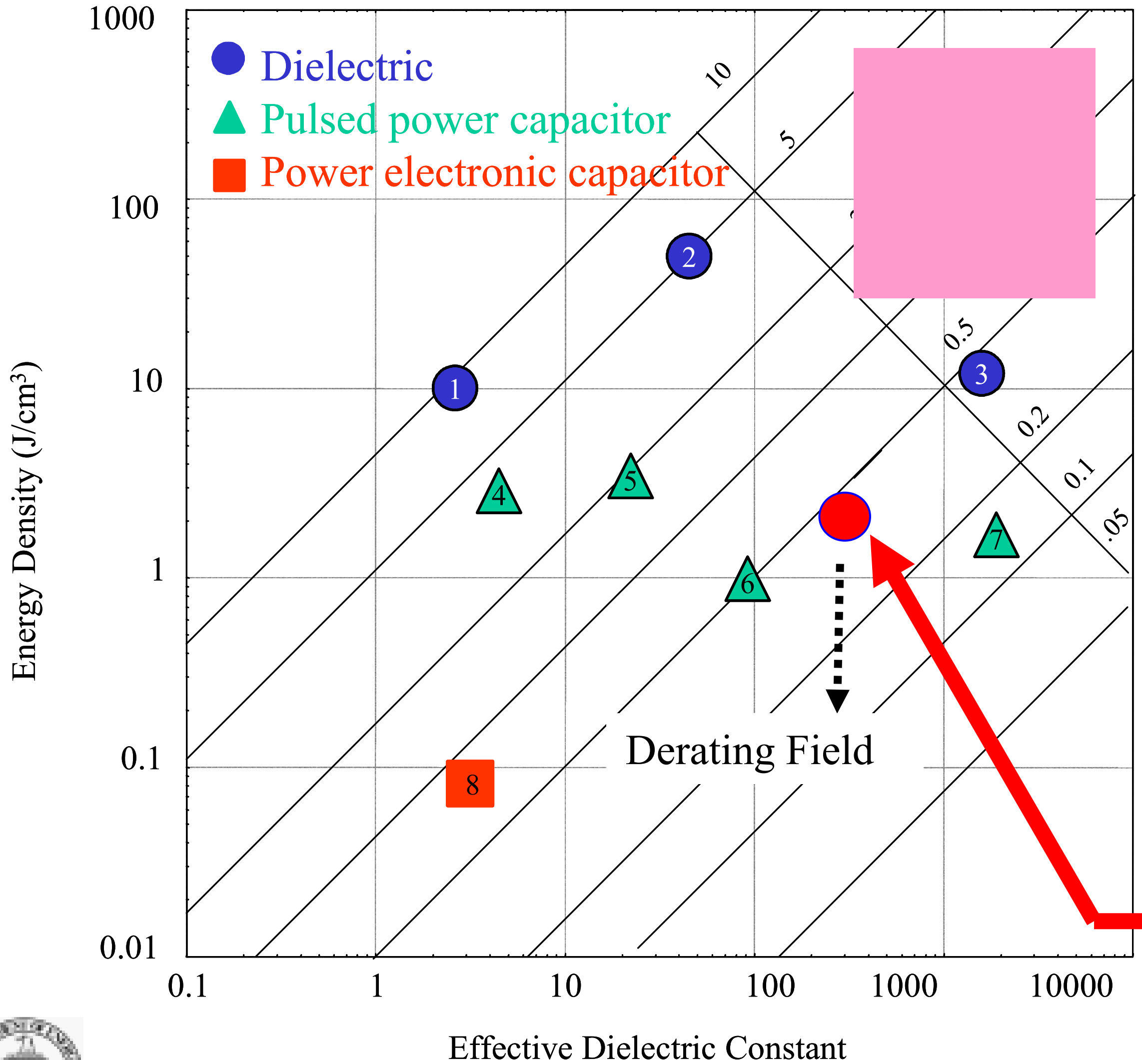
Murata multilayer ceramic capacitor
500 μF in 15.6 in^3 = 255 cm^3
2 μF/cm^3 ; 5 μF/cm^3 is achievable



5 inches

Murata 700 volt, 60 μF MLC BME capacitor

Energy Density Comparison for Dielectric Materials and Capacitors



1) Biaxially oriented polypropylene
2) Niobium oxide thin film
3) Antiferroelectric/ ferroelectric
4) Polypropylene film capacitor
5) PVDF film capacitor
6) Titania ceramic capacitor
7) Antiferroelectric/ ferroelectric phase switch capacitor
8) Commercial polymer film capacitor
9) Commercial multilayer ceramic capacitor

This Study

Further improvement Anticipated!

M. Lanagan, PSU

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High Volume Production Necessary to Reduce Capacitor Cost

Class 1000 Clean Room Conditions

60” roll widths

115 ft. Thermal Chambers

Superior air flow - temperature control more uniform thickness Fewer defects

30 to 60 ft. per minute

two 200 µF capacitors each minute (K=4.5, t=3µm)

Brady Corporation, Milwaukee, WI

In-situ video monitored Krypton Thickness monitors - real time feedback

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Summary

- Optimum Capacitor for Inverter is Application Specific
- For large capacitors: electrolytic, multilayer polymer and multilayer ceramic appear to be the best commercially available technologies
- Electrolytic capacitors superior in cost, while ceramic capacitors superior with regard to high temperature and reliability
- Polymer film capacitors are an intermediate cost, intermediate reliability, soft breakdown alternative

Electric Hybrid Vehicle

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