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’)

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

\[ E_{CSW} = \frac{C\Delta V^2}{2} \]
\[ E_1 = \int_0^\infty \Delta V I(t) dt = C\Delta V \int_0^\infty \dot{V}_C(t) dt = C\Delta V^2 \]
\[ P_{loss} = 2 \frac{C\Delta V^2}{2} f_s = C\Delta V^2 f_s \]
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’)

• \( \tau \gg T_s \)
• 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’)

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

\[ R_{\text{eq}} = 4R \]

Average Model

\[ R_{\text{eq}}^* = \frac{R_{\text{eq}}}{f_s^*} \]

\[ f_s^* = f_s R_i C_i \]

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

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

\[ R_{\text{eq}} = \frac{1}{2 f_s C_1} \cdot \coth \left( \frac{\beta_1}{2} \right) + \frac{1}{2 f_s C_2} \cdot \coth \left( \frac{\beta_2}{2} \right) \]

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

- A good \( \beta \) is around
Disadvantages

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

Hard Switching raises \( R_s \)

Soft Switched SCC

• Utilizes the resonant characteristics of an RLC branch
• Switch transition occurs at half resonance time
The Capacitor Voltage and Currents for $Q \gg 1$ will behave as following:

- $I_C(t) = \omega_0 C \Delta V e^{-at} \sin(\omega_0 t)$
- $V_C(t) = V_i - \Delta V e^{-at} \cos(\omega_0 t)$

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: $V_{C,1} > 2V_{in}$
A good Q factor is around 1