Switched Mode Power Conversion

Capacitors

Devices for Efficient Power Conversion

Switches
Inductors
Transformers
Capacitors
Switched Mode Power Conversion

Capacitors

Capacitors Store Energy
Capacitors Store Energy in an Electric Field
Switched Mode Power Conversion

Capacitors

Capacitors are also used as Switch-Protection Elements

In Switching Aid Networks Capacitors Provide Turn-Off dv/dt Protection
Switched Mode Power Conversion

Capacitors

Electrical Circuit Element Equation

\[ V, C, I \text{ are Electrical Circuit Quantities} \]

\[ I = C \frac{dV}{dt}; \quad V(t) = V_t + \frac{1}{C} \int_{0}^{t} I \, dt \]
Switched Mode Power Conversion

Capacitors

\[ \frac{V}{C} \]

\[ V(t) = V_I + \frac{1}{C} \int_0^t I dt = V_I + \frac{Q}{C} \]

Capacitor Accumulates Charge to Store Energy
Switched Mode Power Conversion

Capacitors – Charge Balance in AC

\[
\begin{align*}
V & \quad \text{C} \quad \text{I} \\
\text{V(t)} & = \text{V(t + T)} \\
\frac{1}{C} \int_{t}^{t+T} \text{Idt} & = 0 ; \int_{t}^{t+T} \text{Idt} = 0
\end{align*}
\]

In Periodic AC Application Net Charge Accumulation Per Cycle is Zero
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**Capacitors**

\[ V(t) = V(t + T) \]

**Capacitor Current is Proportional to \( \frac{dV}{dt} \)**
Switched Mode Power Conversion

Capacitors

\[ V(t) = V(t + T) \]

Charge Balance
Switched Mode Power Conversion

Inductor – Flux Balance

\[ V \]
\[ \begin{array}{c} \mathbb{L} \\ \downarrow \end{array} \]
\[ I \]

\[ I(t) = I(t + T) \]

\[ \frac{1}{L} \int_{t}^{t+T} V \, dt = 0 ; \quad \int_{t}^{t+T} V \, dt = 0 \]

In Periodic AC Application Net Flux Accumulation Per Cycle is Zero Volt-Sec Balance in an Inductor
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Capacitors

\[ V(t) = V_i + \frac{1}{C} \int_0^t I \, dt = V_i + \frac{Q}{C} \]

Capacitor Accumulates Charge to Store Energy
Switched Mode Power Conversion

Capacitors

\[ E = \frac{1}{2} C V^2 \]

Stored Energy Relationship
Switched Mode Power Conversion

Capacitors

\[ E = \frac{1}{2} CV^2 \]

Capacitors are
Selected from Manufacturer’s Catalogue
Switched Mode Power Conversion

Capacitors – Construction

\[ D = \varepsilon E \]

**Electric Flux Density:** \((D)\)

**Dielectric Permittivity:** \((\varepsilon)\)

**Electric Field Intensity:** \((E)\)
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Capacitors – Value

Capacitance is Defined as Charge (Q) per Volt (V)

\[
\frac{Q}{A} = \varepsilon \frac{V}{d} \quad \frac{Q}{V} = C = \varepsilon \frac{A}{d}
\]
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Capacitors – Stored Energy

Energy is Work Done to Separate the Charge Through a Potential of $V$

\[ E = \int_{0}^{V} Q \, dV = \int_{0}^{V} CV \, dV = \frac{1}{2} CV^2 \]
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Capacitors – Energy Density

\[ E = \frac{1}{2} CV^2 = \frac{1}{2} \varepsilon A \frac{E^2 d^2}{d} = 0.5 \varepsilon E^2 \text{ (Volume)} \]

Energy Density is \(0.5 \varepsilon E^2\) Joule/m\(^3\)
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Capacitors – Energy Density in Air

\[
E = \frac{1}{2} CV^2 = \frac{1}{2} \varepsilon A E^2 d^2 = 0.5 \varepsilon E^2 \text{ (Volume)}
\]

\[
\varepsilon = 8.854 \times 10^{-12} \text{ F/m}
\]

\[
E = 3 \times 10^6 \text{ V/m}
\]

Energy Density = 39.84 J/m\(^3\)
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Capacitors – Energy Density in Polyester

\[ E = \frac{1}{2} CV^2 = \frac{1}{2} \varepsilon A E^2 d^2 = 0.5 \varepsilon E^2 \text{ (Volume)} \]

\[ \varepsilon = 4 \times 8.854 \times 10^{-12} \text{ F/m} \]

\[ E = 275 \times 10^6 \text{ V/m} \]

Energy Density = 1.34 MJ/m³
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Capacitors – Energy Density (Bipolar)

\[ E = \frac{1}{2} CV^2 \]

Energy = 65 J
Volume: 0.07 m³
Energy Density: 0.94 kJ/m³
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Capacitors – Energy Density (Electrolytic)

Terminal

Dielectric Material

Terminal

\[ E = \frac{1}{2} CV^2 \]

**Electrolytic**

Energy = 243 J
Volume: 0.04 m³
Energy Density: 6.1 kJ/m³
Switched Mode Power Conversion

Capacitors – Packaging

Dielectric

Terminal 1

Terminal 2

Dielectric

MKV

Electrolytic

Cylindrical Geometry
Switched Mode Power Conversion

Types of Capacitors

Ultra-Capacitors
Electrolytic – Unipolar Capacitors
Metallised Dielectric – Bipolar Capacitors
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Capacitors - Specification

Voltage Rating – Volt

Capacitance Value – Farad
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Capacitors – Life

Electrolytic

Standard Life: 105 °C, 8000 hrs
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Capacitors – Nonidealities

Electrolytic

MKV

Equivalent Series Resistance: ESR

Equivalent Series Inductance: ESL

Leakage Current: I_{lk}
Switched Mode Power Conversion

Capacitors – Nonidealities

Equivalent Series Resistance: ESR

\[ P = I^2 R_{ESR} \]
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Capacitors – Thermal Design

\[ \theta_{\text{rise}} = P R_{\text{th}} \]

**Thermal Resistance:** \( R_{\text{th}} \ ^\circ \text{C/W} \)

[Capacitor]
Switched Mode Power Conversion

Capacitors – Nonidealities

\[ \omega_0 = \frac{1}{2\pi \sqrt{CL_{ESL}}} \]

Equivalent Series Inductance: ESL

Capacitor
Switched Mode Power Conversion

Capacitors – Nonidealities

Leakage Current: $I_{lk}$

Shunt Loss: $V_C I_{lk}$
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Capacitors – Some Calculations

\[ \text{C} = 100 \, \mu\text{F} \]
Switched Mode Power Conversion

Capacitors – Current Calculations

\[ V = 800 \text{ V} \]
\[ I = 80 \text{ A} \]

\[ C = 100 \, \mu\text{F} \]
Switched Mode Power Conversion

Capacitors

\[ V(t) = 800 \text{ V} \]

\[ I(t) = -80 \text{ A} \]

\[ C = 100 \mu\text{F} \]
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Capacitors – Voltage Calculations

\[ C = 100 \, \mu F \]
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Capacitors – Voltage Calculations

\[ \Delta V = \frac{1}{C} \int_{0}^{1.25 \text{ms}} 80 \cos(\omega t) \, dt; \quad \omega = 2\pi \times 200 \text{ rad/sec} \]

\[ C = 100 \, \mu\text{F} \]
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Capacitors – Voltage Calculations

\[
\Delta V = \frac{80}{100 \mu \cdot 400\pi} \left[ \sin(\omega t) \right]_0^{\pi/2} = 637 \text{ V}
\]

\[C = 100 \ \mu\text{F}\]
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Capacitors – Current & Voltage Calculations

\[ V = 800 \text{ V} \quad \text{and} \quad \Delta V = 637 \text{ V} \]

\[ I = 80 \text{ A} \quad \text{and} \quad -80 \text{ A} \]

\[ C = 100 \ \mu\text{F} \]
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Capacitors – Dissipation Calculations

\[ I_{\text{rms}} = \left[ \frac{80^2}{0.125} \right] + \left[ \frac{80^2}{0.125} \right] + \left[ \frac{80^2}{0.5} \times 0.31 \right] = 80^2 \times 0.41 \]

\[ P = 80^2 \times 0.41 \times 1.4 \text{m} = 3.67 \text{W} \]

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\[ C = 100 \, \mu \text{F} \; ; \; R_S = 1.4 \, \text{m} \Omega \]
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Measurement of $C$

\[ V \]
\[ \frac{dV}{dt} \]
\[ \frac{dI}{dt} \]

$I = C \frac{dV}{dt}$

Pulsed Current and Voltage Rise
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Measurement of C with LCR Meter

\[
\vec{I} = \frac{\vec{V}}{j\omega L}
\]

\[
\left| \frac{V}{I} \right| = \frac{1}{\omega C}
\]

Sinusoidal Voltage and Current
Switched Mode Power Conversion

Impedance as a Function of $\omega$

$$\vec{Z} = \frac{\vec{V}}{\vec{I}} = j \omega L$$

Impedance Plot [dBΩ vs log ($\omega$)]
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Impedance with Non-idealities

\[ R_{ESR} = 1.4 \text{ m}\Omega \]
\[ L_{ESL} = 180 \text{ nH} \]
\[ C = 100 \text{ \mu F} \]
\[ \omega_O = 235.7 \text{ krad/sec} \]

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Impedance with Non-idealities

Impedance Plot $[\text{dB} \Omega \text{ vs } \log(\omega)]$
Switched Mode Power Conversion

Impedance with Non-idealities

Impedance Plot \([\text{dB}\Omega \text{ vs log } (\omega)]\)
Switched Mode Power Conversion

Capacitors - Safety

Charge Holding

Discharge Time Constant

> 10000 s : 3 Hours

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Switched Mode Power Conversion

Capacitors – Series Operation

Electrolytic

Capacitors May be Operated in Series
To Obtain Higher Voltage Rating.
(specially for Electrolytic)

Bleeder Current is Chosen Higher than Leakage Current
Switched Mode Power Conversion
Capacitors – Parallel Operation

Capacitors May be Operated in Parallel
To Obtain Higher Ripple Current Rating

Physical Layout to Obtain Symmetry
Switched Mode Power Conversion

Capacitors

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