Capacitor Fundamentals 201

This Webinar is offered by the PSMA Capacitor Committee.

PSMA, or the Power Sources Manufacturers Association is an organization of companies that believe that there is much to gain by uniting in a common goal to educate and network industry on new technologies, trends and capabilities.

PSMA is one of the hosting organizations of APEC which is an annual Exhibition and Conference that has over 6,000 attendees. Next year’s APEC will be held in New Orleans in mid-March.

The PSMA Capacitor Committee offers several events that you should keep an eye out for:
1) Road Map Webinars defining upcoming technologies and trends. This is part of the PSMA’s bi-annual Roadmap publication.
2) APEC Capacitor Industry Session – part of APEC
3) Capacitor Workshop – a full day of Capacitor design training offered just prior to APEC in the same venue.
4) Continuing “Fundamental” Webinars – for General Education
Capacitor Fundamentals 201

Defining ESL, ESR, & how to de-rate your cap requirement, including Parameter review of Polymer Technology – also a little bonus - defining alternatives to MLCC caps – since they are becoming short on supply.

Stephan Menzel – Wurth Technologies

MLCC Capacitor Parameter Comparison

William Mak– KEMET

Film Capacitor Parameter Comparison

Eduardo Drehmer– TDK / formerly EPCOS
Short Introduction of Today’s Presenters

Stephan Menzel
Head of Product Marketing & Technical Engineering
eiCap - Capacitor Division

Background:
• More than 10 years of work experience in electronics industry
• Background in Global Sales & Marketing, Industrial Engineering and Quality Management
• In charge for strategic sales conception and global market penetration of capacitor division at WE
Equivalent Circuit of each Capacitor

- The equivalent circuit diagram is described like following:

beside the capacitance you have 3 major parameters:

- **ESR** – Equivalent Series Resistance
- **ESL** – Equivalent Series Inductance
- **R_{ISO} / R_{Leak}** – Isolation Resistance
Equivalent Circuit: ESR - Equivalent Series Resistance

- The equivalent circuit diagram is described like following:

- \( R_{ESR} \) – Equivalent Series Resistance
  - Reason for self heating in case of Ripple or AC load
  - Values are typically specified @ 120Hz or 100kHz with 20°C ambient condition
  - Can be calculated like following:

\[
ESR = \frac{\tan \delta}{2 \pi f C} = \tan \delta \times X_C \quad \text{mit} \quad X_C = \frac{1}{2 \pi f C} = \frac{1}{\omega C}
\]
Equivalent Circuit: ESL - Equivalent Series Inductance

- The equivalent circuit diagram is described like following:

![Equivalent Circuit Diagram]

- ESL – Equivalent Series Inductance
  - Is mainly driven by inner construction of capacitor element and connections to it
  - New cap designs are optimized for low ESL to drop these parasitic effects
  - Can be calculated as following:

\[
ESL = \frac{X_L}{\frac{2}{\pi} \cdot \frac{f}{f}} \Rightarrow X_L = (2 \cdot \pi \cdot f \cdot ESL) = (\omega \cdot ESL)
\]
Equivalent Circuit: $R_{ISO} / R_{leak}$ - Isolation Resistance

- The equivalent circuit diagram is described like following:

- $R_{ISO} / R_{leak}$ – Isolation Resistance
  - Is the ohmic resistance between the electrodes
  - Will be given as $[M\Omega]$ or as $\tau [s]$
    - $\tau [s] = R_{ISO} [M\Omega \mu F] = R_{ISO} [M\Omega] \times C [\mu F]$
  - Humidity can reduce the isolation resistance drastically
Equivalent Circuit: $Z$ - Impedance

- The equivalent circuit diagram is described like following:

- **$Z$ – Impedance Z**
  - Describes the AC mode characteristics
  - Is based on 3 parameter - ESR, $X_L$ and $X_C$
  - Can be calculated as following:

$$Z = \sqrt{\text{ESR}^2 + (X_L - X_C)^2}$$
Equivalent Circuit: \( Z \) - Impedance

\[
Z = \sqrt{ESR^2 + (X_L - X_C)^2} = \sqrt{ESR^2 + \left( (2 \pi f \cdot ESL)^2 - \left( \frac{1}{2 \pi f C} \right)^2 \right)}
\]

the result you see in real world:

the cumulation in behind:
DF / tan δ - Dissipation Factor

• The dielectric loss angle δ is the difference to the ideal phase angle of 90°

• The Dissipation Factor - DF / tan δ:
  • Is a measure for the occurring losses
  • Is based on the relation of ESR to Xc

• Calculation by:

\[
tan \delta = DF = \frac{ESR}{Xc} = ESR \times 2 \times \pi \times f \times C
\]

• There is a dependence given related to frequency, temperature and used materials of cap construction
Capacitor Types

- Film Capacitors
  - Paper Film Capacitors
  - Plastic Film Capacitors
- Ceramic Capacitors
- Electrolytic Capacitors (E-Caps)
  - Aluminum Electrolytic Capacitors
  - Tantalum Electrolytic Capacitors
  - Niobum Electrolytic Capacitors
- Supercapacitors
- Mica Capacitors
- Glass Capacitors
- Feedthrough Capacitors
- Electrolytic Capacitors (E-Caps)
  - Aluminum Electrolytic Capacitors
  - Tantalum Electrolytic Capacitors
  - Niobum Electrolytic Capacitors
- Electric Double Layer Capacitors
- Pseudo Capacitors
- Hybrid Capacitors
- Rotary Capacitors
- Trimming Capacitors

fixed capacitance

variable capacitance
## Most Common Capacitor Types in Comparison

<table>
<thead>
<tr>
<th>capacitor type</th>
<th>max. possible capacitance</th>
<th>voltage range</th>
<th>max. permissible current</th>
<th>max. operating temperature</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Electrolytic Capacitor</td>
<td>&gt; 1F</td>
<td>ca. 650 V</td>
<td>ca. 0.05 A/µF</td>
<td>85°C up to 150°C</td>
<td>smoothing, buffering, DC Link</td>
</tr>
<tr>
<td>Film Capacitors</td>
<td>&gt; 8mF</td>
<td>ca. 3kV</td>
<td>ca. 3 A/µF</td>
<td>max. 110°C</td>
<td>DC Link, EMI suppression, filtering</td>
</tr>
<tr>
<td>MLCC's</td>
<td>&gt; 100 µF</td>
<td>ca. 10 kV</td>
<td>ca. 10 A/µF</td>
<td>85°C up to 200°C</td>
<td>EMI suppression, buffering, coupling</td>
</tr>
</tbody>
</table>
Challenges at Downsizing of MLCCs
The MLCC Downsizing Challenge

!!! Watch Out !!!

DC Bias is chip size related
Disadvantages by changing to a smaller sizes?

- **Worse electrical stability / performance**
  - For class 2 ceramics X7R / X5R >> higher capacity loss due to DC bias

- **Assembly times are possibly rising**
  - With smaller sizes positioning runs more slowly
  - In the future also several components need to be picked as replacement

- **Many companies need to invest in new production equipment**
  - It may require new feeder benches, nozzles and pick & place machines

- **Redesign necessary**
  - Blocks engineering resources for new projects
  - Releases (such as e.g. UL) must be repeated
  - Changes in the manufacturing process needed
What‘s a proper alternatives against MLCC‘s?

- **>1 µF – high capacitance**
  - Classic Aluminum E-Caps (like SMT V-Chips - also down to 3mm in size)
  - Aluminum Polymer E-Caps >> specially **H-Chips**
  - Tantalum - Capacitors

- **< 1 µF – low capacitance**
  - No real alternatives against conventional MLCCs
  - Film Caps could work, but are way too big / bulky
What's a proper alternatives against MLCC's?

- **Aluminum Polymer Capacitors – H-Chips**
  - H-Chip are interesting for
    - Miniaturization - possible to shrink by replacing MLCCs
    - Replacement for Tantalum- & MLCCs because:
      - no DC Bias Effect / no Voltage Derating
      - for low profile / height critical design
  - Capacitance Range:
    - 15 µF - 560 µF
  - Voltage Range:
    - 2V up to 35V
Impedance vs. Frequency

(typical sample curve)
Capacitance Change vs. DC-Bias Voltage

Possible Capacitance Change for MLCC with Class 2 Ceramic

(typical sample curve)
Let's optimize your integration density

Save Space on your PCB

24 x MLCCs
- P/N: 885012107006
  with 47 μF
- 24 x 47 μF = 1128 μF
- $V_R = 6.3\, V(DC)$
- Size 0805 $\rightarrow$ 2 x 1.5 mm
- $C @ 6\, V(DC) = 216\, \mu F$ due to DC - Bias
- $A = 255\, \text{mm}^2$

1 x H-Chip Aluminum Polymer Capacitors
- P/N: 875015119006
  with 220 μF
- 1 x 220 μF = 220 μF
- $V_R = 6.3\, V(DC)$
- Size 2917 $\rightarrow$ 7.3 x 4.3 mm
- $C @ 6\, V(DC) = 220\, \mu F$
- $A = 44\, \text{mm}^2$
Short Introduction of Today‘s Presenters

William Mak
Senior Applications Engineer
KEMET Application Intelligence Center

Background:
- 8 years of work experience in the electronics industry for product development
- Background in electrical engineering with a focus on board layout and digital signal communication
- In charge of KAIC, a lab focused on creating technical content for engineers

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Form Factor
Not Just Cap But ESR Matters Too
Parasitics and Ripple Voltage
Capacitor Charge

ESR Impact

\[ V_{\text{Cap}} = V_{\text{load (Closed)}} \]

Switch Closed

Current ON

Load Current

Supply Load Requirements

Charge Capacitor

ESR
Capacitor Discharge

ESR Impact

\[ V_{L(\text{Open})} = V_{L(\text{Closed})} - (I_{\text{Load}} \times R_{\text{ESR}}) \]
Ripple Voltage Effects

- + ESR
- + L
- + DC Bias
- + Cap Roll-Off
Transient Response
\((C+ESR+ESL)\)

- Capacitance: 200 \(\mu\)F
- ESR: 33 m\(\Omega\)
- ESL: 100 nH

Voltage recovery from Power Supply Unit (PSU)

ESR Voltage drop
Capacitance Induced Voltage drop
ESL Voltage Spikes

Load Current 500 mA

20 mv per division
Ripple Current Capability

- Ripple current refers to the AC portion of the current signal applied to a device.

- Heat is generated by ripple currents.

- Several factors contribute to the ripple capability of a capacitor:
  - Dielectric material and associated DF
  - Electrodes
  - Frequency
  - Package size (surface area)
  - Package leads
  - Allowable temperature rise
  - Heat sink & cooling system
Ripple Current

ESR Changes with Temperature

\[ P = I^2 R \]
Ripple Current
Temperature Rise
Why ESR is Important

- **Why ESR is important:**
  - **Power Loss** = $I_{RMS} \times I_{RMS} \times ESR$ or $P = I^2 R$
  - Simplified to $I_{AVG}$ below (loss is a little higher with $I_{RMS}$)

Average Calculation (general trapezoidal waveforms)

$$I_{AVG} = \frac{t}{T} I_M$$

$$I_M = \frac{I_2 + I_1}{2}$$

$$P_{AVG} = 1A \times 1A \times 0.010\Omega = 10mW$$ (using 1A average current)

$$P_{AVG} = 5A \times 5A \times 0.010\Omega = 250mW$$ (using 5A average current)

Lower ESR $\Rightarrow$ Lower Power Losses $\Rightarrow$ Higher Efficiency
Why ESR is Important

Power Consumption (Heat)

\[ P = I^2 R \]

Lower ESR \( \Rightarrow \) Lower Power Losses \( \Rightarrow \) Higher Efficiency
ESR Comparisons Across Dielectrics

Minimum ESR in Ohms

Temperature Dependence
Red = High
Gold = Medium
Blue = Low

<table>
<thead>
<tr>
<th>Material</th>
<th>Minimum ESR in Ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Polymer</td>
<td>0.003</td>
</tr>
<tr>
<td>Aluminum Electrolytic</td>
<td>0.12</td>
</tr>
<tr>
<td>Ceramic</td>
<td>0.001</td>
</tr>
<tr>
<td>Tantalum Polymer</td>
<td>0.006</td>
</tr>
<tr>
<td>Tantalum MnO2</td>
<td>0.035</td>
</tr>
<tr>
<td>Film</td>
<td>0.001</td>
</tr>
</tbody>
</table>
# Comparison of Parasitics

<table>
<thead>
<tr>
<th>Capacitor Type</th>
<th>ESR</th>
<th>ESL</th>
<th>Piezo</th>
<th>Temp Drift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>Low</td>
<td>Low</td>
<td>High (Class 2)</td>
<td>High (Class 2)</td>
</tr>
<tr>
<td>Tantalum</td>
<td>Med</td>
<td>Med</td>
<td>None</td>
<td>Med</td>
</tr>
<tr>
<td>Polymer</td>
<td>Low</td>
<td>Med</td>
<td>None</td>
<td>Low</td>
</tr>
<tr>
<td>Film</td>
<td>Low-Med</td>
<td>High</td>
<td>None</td>
<td>Low</td>
</tr>
<tr>
<td>AIE</td>
<td>High</td>
<td>High</td>
<td>None</td>
<td>Low</td>
</tr>
</tbody>
</table>
Short Introduction of Today’s Presenter

Eduardo Drehmer
Director of Marketing
FILM Capacitors

Background:

- Over 20 years experience with knowledge on Manufacturing, Quality and Application of Electronic Components.
- Responsible for Technical Marketing for Film Capacitors

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## Caps Technology Comparison

<table>
<thead>
<tr>
<th></th>
<th>MLCCs</th>
<th>Aluminum Electrolytic</th>
<th>Film</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size (Capacitance Density)</strong></td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td><strong>ESR</strong></td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td><strong>ESL</strong></td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td><strong>Polarity reversal</strong></td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td><strong>Max Temperature</strong></td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td><strong>High Voltage (Power)</strong></td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td><strong>Low Voltage</strong></td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td><strong>SMD compatibility</strong></td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td><strong>Safety (Failure Mechanisms)</strong></td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
</tr>
</tbody>
</table>
Film Cap Construction Technologies

Wound Film Capacitors

Stacked Film Capacitors

Electrodes (metallization)

Wound capacitor

Dielectric (plastic film)

Stacked-film capacitor

Electrodes (metallization)

Wound capacitor

Dielectric (plastic film)
**Film Cap Technologies**

<table>
<thead>
<tr>
<th>Simple connection</th>
<th>Film and foil arrangements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Metalized Film Simple Connection**

- Electrodes (metallization)
- Dielectric (plastic film)

**Reliability**

**Film / Foil Series Connection**

- Electrodes (metal foil)
- Dielectric (plastic film)

**Current**
Common types of dielectric material used

<table>
<thead>
<tr>
<th>Dielectric</th>
<th>PP</th>
<th>PET</th>
<th>PEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric constant ($\varepsilon_r$)</td>
<td>2.2</td>
<td>3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>C drift with time ($i_x = \Delta C/C$)</td>
<td>%</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>C temperature coefficient $\alpha_c$</td>
<td>$10^{-6}$/K</td>
<td>−250</td>
<td>+600</td>
</tr>
<tr>
<td>C humidity coefficient $\beta_c$</td>
<td>$10^{-6}$/% r.h.</td>
<td>40 ... 100</td>
<td>500 ... 700</td>
</tr>
<tr>
<td>Dissipation factor (1 kHz)</td>
<td>0.0005</td>
<td>0.0050</td>
<td>0.0040</td>
</tr>
<tr>
<td>Time constant</td>
<td>s</td>
<td>100 000</td>
<td>25 000</td>
</tr>
</tbody>
</table>
Package and Connections

PCB / Through Hole connections
Package and Connections

Busbar / Screw Type connections
Characteristics and Modeling

ESR & ESL

Figure 8
Real capacitor model

$L_S$ Series inductance
$R_S$ Series resistance, due to contacts (leads, sprayed metal and film metallization)
$R_P$ Parallel resistance, due to insulation resistance
$C$ Capacitance

$C$, $R_S$ and $L_S$ are magnitudes that vary in the frequency domain (AC).
$R_P$ is a magnitude defined in DC (insulation resistance).

$I_{RMS} = V_{RMS} \cdot 2\pi f \cdot C$

$\tan \delta = ESR \cdot 2\pi f \cdot C$

$V_{C} = \frac{1}{2 \pi f \cdot C}$

$V_{ESR} = 1 - ESR$
DC Applications

Important design aspects to observe:

- Continuous Vdc level
- Transients / Surges (Vp)
  - Normally Film caps can withstand up to 1.6x Vrated
- Temperature Derating
- Ripple Vrms & Frequency

Typical Temp Derating for Film Caps: 1.3%/°C
AC Applications

Important design aspects to observe:

- Vrms & Frequency
- Corona Inception Voltage (Vrms rating)
- Heat Management
General Design Rules

Important to validate your design:

• **Self-Heating** (Difference between case and ambient temp)
  
  *should not exceed +10 ~ 15°C*

• **Compare ratings for caps near end of life:**
  
  • Max ESR increase,
  • Min Capacitance allowed
  • Min Insulation Resistance allowed

• **Heat Management:**
  
  • Evaluate if Capacitor is near hot spots caused by other components

Film Caps are normally the most temperature sensitive component in a PCB!!!
Failure Mechanisms

Most common Failure mechanisms for Film Caps:

- Corona Discharges (Make sure Vac rating is adequate)
- Dielectric Stress/Aging (Too high Vdc and/or Temperature)
  - Thermal Breakdown
- Over Current (Look at Vrms capability x frequency)
- Humidity (Look for new IEC/UL 60384-14 Grades)
- Thermal stress (Self-Heating, Soldering, etc...)

Vast majority of Film Caps failures result in:

1. Increase of Loss Factor (TanD, ESR)
2. Capacitance Reduction
3. Insulation Resistance Reduction
EMI Capacitors (X & Y capacitors)

IEC/UL 60384-14

Characteristics that make Film popular as EMI protection:
- AC Capable
- Self Healing Capability
- Safe Failure

<table>
<thead>
<tr>
<th>Sub-class</th>
<th>Peak pulse voltage (V_p) in operation</th>
<th>Application</th>
<th>Peak values of surge voltage (V_p) (before endurance test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>2.5 kV &lt; (V_p) ≤ 4.0 kV</td>
<td>High pulse application</td>
<td>(C_n \leq 1.0 \mu F: V_p = 4.0 \text{ kV})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(C_n &gt; 1.0 \mu F: ) (V_p = \frac{4}{\sqrt{C_n}} \text{ kV})</td>
</tr>
<tr>
<td>X2</td>
<td>(V_p \leq 2.5 \text{ kV})</td>
<td>General purpose</td>
<td>(C_n \leq 1.0 \mu F: V_p = 2.5 \text{ kV})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(C_n &gt; 1.0 \mu F: ) (V_p = \frac{2.5}{\sqrt{C_n}} \text{ kV})</td>
</tr>
<tr>
<td>X3</td>
<td>(V_p \leq 1.2 \text{ kV})</td>
<td>General purpose</td>
<td>No test</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub-class</th>
<th>Type of bridged insulation</th>
<th>Rated AC voltage (V_R)</th>
<th>Peak values of surge voltage (V_p) (before endurance test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y1</td>
<td>Double or reinforced insulation</td>
<td>(V_R \leq 250 \text{ V})</td>
<td>(8.0 \text{ kV})</td>
</tr>
<tr>
<td>Y2</td>
<td>Basic or supplementary insulation</td>
<td>(150 \text{ V} \leq V_R \leq 250 \text{ V})</td>
<td>(5.0 \text{ kV})</td>
</tr>
<tr>
<td>Y3</td>
<td>Basic or supplementary insulation</td>
<td>(150 \text{ V} \leq V_R \leq 250 \text{ V})</td>
<td>No test</td>
</tr>
<tr>
<td>Y4</td>
<td>Basic or supplementary insulation</td>
<td>(V_R &lt; 150 \text{ V})</td>
<td>(2.5 \text{ kV})</td>
</tr>
</tbody>
</table>