Capacitor Technology for High Density and High Temperature Power Systems Used in EV, HEV and PHEV Automotive Applications

John Prymak – KEMET Electronics
Ian Clelland – Paktron
Laird Macomber – Cornell Dubilier
Overview on the application of the “Double Bank Capacitor”
Function:
To support a DC network by supplying periodically high currents (High Power Decoupling)

General Requirements:
- Life Expectancy: >10 years (20k hours in operation)
- ESR: low
- Ripple Current: High capability

Proposed Capacitor Technologies:
- Film
- Aluminium Electrolytic
Automotive EV, HEV Drive

DC-link

Capacitor Functions:
a) enable quick energy transfer into IGBT circuit
b) smooth out DC-bus voltage variation
c) prevent ripple from interfering back to DC power source

DC-link (Film)
- Voltage capability requires no cascading
- Self-healing optimized with necked-down electrode patterns
- Self-healing maximized with polypropylene (PP)
- Higher cost solution

DC-link (Electrolytic)
- Requires cascading for high voltage (multiples of 2x to 9x for capacitance)
- Low temperature greatly reduces cap
- Dry-out over time results in lower cap, higher ESR, greater heat – eventually to short
- Lower cost solution
## Design Conditions of DC-Link Capacitor for 3 phase AC Motor Drive

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Output V</td>
<td>690Vac</td>
</tr>
<tr>
<td>DC-Link Voltage</td>
<td>1,000Vdc</td>
</tr>
<tr>
<td>Max Ripple Voltage allowed</td>
<td>100V</td>
</tr>
<tr>
<td>Frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Min Capacitance</td>
<td>500μF</td>
</tr>
<tr>
<td>Ripple Current</td>
<td>30A</td>
</tr>
<tr>
<td>DC-Link Frequency</td>
<td>300Hz</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>75°C</td>
</tr>
</tbody>
</table>
Comparison of Film and Electrolytic Technologies

**ELECTROLYTIC CAP**

- 30A
- 10A
- 10A
- 10A

Total Volume 2.94

- 1050 Vdc
- 1500 µF
- 9x1500 µF @ 350 Vdc
- 3 times Capacitance Project

**FILM CAP**

- 30A
- 15A
- 15A

Total Volume 1.59

- 1100 Vdc
- 500 µF
- 2x250 µF @ 1100 Vdc
- (stable over years)
## Dominant Film Types

<table>
<thead>
<tr>
<th>Film</th>
<th>Code</th>
<th>Best Tol. (±%)</th>
<th>(C/Cn-1) -25°C to 85°C</th>
<th>Aging (%/yr)</th>
<th>DF (Typ)</th>
<th>Max. Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>polypropylene</td>
<td>PP</td>
<td>1</td>
<td>-3%</td>
<td>0.2</td>
<td>0.05%</td>
<td>120</td>
</tr>
<tr>
<td>polyethylene napthalate</td>
<td>PEN</td>
<td>5</td>
<td>5%</td>
<td>0.4</td>
<td>0.48%</td>
<td>155</td>
</tr>
<tr>
<td>polyethylene terapthalate</td>
<td>PET</td>
<td>5</td>
<td>5%</td>
<td>0.4</td>
<td>0.50%</td>
<td>140</td>
</tr>
<tr>
<td>polyethylene sulfide</td>
<td>PPS</td>
<td>2</td>
<td>±0.5%</td>
<td>0.3</td>
<td>0.20%</td>
<td>260</td>
</tr>
</tbody>
</table>

*Clelland, I., ITW Paktron and Laird Macomber, Cornell-Dublier; iNEMI 2006 Report - Passives*
Comparison between different materials:

<table>
<thead>
<tr>
<th>FILM</th>
<th>C</th>
<th>H</th>
<th>O</th>
<th>S</th>
<th>C/(H+O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPS</td>
<td>6</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>1.50</td>
</tr>
<tr>
<td>PEN</td>
<td>14</td>
<td>10</td>
<td>4</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>PET</td>
<td>10</td>
<td>8</td>
<td>4</td>
<td>0</td>
<td>0.83</td>
</tr>
<tr>
<td>PP</td>
<td>3</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0.50</td>
</tr>
</tbody>
</table>

The graph shows what follows:
- the worst material is PPS;
- the best material is PP;
- PET is slightly better than PEN.
Essential questions for a DC Link capacitor are:
- What is the Capacitance and Voltage profile
- What is the AC Spectrum Frequency and Ripple Current
- What is the Ambient Temperature and possible Cooling
- What is the Inductance needed
- What are the Mechanical Stresses / Vibration and Shock
- What is the Mechanical Shape/Dimensions/Connections
- Is self-healing required? (Fail-open versus Fail-short)

Hybrid Vehicles’ Internal Combustion Engine requires in general higher temperature capacitors than Full Electric vehicles
FILM Dielectric Technologies: PET, PEN, PPS, and PP

wound elements

- Film width up to 60mm
- Simple or series construction
- High Cap
- Max. voltage 2000Vdc
- DC-Link PET < 300V or PP

Stacked elements

- Film width up to 45mm
- Simple or series construction
- Typical x 100uF blocks
- Max. voltage 500Vdc
- DC-Link PET <300V or PP
DC-Link Film Capacitors: Automotive High ripple & Cap & Temp Modules

- **“Soft-winding Brick Thin Film”**
  - Dielectric: metalized polypropylene (PP) film, thickness < 3.5μm
  - Winding: non-inductive type with flattened oval shape
  - Case: plastic or metal material
  - Terminals: high current screw or tinned copper bus-bar

- **“Stacked” – Brick**
  - Dielectric: metalized polypropylene PP and polyethylene teraphthalate PET
  - Winding: non-inductive type with several stacked cut elements
  - Case: plastic or metal material
  - Terminals: high current screw or tinned copper bus-bar
Automotive DC-Link Capacitors
Heat Dissipators, Soft Winding

DC-Link Capacitor for Hybrid Vehicle

AMBIENT = 125°C
CAPACITOR
COOLING = 70°C
Advances in Film Capacitors
- Ripple Current and Thermal Stability

Self-heating and Thermal Stability
C=2000 μF; Un=750Vdc; Irms=90A; Freq=10KHz
for Automotive Application

Temperature (°C)

Temperature (°C)

Hours

Thermal Stability Test @ In=300Arms; Ta= 70°C
Brick Type (Soft-winding Technology for high energy)
Cn= 2400 μF  Un= 900 Vdc
Film Capacitors: Working Life Time

- Film Advantages:
  - High rated voltages (no need of series connections and balancing resistors)
  - Stability vs. time of Capacitance and ESR
  - Long life
  - Low dissipation / high ripple current
  - Low losses and high efficiency

- Long life contributing factors:
  - new metallization configuration of the film,
  - plastic or metallic housing, sealed by epoxy or polyurethane resins,
  - new production process for the thermal treatment.

- Working life time at rated voltage using these technologies:
  - “Soft-winding for thin film in Brick” for Automotive applications:
    20,000 hours at 90°C ambient temperature.
General Construction

Typical rated voltages:
- 600-700 Vdc automotive, (welders)
- 900 Vdc solar converters
- 1100 Vdc wind converters
- 1300 Vdc wind converters

Typologies:
- Mainly dictated by the layout and the mechanical needs:
  - Individual or Box types for PCB mounting
    - Most adaptable, least expensive
  - Aluminum Can types for modular configurations (cable and bus bar)
    - Cheaper than brick if less than 2000 µF required
    - Less efficient in terms of dimensional occupation / flexibility of form factor
  - Custom Brick for the best dimensional efficiency (cap density/volume)
    - Can work at higher power / temperatures due to the special soft winding capacitive elements used that optimize the thermal dissipation
**General Construction**

**Typologies:**
Snap-In types for low power drives/inverters/(UPS, )

**PCB mounting**
- ALC10, ALC40 (European manufacture)
- PEH506, PEH536 (Chinese manufacture)

**Screw Terminal** for medium to high power drives/inverters/(UPS)
- ALS30/31, ALS40/41, PEH200, PEH169 (European manufacture)
- ALS32/33, ALS42/43 (Chinese manufacture)

All electrolytic capacitors manufactured using extended cathode construction for enhanced thermal dissipation.
KEMET DC Link Capacitors
Custom Brick Design Examples

500μF-450VDC

850μF-450VDC

1000μF-600VDC

1000μF-450VDC
DC Link Capacitor
Commercial Solutions – CD Electrolytic

**General Construction**

Typologies:
- Snap-In types for low power drives/inverters/(UPS, )
- PCB mounting
- Screw Terminal for medium to high power drives/inverters/(UPS)

All electrolytic capacitors manufactured using extended cathode construction for enhanced thermal dissipation.
HEV Inverter Power Film Capacitor
Cornell Dubilier
Paktron 500-volt Technology
For On-Board Converters

Parameter                     0.47µF   1.00µF   0.50µF
Capacitance Tolerance         ± 10%    ± 10%    ± 10%
Dissipation Factor            ≤1.0%    ≤1.0%    ≤1.0%
Insulation Resistance (MΩ)    >1000    >1000    >1000
Temperature Range (°C)        -55 to 125 -55 to 125 -55 to 125
ESR @ 500 kHz (Ω)             0.011    0.008    0.100
Irms @ 500 kHz (A)            6.2      9.5      5.8
Max dV/dt (V/µs)              120      120      120

Multilayer Polymer Film (MLP)
Stable under DC voltage
Stable under AC voltage
Chip is plastic with good TCE
Stable over temperature
No aging mechanism
Resilient under thermal shock
Self-clearing thin electrodes
Stable under mechanical stress
Low Cost
Ultra Low ESR
Dissipation Factor ≤ 1%
High dV/dt
SMD and Thru-hole Mounting
Flame Retardant Enclosures
Detailed
LIGHTING/AUTOMOTIVE
HID – Xenon Technology
H.I.D. = High Intensity Discharge Lamps

Benefits:
- 3 x brighter
- 3 x longer life  ~ 6000 hours
- 2 x as efficient  ~ 35W

Process:
- Initial ionized Xenon gas in the bulb changes energy states.
- After initial ionization, the light-emitting arc is sustained by 90VAC
- The resulting arc emits high intensity light
HID – Xenon
Two-Stage Electrical System

**Ballast**

**DC-DC Step-up converter:**
boosts the battery voltage to the ignition voltage.

**DC-AC full bridge inverter:**
converts DC to a low frequency square wave.

**Ignitor**

Two Inverter operating modes:

i) voltage-source mode prior to ignition
ii) current-source mode after ignition during steady state operation.
C1: Ballast filter capacitor Function
filters the 100kHz current pulses from the flyback inverter

C2: Ballast boost capacitor energy preheats the lamp electrodes and enables the glow to arc transition of the HID lamp.

- Max working temperature: 135°C → high temperature rating
- High switching frequency 100 kHz → low DF
- Severe vibration characteristics → robust design

C3 Ignitor Capacitor Function:
The ignition transformer, the ignitor capacitor and spark gap generate a high voltage pulse to ignite the lamp.

- Max working temperature: 150°C → 170°C hotspot temperature
- Max dv/dt :6000 V/μs → 300 to 600A peak currents
- Severe vibration characteristics → robust design
- fit in the integrated ignitor assembly → small dimensions
C1 Ballast Filter Capacitor PEN: SWN / GMW
Capacitance range: 0.33μF to 0.56μF
Rated voltage: 400 Vdc

C2 Ballast Boost Capacitor:
Capacitance range: 1μF to 1.5μF
Rated voltage: 250 Vdc

C3 Ignitor Capacitor PEN: HNS Series
Capacitance range: 70nF to 120nF
Rated voltage: 1000 Vdc
## Paktron Technology For Lighting

<table>
<thead>
<tr>
<th>Part</th>
<th>Lead Spacing (in.)</th>
<th>Dimensions (TxHxW) (in.)</th>
<th>Temperature Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.00 µF @ 100 Vdc</td>
<td>0.400</td>
<td>0.200x0.380x0.394</td>
<td>–55 to 85</td>
</tr>
<tr>
<td>10.00 µF @ 100 Vdc</td>
<td>0.400</td>
<td>0.250x0.995x0.500</td>
<td>–55 to 85</td>
</tr>
<tr>
<td>1.00 µF @ 250 Vdc</td>
<td>0.600</td>
<td>0.300x0.440x0.700</td>
<td>–55 to 85</td>
</tr>
<tr>
<td>0.47 µF @ 500 Vdc</td>
<td>0.600</td>
<td>0.320x0.625x0.700</td>
<td>–55 to 125</td>
</tr>
<tr>
<td>1.00 µF @ 500 Vdc</td>
<td>0.600</td>
<td>0.320x1.135x0.700</td>
<td>–55 to 125</td>
</tr>
<tr>
<td>0.50 µF @ 500 Vdc</td>
<td>0.600</td>
<td>0.280x0.540x0.650</td>
<td>–55 to 125</td>
</tr>
</tbody>
</table>
MLCC Lighting Application: Customer Requirement Example

- 500nF @ 430v and 150°C
- 3 positions currently available with 1812 pad sizes
- 4000 hour life time required at these conditions
- Customer considering Aluminum substrate

Current Status:
- Supplied 1812 330nF 500V rated prototypes
- TCVC @ 330nF 430V and 150°C loses 80% of cap = 66nF X 3 positions = 198nF

Based on these design constraints we recommend (see next slide)…
MLCC Lighting Application: KEMET Solution Alternatives

• Option 1
  • Use 3 KEMET KPS 2x1812 330nF J lead stacks with current pad layout
  • Total cap 396nF at required conditions lower than 500nF but may be enough

• Option 2
  • Use 3 KEMET KPS 2x2220 470nF J lead stacks but with larger pad layout for 2220
  • Total cap 564nF at required conditions meeting the 500nF requirement
Thank You