Loss Modeling of Ceramic Capacitors Under High DC Bias Voltage and AC Current Ripple in High Density Power Converters

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March 16th, 2019
PSMA/PELS Capacitor Workshop
Acknowledgment
Outline

- Introduction and Motivation
  - Why capacitors as energy transfer element?
  - The need for better loss models under realistic conditions
- Loss measurements
  - Calorimetric based MLCC characterization.
- Results and modeling of MLCC.
- Next steps and conclusion.
Why Capacitors?

Survey of Inductors and Capacitor Energy Density


Comparison showing \(~1.5\text{mJ}\) of energy storage in a capacitor versus an inductor. (Picture to relative size)
Example using capacitors for energy transfer

First stage

Second stage

Input voltage range 36 – 60 V
Conversion ratio 4 : 1
Output current 60 A
Power density 2500 W/in³
Peak efficiency 99 %

Z. Ye, Y. Lei, R.C.N. Pilawa-Podgurski, “A 48-to-12 V Cascaded Resonant Switched-Capacitor Converter for Data Centers with 99% Peak Efficiency and 2500 W/in³ Power Density”, APEC 2019 (Tuesday Session, T01)
Comparison with the state-of-the-art


Motivation

- Power losses can be reduced to an equivalent series resistance (ESR).
- These losses are dependent on a number of operating conditions.
  - Temperature, frequency, AC amplitude, DC bias, excitation shape/harmonics
- Most data sheets only detail losses under small signal, no bias sinusoidal excitations.
Motivation

- Operating conditions which effect ESR
  - Temperature
  - Frequency
  - AC amplitude
  - DC bias
  - Excitation shape/harmonics
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Motivation for Calorimetric Measurements

- Desired measurement specifications
  - Current: 6 A RMS
  - Voltage: 400 V ($\Delta v = 10$ V)
  - Transferred Power: 2.4 kW
  - Power loss: ~1 W
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- Electrical Measurement Accuracy
  - 500 kHz: $\pm 10.2$ W

Yokogawa WT3000
Capacitor operating conditions

- High Harmonic Excitation
- Hundreds of kHz Frequency
- Large AC Excitation
- DC Voltage Bias
Electrical Test Configuration

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Electrical Test Configuration
Rise in temperature of oil is measured to determine power dissipated by device under test (DUT).

\[ P_{\text{diss}} = \frac{1}{T_{\text{final}}} \left( k_{\text{oil}} \Delta \text{temp} + \int_{0}^{T_{\text{final}}} \frac{\text{temp}_{\text{oil}} - \text{temp}_{\text{amb}}}{R} \, dt \right) \]

Calorimetric Calibration Testing

- Resistive testing is used to determine thermal resistivity of set-up, $R_{TH}$.
- A precision resistor is used to determine accurate power loss.

![Graph showing change in temperature over time](image-url)
DC Bias Analysis \[1\]

- Measured ESR increases with applied DC bias.
- Relationship is linear allowing for interpolation of operating conditions to approximated losses.

![Graph showing TDK X6S Voltage Bias Effect on Losses with 6 A RMS Excitation](image)

- Estimated accuracy of measurement is ±0.117 mΩ.
- Results at 0V bias are slightly higher than datasheet values due to high harmonic components[1]

DC Bias Analysis

- Measured ESR increases with applied DC bias.
- Relationship is linear allowing for interpolation of operating conditions to approximated losses.
Effect of Current Amplitude on Losses

- Measured ESR increases with varying AC amplitude.
- Relative to DC bias dependent loss the AC amplitude has little effect on ESR.
The AC current impact was tested on capacitors with different dielectrics as well as manufacturers.
With varying current amplitude the DC bias still shows dominant effect on ESR.
# Application of Results

<table>
<thead>
<tr>
<th>Capacitor Manufacturer</th>
<th>Capacitor Type</th>
<th>Capacitor De-rating (at 400 V)</th>
<th>ESR increase (at 400 V, 125 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDK</td>
<td>X6S</td>
<td>80%</td>
<td>200%</td>
</tr>
<tr>
<td>Knowles</td>
<td>X7R</td>
<td>82%</td>
<td>243%</td>
</tr>
<tr>
<td>Kemet</td>
<td>X7R</td>
<td>72%</td>
<td>142%</td>
</tr>
</tbody>
</table>
Conclusions

- Capacitor losses depend on:
  - Temperature
  - Frequency
  - AC amplitude
  - DC bias
  - Excitation shape/harmonics

- DC bias in particular can greatly affect the ESR, which must be taken into account in power converter design.

How can industry best measure/report these dependencies?
Can we use this data to design lower loss capacitors for real-world conditions?
Acknowledgements

- This work was partially sponsored by NASA