Switch-Mode Power Supplies

Lesson 10:
Introduction to
Switched-Capacitor Converters

Inductor Disadvantages

- Inductors have several disadvantages:
  - High cost
  - Low power density
  - EMI Pollution
  - Large size
  - Discrete
Steady State Operation Demands

- **Duality:**
  - Inductor: Volt Sec. = 0
  - Capacitor: Ampere Sec = 0

Basic Example (1:1)

- The topology creates voltage balance
- Seemingly no straightforward regulation can be done
Charge Profile (‘Complete Charge’)

- $\tau \ll T_s$
- What are losses dependent on?

\[ E_{C_{SW}} = \frac{C\Delta V^2}{2} \]

\[ E_1 = \int_0^{\infty} \Delta V I(t) dt = C\Delta V \int_0^{\infty} \dot{V}_c(t) dt = C\Delta V^2 \]

\[ P_{loss} = 2 \frac{C\Delta V^2}{2} f_s = C\Delta V^2 f_s \]
Charge Profile ('Complete Charge')

- An average model can be then composed:
  \[ R_{eq} = \frac{\Delta V^2}{P} = \frac{1}{f_s C} \]

Charge profile ('No-charge')

- \( \tau >> T_s \)
- Current can be considered constant
- What are the losses dependent on?
- Both sub-circuits are literally the same and can be considered as one
Charge profile ('No-charge')

\[ P_{\text{Loss}} = \left( \frac{\Delta V}{2} \right)^2 \frac{2}{R} \]

\[ R_{eq} = 4R \]

\[ \Delta V/2 \]

\[ R_{eq} \]

Load

\[ \Delta V^2 \]

\[ R_{eq} \]

\[ I_C \]

\[ \text{Average Model} \]

\[ R_{\text{eq}} \]

Load

\[ R_{el}^* = \frac{R_{el}}{R_i} \]

\[ f_s^* = f_s R_i C_i \]

\[ R_i - \text{charge/discharge Ohmic loop resistance} \]

\[ C_i - \text{charge/discharge loop capacitance} \]

\[ R_{eq} = \frac{1}{2} \frac{C_i}{C_i} \cdot \coth \left( \frac{\beta_1}{2} \right) \cdot \frac{1}{2} \frac{C_i}{C_i} \cdot \coth \left( \frac{\beta_2}{2} \right) \]

\[ \beta_i = \frac{t_i}{R_i C_i}, \quad \frac{1}{2} \frac{t_i}{2 R_i C_i} \quad i = \{1, 2\} \]

\[ \text{A good } \beta \text{ is around} \]
Disadvantages

Conversion ratio impacts efficiency
\[ \eta = \frac{V_o}{V_T} \]

Hard Switching raises \( R_S \)

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Soft Switched SCC

- Utilizes the resonant characteristics of an RLC branch
- Switch transition occurs at half resonance time

\[ \eta = \frac{V_o}{V_T} \]
How SSW-SCC works

For $Q \gg 1$ losses are negligible and at first break $V_{C,1} \approx 2V_{in}$.

- $V_0 = V_{in}$: at second break $V_C \approx 0$.
- $V_0 < V_{in}$: at second break $V_C < 0$.
  - Next cycle: $V_{C,1} > 2V_{in}$
  - The solution diverges, current increases, output voltage increases.
- $V_0 > V_{in}$: at second break $V_C > 0$.
  - Next cycle: $V_{C,1} > 2V_{in}$

\[ V_C(\frac{T_0}{2}) = \frac{C V_c^2}{2} = \frac{C (2V_{in})^2}{2} = 2C V_{in}^2 \]
Soft Switched Capacitor Average Model

\[ R_e = \frac{4Q_1^2 R_1 \cdot \phi_1 \cdot \tanh(\phi_1)}{R_{e1}} + \frac{4Q_2^2 R_2 \cdot \phi_2 \cdot \tanh(\phi_2)}{R_{e2}} \]

A good Q factor is around 1

\[ R_i = \text{charge/discharge Ohmic loop resistance} \]
\[ C_i = \text{charge/discharge loop capacitance} \]
\[ L_i = \text{charge/discharge loop inductance} \]

\[ \omega_0 = \frac{1}{\sqrt{L_i C_i}} ; \quad Q_i = \frac{\omega_0 L_i}{R_i} = \frac{1}{R_i \sqrt{C_i}} \]
\[ \phi_i = \frac{\pi}{2 \cdot \sqrt{4Q_i^2 - 1}} ; \quad i = (1,2) \]