Switched Mode Power Conversion
Non-Isolated Converters

Basic Converter Cell
Switched Mode Power Conversion

Non-Isolated Converters

Buck Converter

\[ V_o = \frac{D}{1} V_g \quad 0 < D < 1 \]
Switched Mode Power Conversion

Basic Converter Cell

Three Variants of the Switch-Inductor Cell

Buck

Boost
Switched Mode Power Conversion

Buck Converter

Voltage Input Current Output Converter
Switched Mode Power Conversion

Basic Power Converters

\[ V_0 = \frac{V_I}{1-D} \]

0 < D < 1

Current Input Voltage Output Variant
Switched Mode Power Conversion

Basic Power Converters

Current Input Current Output Variant
Switched Mode Power Conversion

Basic Power Converters

Buck, Boost & Flyback Variants
Switched Mode Power Conversion
Analysis of Flyback Converters

Flyback Converter
Switched Mode Power Conversion

Analysis of Flyback Converters

\[ \frac{V_O}{V_G} \]

\[ \frac{I_O}{I_G} \]

\[ \frac{\Delta I_O}{I_O} \]

\[ \frac{\Delta V_O}{V_O} \]

Switch, Source, Storage Non-ideality

Efficiency

\[ \eta = \frac{P_o}{P_i} \]
Switched Mode Power Conversion

Flyback Converter

\[ \frac{V_O}{V_G} = ? \]

Voltage Conversion Ratio
Switched Mode Power Conversion

Flyback Converter

Inductor Volt-Sec Balance
Switched Mode Power Conversion

Flyback Converter

Inductor Volt-Sec Balance
Switched Mode Power Conversion

Flyback Converter

\[
\begin{align*}
(V_G) T_{ON} + (V_O) T_{OFF} &= 0 \\
\frac{V_O}{V_G} &= -\frac{T_{ON}}{T_{OFF}} = -\frac{D}{1-D}
\end{align*}
\]
Switched Mode Power Conversion

Flyback Converter

$$\frac{V_O}{V_G} = -\frac{T_{ON}}{T_{OFF}} = -\frac{D}{1-D}$$
Switched Mode Power Conversion

Flyback Converter

\[ \frac{I_G}{I_O} = ? \]

Current Conversion Ratio
Switched Mode Power Conversion

Flyback Converter

\[ I_{O(t)} \]

\[ I_L \]

\[ I_{O(t)} = I_L T_{OFF} = I_O T_S \]

Average Output Current
Switched Mode Power Conversion

Flyback Converter

\[ I_{G(t)} \rightarrow I_L \rightarrow I_G \]

\[ I_L \cdot T_{ON} = I_G \cdot T_S \]

Average Input Current
Switched Mode Power Conversion

Flyback Converter

\[ \frac{I_G}{T_{ON}} = -\frac{I_O}{T_{OFF}} \]

\[ \frac{I_G}{I_O} = -\frac{T_{ON}}{T_{OFF}} = -\frac{D}{1-D} \]

\[ \frac{V_O}{V_G} \frac{I_O}{I_G} = 1 \]

Current Conversion Ratio
Switched Mode Power Conversion

Flyback Converter

Ideal Efficiency is Unity
Switched Mode Power Conversion

Flyback Converter

Non-Ideality in the Inductor Current
Switched Mode Power Conversion

Flyback Converter

Inductor Current Ripple – Integral of Inductor Voltage
Switched Mode Power Conversion

Flyback Converter

\[ \Delta I_L = \frac{V_G}{L} DT_S \]

Inductor Current Ripple – Integral of Inductor Voltage
Switched Mode Power Conversion

Flyback Converter

Inductor Current Ripple – Integral of Inductor Voltage

\[
\Delta I_L = \frac{V_o(1-D)}{D L} \frac{D T_S}{L} = \frac{V_o(1-D)}{T_S}
\]

\[
I_L = \frac{I_o}{1-D} = \frac{V_o}{R(1-D)} \quad //
\]
Switched Mode Power Conversion

Flyback Converter

Inductor Current Ripple – Integral of Inductor Voltage

\[
\frac{\Delta I_L}{I_L} = \frac{(1 - D)^2}{L/R} \left( \frac{T_S}{\tau} \right)
\]

\[
\frac{T_S}{\tau} \quad \text{[Integration of Inductor Voltage]}
\]
Switched Mode Power Conversion

Flyback Converter

\[
\Delta I_L = \frac{(1-D)^2}{L/R} I_L T_S \quad \text{TS} \ll \frac{L}{R}
\]

Condition for Low Ripple Current
Switching Period TS << Circuit Time Constant (L/R)
Switched Mode Power Conversion

Flyback Converter

\[ \frac{V_O}{V_G} = ? \]

Non-Ideality of the Switches
Switched Mode Power Conversion

Flyback Converter

Volt-Sec Balance on Inductor
Switched Mode Power Conversion

Flyback Converter

\[
\left( V_G - V_T \right) T_{ON} + \left( V_O + V_D \right) T_{OFF} = 0
\]

Volt-Sec Balance on Inductor
Switched Mode Power Conversion

Flyback Converter

\[ V_O = D \frac{1 - \frac{V_{T\|}}{V_{G\|}}}{1 - D \frac{1 + \frac{V_{D\|}}{V_{O\|}}}{1 + \frac{V_D}{V_O}}} \]

\[ \eta = \frac{1 - \frac{V_T}{V_G}}{1 + \frac{V_D}{V_O}} \]

Volt-Sec Balance on Inductor
Switched Mode Power Conversion

Flyback Converter

\[ \frac{I_G}{I_O} = - \frac{D}{1-D} \]

Current Averaging
Switched Mode Power Conversion

Flyback Converter

\[ \eta = \frac{1 - \frac{V_T}{V_G}}{1 + \frac{V_D}{V_O}} \]

Efficiency of Power Conversion
Switched Mode Power Conversion

Flyback Converter

Non-Ideality of the Inductor

Diagram showing the flyback converter circuit with symbols for timing and currents.
Switched Mode Power Conversion

Flyback Converter

\[
(V_G - I_LR_1)T_{on} + (V_O - I_LR_1)T_{off} = 0
\]

\[
V_G D = -V_O(1-D) + I_LR_1 = -V_O(1-D) - \frac{I_O}{(1-D)}R_1
\]

\[
DV_G = -V_O(1-D) - \frac{V_O R_1}{(1-D)}R
\]

Volt-Second Balance
Switched Mode Power Conversion
Flyback Converter

\[ DV_G = -V_o(1-D) - \frac{V_o}{(1-D)} \frac{R_1}{R} \]

Define: \[ \alpha = \frac{R_1}{R} \]

\[ \frac{V_o}{V_G} = \frac{D}{(1-D)} \left( \frac{1}{1 + \frac{\alpha}{1-(1-D)^2}} \right) \]

Voltage Conversion Ratio
Switched Mode Power Conversion

Flyback Converter

\[
\frac{V_O}{V_G} = -\frac{D}{(1-D)} \left(\frac{1}{1 + \frac{\alpha}{(1-D)^2}}\right)
\]

\[
\frac{I_G}{I_O} = -\frac{D}{(1-D)}
\]

\[
\eta = \frac{V_O I_O}{V_G I_G} = \frac{1}{\left(1 + \frac{\alpha}{(1-D)^2}\right)}
\]

Efficiency of Power Conversion
Switched Mode Power Conversion

Flyback Converter

\[
\frac{V_O}{V_G} = - \frac{D}{(1-D)} \left( 1 + \frac{\alpha}{(1-D)^2} \right)
\]

Real Forward Voltage Gain
Switched Mode Power Conversion

Flyback Converter

\[
\frac{V_O}{V_G} = -\frac{D}{(1-D)} \left( 1 + \frac{\alpha}{(1-D)^2} \right)
\]

Real Forward Voltage Gain
Switched Mode Power Conversion

Flyback Converter

\[
\frac{V_O}{V_G} = \frac{-D}{(1-D)} \left( \frac{1}{1 + \frac{\alpha}{(1-D)^2}} \right)
\]

\[
\frac{V_O}{V_G} = \frac{-D(1-D)}{((1-D)^2 + \alpha)}
\]

\[
d \left( \frac{V_O}{V_G} \right) = 0 \Rightarrow \alpha = (1-D)^2
\]

Real Forward Voltage Gain
Switched Mode Power Conversion

Flyback Converter

Efficiency of a Real Converter

$$\eta = \frac{1}{1 + \frac{\alpha}{(1-D)^2}}$$

$$\eta = \frac{(1-D)^2}{(1-D)^2 + \alpha}$$
Switched Mode Power Conversion
Flyback Converter

\[ \eta = \frac{1}{1 + \frac{\alpha}{(1-D)^2}} \]
\[ \eta = \frac{(1-D)^2}{(1-D)^2 + \alpha} \]

Preferred Operating Region

Preferred Range of Duty Ratio

Ideal
Real

Efficiency Gain

Gain

\[ V_o/V_G \]

\[ \eta > 0.5 \]

\[ 1 - \sqrt{\alpha} \]

\[ 1 - \frac{1}{2\sqrt{\alpha}} \]
Switched Mode Power Conversion

Flyback Converter

Output Voltage Ripple
Switched Mode Power Conversion

Flyback Converter

- Capacitor Charge Balance
Switched Mode Power Conversion

Flyback Converter

Capacitor Charge Balance
Switched Mode Power Conversion

Flyback Converter

\[ \Delta V_o = \frac{I_o D T_s}{C} = \frac{V_o D T_s}{R C} \]

Capacitor Charge Balance
Switched Mode Power Conversion

Flyback Converter

\[ \Delta V_o = \Delta V_o(t) \]

Design Guideline: \( T_s \ll RC \)

Capacitor Charge Balance
Switched Mode Power Conversion

Flyback Converter

Ideal Voltage Gain

\[ \frac{V_O}{V_G} = \frac{-T_{ON}}{T_{OFF}} = \frac{D}{1-D} \quad \text{VOLT-SEC} \]
Switched Mode Power Conversion
Flyback Converter

Ideal Voltage Gain

Ideal Current Gain

\[
\frac{I_G}{I_O} = -\frac{T_{ON}}{T_{OFF}} = -\frac{D}{1-D}
\]
Switched Mode Power Conversion
Flyback Converter

Ideal Voltage Gain
Ideal Current Gain
Current Ripple

\[
\Delta I_L = \frac{(1 - D)^2 T_s}{(L/R)} I_L
\]

\[
T_s \ll \frac{T_s}{4R} = \frac{L}{R}
\]
Switched Mode Power Conversion

Flyback Converter

- Ideal Voltage Gain
- Ideal Current Gain
- Current Ripple
- Voltage Ripple

\[
\frac{\Delta V_o}{V_o} = \frac{D T_s}{R C}
\]

Select \( L \) and \( C \)...
Switched Mode Power Conversion
Flyback Converter

Ideal Voltage Gain
Ideal Current Gain
Current Ripple
Voltage Ripple
Real Voltage Gain

\[
\frac{V_O}{V_G} = - \frac{D}{(1-D)} \frac{1}{1+\frac{\alpha}{(1-D)^2}}
\]

\[
\frac{V_O}{V_G} = - \frac{D}{1-D} \left( \frac{1-\frac{V_T}{V_G}}{1+\frac{V_D}{V_O}} \right)
\]

\[
V_T \ll V_G, \quad V_D \ll V_O
\]
Switched Mode Power Conversion
Flyback Converter

Ideal Voltage Gain
Ideal Current Gain √
Current Ripple
Voltage Ripple
Real Voltage Gain
Real Current Gain √

\[ \frac{I_G}{I_O} = -\frac{T_{ON}}{T_{OFF}} = -\frac{D}{1-D} \]
Switched Mode Power Conversion

Flyback Converter

Ideal Voltage Gain
Ideal Current Gain
Current Ripple
Voltage Ripple
Real Voltage Gain
Real Current Gain
Efficiency
Switched Mode Power Conversion
Flyback Converter

Ideal Voltage Gain
Ideal Current Gain
Current Ripple
Voltage Ripple
Real Voltage Gain
Real Current Gain
Efficiency
Preferred Operating Range

\[ 0 \leq D \leq \left(1 - \sqrt{\alpha}\right); \quad \alpha = \frac{R_1}{R} \]
Switched Mode Power Conversion

Buck-Boost Converter

\[ V_a \]

\[ R \]
Switched Mode Power Conversion
Converter Cells

\[ \frac{V_b}{V_a} = \frac{D}{1-D} \]

\[ \frac{V_a}{V_a} = 1 \]

\[ I \]

\[ T_1 \]

\[ T_2 \]

\[ V_o \]

\[ V_a \]

\[ V_b \]

\[ \frac{V_b}{V_a} \]

\[ \frac{V_a}{V_a} \]
Switched Mode Power Conversion

Basic Power Converters

Buck, Boost & Flyback Variants
Switched Mode Power Conversion
Dual Converter Cell

Diagram showing the dual converter cell with switches T1 and T2, inductance L, and capacitors C. The diagram illustrates the concept of dual converter cells with ON and OFF states for the switches.
Switched Mode Power Conversion

Dual Converter Cell

Buck Current Converter
Switched Mode Power Conversion

Dual Converter Cell

\[ T_{\text{ON}} : \quad I_c = (I_G - I_O) \]
\[ T_{\text{OFF}} : \quad I_c = -I_O \]
\[ (I_G - I_O) T_{\text{ON}} - I_O T_{\text{OFF}} = 0 \]
\[ \frac{I_G}{I_O} = \frac{T_{\text{ON}}}{T_{\text{OFF}}} = \frac{1 - D}{D} \]

Buck Current Converter
Switched Mode Power Conversion

Dual Converter Cell

\[ I_G \cdot T_{ON} + (I_G - I_O) \cdot T_{OFF} = 0 \]

\[ I_O = I_G \]

\[ \frac{I_S}{T_{OFF}} = \frac{I_G}{(1 - D)} \]

Boost Current Converter
Switched Mode Power Conversion

Dual Converter Cell

Buck-Boost Current Converter
Switched Mode Power Conversion

Steady State Performance

- Ideal Voltage Gain
- Ideal Current Gain
- Current Ripple
- Voltage Ripple
- Real Voltage Gain
- Real Current Gain
- Efficiency
- Preferred Operating Range
Switched Mode Power Conversion

Non-Isolated Converters

Input and Output are Electrically Connected
Switched Mode Power Conversion

Isolated Converters

Electrical Isolation Between Input & Output