Electronic Components

AC Line

Applications
Overview
Switched Mode Power Supply (SMPS)

<table>
<thead>
<tr>
<th>$C_X$</th>
<th>$C_Y$</th>
<th>$C_S$</th>
<th>$C_F$</th>
<th>$C_T$</th>
<th>$C_C$</th>
<th>$C_R$</th>
<th>$L_C$</th>
<th>$L_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1/X2 Safety</td>
<td>Y2/Y1 Safety</td>
<td>PFC</td>
<td>Bulk Capacitor</td>
<td>Snubber Switching</td>
<td>Coupling</td>
<td>Resonant</td>
<td>Common Mode</td>
<td>Differential (Normal) Mode</td>
</tr>
<tr>
<td>Film, Paper &amp; Ceramic</td>
<td>Film, Paper &amp; Ceramic</td>
<td>Film</td>
<td>AI Electrolytic Tantalum KO Ceramic (X7R) Film PET</td>
<td>Film &amp; Ceramic (C0G)</td>
<td>Film &amp; Ceramic (C0G)</td>
<td>Film &amp; Ceramic (C0G)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
EMI Filters
EMI Filters (AC)

AC Line Filter

- **L_C**: Common Mode Choke
- **L_D**: Differential (Normal) Mode Choke
- **C_X**: X2/X1
  - Safety Film, Paper, & Ceramic
- **C_Y**: Y2/Y1
  - Safety Film, Paper, & Ceramic

**Functions**
- Filter EMI Signals
- Protect Against Surges and Transients
EMI (Safety) Capacitors
Filtering, Coupling Modes (AC)

**Common Mode**

- Line to Neutral, or Line to Line
- Protect against **Differential Mode** interferences
- Failure does not create electric shock risk, but potential fire

**X Capacitors**
- Line to Neutral, or Line to Line
- Protect against **Differential Mode** interferences
- Failure does not create electric shock risk, but potential fire

**Y Capacitors**
- Lines to Ground (Chassis)
- Protect against **Common Mode** interference
- Failure can create a risk of electric shock to the users

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EMI (Safety) Capacitors

Because of the potential for injury the various safety agencies provide testing and recognition for X and Y capacitors.

<table>
<thead>
<tr>
<th>Region</th>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>Across-the-line EMI Filter</td>
<td>EN/IEC 60384–14</td>
</tr>
<tr>
<td>USA</td>
<td>Across-the-line EMI Filter</td>
<td>UL 60384–14 and CAN/CSA–E60384–14</td>
</tr>
<tr>
<td>Canada</td>
<td></td>
<td></td>
</tr>
<tr>
<td>China</td>
<td></td>
<td>GB/T 14472</td>
</tr>
</tbody>
</table>

“Safety agency approvals do not insure product performance. Simply stated, equipment may fail after a line transient provided it fails safely.”
## EMI Capacitors

**X & Y Sub-Class Capacitors**

<table>
<thead>
<tr>
<th>Sub Class</th>
<th>Peak Voltage Test (KV) $C \leq 1\mu F$</th>
<th>Peak Voltage Test (KV) $C \geq 1\mu F$</th>
<th>Insulation / Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y1</td>
<td>8</td>
<td>-</td>
<td>Double or Reinforce Insulation</td>
</tr>
<tr>
<td>Y2</td>
<td>5</td>
<td>-</td>
<td>Basic or Supplementary insulation</td>
</tr>
<tr>
<td>X1</td>
<td>4</td>
<td>$4/\sqrt{C}$</td>
<td>High Pulse Applications</td>
</tr>
<tr>
<td>X2</td>
<td>2.5</td>
<td>$2.5/\sqrt{C}$</td>
<td>General Purposes</td>
</tr>
</tbody>
</table>

### Impulse

![Impulse Diagram](image)

### Endurance

![Endurance Diagram](image)

### Active Flammability

![Active Flammability Diagram](image)
EMI Safety Capacitors

X & Y Film (Polypropylene)

- Zn/Al Metallization (R: 10 to 20 Ω/sq)
- Vac: 275, 310, 330, 440, 600, 760
- Available as AEC Q200 Certified (85°C / 85% R.H., 1,000h)

- Very Good Self-Healing (PP)
- Resistant Against Voltage Spikes
- Very Low Dissipation Factor & Dielectric Absorption

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EMI Safety Capacitors
X & Y Metallized Impregnated Paper

Multi-Layer Impregnated Dielectric

- High Dielectric Constant
- Excellent Self-healing
- High dv/dt (Transient Handling Capability)
- High Ionization Level (Resin)
- Stable Capacitance in Harsh Environment & Voltage Conditions

- Zn Metallization (R: 2.5 Ω/sq.)
- VAC: 275, 300, 480, 500, 660
Metallized Film

Self-Healing

- Metal layer < 0.02µm
- Dielectric 1µm
- Breakdown Channel
- Weak Point
- Metallization Evaporates
- The Insulation Is Restored

• Metallized Film
  - Smaller Size
  - Higher C Value
  - Higher Reliability
  - Lower Cost
  - Lower Weight

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AC Line Filters (Coils)

Applications

Applications:
- Chargers/Power Supply
- Smart Phone
- PC/Tablet
- xDSL Modem
- Printer
- Copy Machine
- White Goods (Inverter)
- Induction Heating
- Fluorescent Light Fittings
- Flat Panel TV
- UPS
- Solar Inverter
- Smart Meter
- HEV/EV AUTO

Circuit
- Battery Charger
- AC Adapter
- Switching Power Supply
- EMI Filters

Input Transient Filters of a Power Supply
L1 and L2 are AC (Common mode) Filters
Hybrid Choke Coil

Existing magnetic circuit causing the interference to outer field by leakage flux

New magnetic circuit suppresses the leakage flux to inside and it does not cause interference
Measurement Comparison
Discrete Solution vs. Hybrid Solution

Noise level with single Hybrid (CMC DMC) choke. Level is the same as using conventional CMC and DMC.

Noise level with conventional Common Mode Choke (CMC) Only. Level is exceeded in middle range.

Noise level with conventional Common Mode Choke (CMC) and 2 Differential Mode Chokes (DMC). Level is almost below the limit.

Noise level with single Hybrid (CMC DMC) and 1 Conventional Common Mode Choke (CMC) and 2 Differential Mode Chokes (DMC). Level is almost below the limit.
# Customer Optimized Solution

**Example for Hybrid Choke Coil**

## Proposal Specification

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrite material</td>
<td>5HT ($\mu=5000$)</td>
</tr>
<tr>
<td>Wire dia.</td>
<td>$\Phi1.2$ mm</td>
</tr>
<tr>
<td>Turns</td>
<td>16 T</td>
</tr>
<tr>
<td>Common mode Inductance</td>
<td>1.5mH Min. @10kHz</td>
</tr>
<tr>
<td></td>
<td>2.1mH Typ. @10kHz</td>
</tr>
<tr>
<td>Differential mode Inductance</td>
<td>16.9uH Typ. @10kHz</td>
</tr>
<tr>
<td>RdC</td>
<td>14.8mΩ/line Typ.</td>
</tr>
</tbody>
</table>

## Appearance & Dimension

![Mock-up actual measured values.](image)

## Frequency Characteristics

![Graphs showing Common Mode and Differential Mode frequency characteristics.](image)

Reference Only: All numerical data are electromagnetic simulation values.
EMI Filters
Selecting Safety Capacitors and Common Mode Chokes
How to Select a Safety Capacitor

1. Determine where the capacitor will be placed in the circuit.
   a) If the capacitor is directly connected to the AC power input, then a safety-certified capacitor will be needed to minimize the generation of EMI or RFI. These capacitors are also known as EMI/RFI suppression capacitors and AC line filter safety capacitors.

2. Determine if the capacitor will be placed between line and neutral or line and ground.
   a) Capacitors placed between line and neutral or line and line are Class-X which are referred to as “across the line”. These capacitors suppress Differential (Normal) Mode Noise.
   b) Capacitors placed between line and ground are Class-Y which are referred to as “line to ground”. These capacitors suppress Common Mode Noise.

3. Determine peak voltage, rated voltage, and peak impulse voltage.
4. Pick a subclass
   
a) Both Class-X and Class-Y are broken up into subclasses based on voltage ratings.

<table>
<thead>
<tr>
<th>Subclass (IEC 60384-14)</th>
<th>Peak Voltage Pulse (while in service)</th>
<th>Peak Impulse Before Endurance Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>&gt; 2.5kV</td>
<td>4kV per C ≤ 1μF</td>
</tr>
<tr>
<td></td>
<td>≤ 4.0kV</td>
<td>4/√C kV per C &gt; 1μF</td>
</tr>
<tr>
<td>X2</td>
<td>&lt; 2.5kV</td>
<td>2.5kV per C ≤ 1μF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5/√C kV per C &gt; 1μF</td>
</tr>
<tr>
<td>X3</td>
<td>≤ 1.2kV</td>
<td>None</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subclass (IEC 60384-14)</th>
<th>Rated Voltage</th>
<th>Peak Impulse Before Endurance Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y1</td>
<td>≤ 500VAC</td>
<td>8kV</td>
</tr>
<tr>
<td>Y2</td>
<td>150VAC ≤ V &lt; 300VAC</td>
<td>5kV</td>
</tr>
<tr>
<td>Y3</td>
<td>150VAC ≤ V &lt; 250 VAC</td>
<td>None</td>
</tr>
<tr>
<td>Y4</td>
<td>&lt; 150VAC</td>
<td>2.5kV</td>
</tr>
</tbody>
</table>

a) X2 and Y2 are the most commonly used safety capacitors since they are typically used in common appliances that are plugged into wall sockets.
b) X1 and Y1 are commonly used in industrial settings such as industrial lighting ballast connected to a 3-phase line.
c) X1 and Y1 can be used in place of X2 and Y2 but will cost more.
d) Class-Y can be used in place of Class-X, but not vice versa. Class-X does not meet the line-to-ground safety standards, are less robust, and withstand lower peak impulse voltages.
5. Determine the dielectric technology.

a) Ceramic Pros
   1. Leaded ceramic capacitors have the highest dielectric and pulse strength of all technologies.
   2. Leaded ceramic capacitors are the only ones available in the X1/Y1 safety classification.
   3. Leaded ceramic capacitors can handle pulses up to 10 kV.
   4. Surface-mount ceramic capacitors are available with a capacitance value of 1 nF and an NP0 temperature coefficient of capacitance.
   5. Leaded ceramic capacitors are usually less expensive than film capacitors.

b) Ceramic Cons
   1. Ceramic capacitors have relatively low capacitance value compared to other technologies, so they cannot be used in some applications.
   2. They typically fail short.
5. Determine dielectric technology

b) Film Pros
1. Film capacitors offer higher capacitance values compared to other technologies.
2. Film capacitors have the ability to recover from a dielectric breakdown with just a tiny decrease in capacitance. This is called a “self-healing” effect. It happens because the arc created during a dielectric breakdown evaporates the metallization layer and thus clears the fault condition.
3. The capacitance and dissipation factor of film capacitors are highly stable across a wide temperature range from −40 to +110°C.
4. The internal series construction of X2 film safety capacitors helps the device last longer and maintain capacitance in series impedance or across-the-line applications.

c) Film Cons
1. Film safety capacitors are through-hole devices, and if the application uses surface-mount components, they may need a different soldering process than the other components on the board.
2. Film capacitors are usually more expensive than ceramic capacitors.
6. Determine the style, footprint, and other dimensions
   a. The packaging can be leaded or SMD.

7. Determine the capacitance and tolerance.

8. Determine the temperature range.

9. After selecting a capacitor, determine if it’s characteristics such as impedance, insulation resistance, and dissipation factor will work for your application.
   a. It is also important to determine if the capacitor can handle the applications dV/dt (instantaneous rate of voltage change).

10. Additionally, it is important to note that capacitors that combine aspects of Class-X and Class-Y do exist and can be used in place of either an X or Y capacitor’s place.
How to Select a Choke

- L = Inductance
- N = Number of turns
- $\mu_r$ = Relative permeability (dimensionless)
- $\mu_0 = 4\pi \times 10^{-7}$ H/m (permeability of free space)
- $1 \text{ mm} = 0.03937 \text{ inches} \quad \longleftrightarrow \quad 1 \text{ inch} = 25.4 \text{ mm}$
- $Z=j\omega L$

$$L = 0.00508 \times \mu_r \times N^2 \times h \times \ln \frac{b}{a} \quad [\text{in}, \mu\text{H}]$$
Steps to select chokes to filter noise

1. Select AC or DC line and rated voltage.
2. Select Common Mode or Differential Mode Choke.
3. Determine the Rated Current.
4. Determine DCR.
5. Determine Frequency.
   - Generally, needs to cover wide range such as 150 kHz to 30 MHz, which is the whole range of conduction, emission regulation frequency. Sometimes targeting to a specific frequency exceeds the limit and fails compliance test.
6. Determine the Inductance value (L).
   - Based on the frequency range, select the highest impedance (Z) at the desired frequency.
   - Use $Z = j\omega L$ and $\omega = 2\pi f$, but remember that the value drops after resonance due to parasitic capacitance.
   - In the case of a filter circuit using a capacitor with capacitance of (C), resonance frequency (f) is obtained by the formula $f = \frac{1}{2\pi\sqrt{LC}}$ should be considered to select adequate inductance (L).
7. Determine dimension/footprint limitations.
   - There will be height and footprint limitations.
8. Tradeoffs.
   - The above values have tradeoffs such as limited dimensions and if the rated current increased, then inductance will drop. Increasing the inductance will also increase DCR, which decrease the rated current.

Following these steps, engineers will need to find optimized parameters, which can meet design requirements.
Harsh Environment and Series Connection
Film Capacitance Loss

- **(1) Dielectric Defect**
- **(2) Trapped Air**
- **(3) Corona Discharge**
- **End Spray**

- **Dielectric**
- **Metallization**

AC Field $\geq 240V_{AC}$
RFI Suppressors for Harsh Environment
Applications and Characteristics

• Parallel Connection

• RFI suppression
• Surge voltage protection
✓ Safety approvals
• Ripple filtering*

• Series Connection

• Power supply
• Surge voltage protection*
✓ Capacitance stability
• THB test: 85°C, 85%r.h., 240Vac
  1000h     dC/C <10%
(X2 approval requirement)
Other Capacitors in Series with Mains (AC)

Typically requires stable capacitance over 10 years.
- Film: Require avoiding internal ionization and oxidation
- Ceramic(C0G): Require low distortion (piezo-noise), not aging, not DC bias

Example of Applications
- Smart Electricity Meters
- Refrigerator Compressor Controllers
- Electric Heating Thermostats
- Gas Heater Controllers

This application does not need an X2 capacitor.
RFI Suppression Capacitors
Capacitance Decreasing Mechanisms

1. Self-healing

- Key parameters:
  - Dielectric material
  - Metallization material/thickness
  - Processing
2. Erosion / partial discharge

- Active at low temperature
- Requires inception voltage
- Localized mostly where electric field is higher: metallization edge
3. Electrochemical Corrosion

Reactions in the electrochemical cell are driven by applied voltage.

Corrosion rate is directly proportional to: Temperature - Humidity - Bias
Protection against severe ambient conditions is critical for heavy duty and in series with the main applications.
Aliphatic polymers such as polypropylene (& paper) are highly efficient at self-healing.

- Pyrolysis reaction during clearing results in stable gaseous products.
  - This allows for full recovery of insulation resistance.

Self-healing of polyester type polymers is lower.

- The aromatic group in the polymer is very stable and pyrolysis will be less effective.
  - High magnitude clearings could result in ‘carbon’ byproducts (soot).
  - This could be detrimental for insulation resistance.
# RFI Suppressor Technologies Comparison

## Polypropylene and Polyester Capacitors

<table>
<thead>
<tr>
<th>Properties</th>
<th>B OPP</th>
<th>PET</th>
<th>PEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (µm)</td>
<td>2.7 - 10</td>
<td>0.7 - 6</td>
<td>1.4 - 6</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>0.91</td>
<td>1.34</td>
<td>1.35</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>169</td>
<td>254</td>
<td>266</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>2.25</td>
<td>3.25</td>
<td>3.05</td>
</tr>
<tr>
<td>BDV (V/µm) 4µm Film, 25°C</td>
<td>500</td>
<td>350</td>
<td>320</td>
</tr>
<tr>
<td>Water Absorption (%)</td>
<td>&lt; 0.1</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Self-Healing</td>
<td>Excellent</td>
<td>Good</td>
<td>Medium</td>
</tr>
</tbody>
</table>
RFI Suppressor Technologies Comparison
Polypropylene and Polyester Capacitors

Dissipation Factor

![Dissipation Factor Graph](image)

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RFI Suppressors

Industry Trends

- Harsh Environment
  - THB
  - 85°C / 85 R.H.

- Output Filters
  - High C Value on X’s > 10 uF

- Output Filters & PFC
  - High Ripple
  - Harmonic Content

- Automotive Qualified
  - AEC-Q200

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Snubber, Pulse, and Damping
Snubber

- **C<sub>T</sub>**
  - Metallized Polypropylene Film
  - Ceramic C0G

**Functions**
- Absorb or supply current surges
- Damp dangerous voltage spikes

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Pulse Capacitors
Snubber, Pulse, and Damping

• Look for:
  – Peak V Ratings
  – dV/dT Ratings
  – Pulse Currents
  – Amplitude and Form of Pulse
  – Thermal Dissipation

• Film Capacitor
  – Pulse-Rated
    • No dv/dt, not metalized for pulse
  – X/Y are not recommended

• Ceramic Capacitor
  – Recommend only C0G
    • Measure dv/dt heating

\[ C = \frac{L \cdot I^2}{\Delta V^2} \]
Excessive Current Degradation of Film Capacitors

Key Considerations for Selection

• Critical Factors
  – Metallized Film Types & Terminations
  – Film-Foil Types
  – Winding Configuration
  – Self-Heating
  – Ambient Temperature
  – Cooling Assistance

• Current fuses electrode plate material = Capacitance loss
• Demands that peak current and $dv/dt$ be specified
• Polypropylene Film and Paper capacitors are recommended
MLCCs for AC Applications

Key Considerations for Selection

- **Peak Voltage**
  - Is peak less than the DC rated voltage of the MLCC?

- **Ripple Current**
  - $P^2 \times ESR$ heating
  - Measure heat rising

- **Self-Heating**
  - Low frequency dielectric absorption

$$P_i = (I_{rms_i})^2 \times ESR_i$$

![C0G vs X7R Temperature Rise](image1)

- **X7R, 10uF**
  - 16.5 $\Omega$ @ 60 KHz
  - 12.8 m$\Omega$ @ 100 KHz
Pulse Rated MLCCs
Key Considerations for Selection

- High $dV/dT = \text{High Current}$
  - Wide Electrodes
  - Solid Termination
  - Multiple Electrode Layers

- Repetitive Pulses
  - Limited Cooling From $I^2R \times \text{ESR}$ Heating
  - Temperature Rise Critical

- Choosing: X7R or C0G
  - X7R
    - High ESR, More Heating
    - Piezoelectric Effect May Result in Cracks Under High $dV/dT$ Events
  - C0G Recommended

$I = C \frac{dV}{dT}$
Coupling
• \( C_C \)
  • Metallized Polyester
  • Metallized Polypropylene
  • Ceramic C0G

• Functions
  – Coupling
  – Blocking
Bulk Capacitor
Bulk Capacitor

- ** Functions
  - Smooth the ripple voltage superimposed on the DC-Bus Voltage (filter)
  - Provide energy (decoupling)

- **$C_F$:**
  - Aluminum (Electrolytic, Polymer, Hybrid)
  - Tantalum ($\text{MnO}_2$, Polymer)
  - Ceramic (X7R, X5R)
  - Film (PET, PEN, PP)
Power Filtering

Smoothing

Input AC voltage waveform

Output waveform without capacitor

Output waveform with capacitor

Capacitor Charge

Capacitor Discharge

Bridge Rectifier

Smoothing Capacitor

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Power Filtering

Smoothing

AC / DC

DC / AC, DC / DC, Load, or Energy Source

CHARGE

DISCHARGE

Charge Current

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Considerations for Film or Electrolytic

- Voltage
- Capacitance
- Size
- Lifetime / Ripple Frequency / Temperature

Examples:
- 480V, 1000uF, 60Hz
- 1000V, 47uF, 50kHz
- 100V, 100uF, 100kHz

<table>
<thead>
<tr>
<th></th>
<th>Electrolytic</th>
<th>Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Capacitance</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Size</td>
<td>Low to Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Ripple Frequency</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Temperature</td>
<td>85°C-150°C</td>
<td>&lt;105°C</td>
</tr>
<tr>
<td>Ripple Current</td>
<td>Low to Medium</td>
<td>High</td>
</tr>
</tbody>
</table>
Thank You!