Switched Mode Power Conversion

Non-Isolated Converters

Basic Converter Cell
Switched Mode Power Conversion

Non-Isolated Converters

Buck Converter
Switched Mode Power Conversion

Non-Isolated Converters

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

Buck Converter
Switched Mode Power Conversion

Non-Isolated Converters

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

Buck Converter
Switched Mode Power Conversion

Non-Isolated Converters

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

\[
\Delta I_O = \frac{(1-D)T_S}{(L/R)}
\]

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

Buck Converter
Switched Mode Power Conversion

Non-Isolated Converters

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

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

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

\[
\frac{\Delta V_O}{V_O} = \frac{(1-D)T_s^2}{8LC}
\]

Buck Converter
Switched Mode Power Conversion

Non-Isolated Converters

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

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

\[
\frac{\Delta V_O}{V_O} = \frac{(1-D)T_s^2}{8LC}
\]

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

Buck Converter
Switched Mode Power Conversion

Non-Isolated Converters

**Buck Converter**

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

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

\[
\frac{\Delta V_O}{V_O} = \frac{(1-D)T_s^2}{8LC}
\]

\[
\frac{V_O}{V_G} = D \left( 1 - \frac{V_T}{V_G} - \frac{(1-D)V_D}{D V_G} \right) \left( 1 + \frac{DR_S + R_1}{R} \right) \]

\[
\eta = \frac{V_O I_O}{V_G I_G} = \frac{1 - \frac{V_T}{V_G} - \frac{(1-D)V_D}{D V_G}}{1 + \frac{DR_S + R_1}{R}}
\]
Switched Mode Power Conversion

Non-Isolated Converters

Step-Down Converter

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

Ideal
Real
Switched Mode Power Conversion

Basic Converter Cell

Three Variants of the Switch-Inductor Cell
Switched Mode Power Conversion

Buck Converter

Voltage Input Current Output Converter
Switched Mode Power Conversion

Basic Power Converters

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 & Buck-Boost Variants
Switched Mode Power Conversion
Analysis of Boost Converters

Boost Converter
Switched Mode Power Conversion

Analysis of Boost Converters

Voltage Gain $\frac{V_O}{V_G}$

Current Gain $\frac{I_O}{I_G}$

Current Ripple $\Delta I_O/I_O$

Voltage Ripple $\Delta V_O/V_O$

Switch, Source, Storage Non-ideality

Efficiency
Switched Mode Power Conversion

Boost Converter

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

Voltage Conversion Ratio
Switched Mode Power Conversion

Boost Converter

Inductor Volt-Sec Balance
Switched Mode Power Conversion

Boost Converter

Inductor Volt-Sec Balance
Switched Mode Power Conversion

Boost Converter

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

\[
\frac{V_O}{V_G} = \frac{T_S}{T_{OFF}} = \frac{1}{1-D}
\]
Switched Mode Power Conversion

Boost Converter

\[
\frac{V_O}{V_G} = \frac{T_S}{T_{OFF}} = \frac{1}{1-D}
\]
Switched Mode Power Conversion

Boost Converter

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

Current Conversion Ratio
Switched Mode Power Conversion

Boost Converter

\[ I_G \cdot T_{OFF} = I_O \cdot T_S \]

Average Output Current
Switched Mode Power Conversion

Boost Converter

\[ I_G \cdot T_{OFF} = I_O \cdot T_S \]

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

Current Conversion Ratio
Switched Mode Power Conversion

Boost Converter

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

Ideal Efficiency is Unity
Switched Mode Power Conversion

Boost Converter

Non-Ideality in the Inductor Current
Switched Mode Power Conversion

Boost Converter

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

Boost Converter

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

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

Boost Converter

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

\[ I_L = \frac{I_o}{1-D} = \frac{V_o}{R(1-D)} \]

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

Boost Converter

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

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

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

Condition for Low Ripple Current
Switching Period \( T_s \ll \) Circuit Time Constant \( (L/R) \)
Switched Mode Power Conversion

Boost Converter

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

Non-Ideality of the Switches
Switched Mode Power Conversion

Boost Converter

Volt-sec balance on inductor

Diagram showing the switch mode power converter with inductor, diode, and capacitor.
Switched Mode Power Conversion

Boost Converter

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

Volt-Sec Balance on Inductor
Switched Mode Power Conversion

Boost Converter

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

\[ \eta = \left( 1 - \frac{DV_T}{V_G} - \frac{(1-D)V_D}{V_G} \right) \]

Volt-Sec Balance on Inductor
Switched Mode Power Conversion

Boost Converter

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

Current Averaging
Switched Mode Power Conversion

Boost Converter

\[
\frac{V_o I_o}{V_g I_g} = \frac{1}{1-D} \left( 1 - \frac{D V_T}{V_g} - \frac{(1-D) V_D}{V_g} \right) \frac{1-D}{1}
\]

\[
\eta = \left( 1 - \frac{D V_T}{V_g} - \frac{(1-D) V_D}{V_g} \right)
\]

Efficiency of Power Conversion
Switched Mode Power Conversion

Boost Converter

Non-Ideality of the Inductor
Switched Mode Power Conversion

Boost Converter

\[(V_G - I_L R_1)T_{on} + (V_G - I_L R_1 - V_O)T_{off} = 0\]

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

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

Volt-Second Balance
Switched Mode Power Conversion

Boost Converter

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

Define: \( \alpha = \frac{R_1}{R} \)

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

Voltage Conversion Ratio
Switched Mode Power Conversion

Boost Converter

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

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

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

Efficiency of Power Conversion
Switched Mode Power Conversion

Boost Converter

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

Real Forward Voltage Gain
Switched Mode Power Conversion

Boost Converter

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

Real Forward Voltage Gain
Switched Mode Power Conversion

Boost Converter

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

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

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

Real Forward Voltage Gain
Switched Mode Power Conversion

Boost Converter

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

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

Efficiency of a Real Converter

Gain: \( V_o/V_G \)

Efficiency: \( \eta \)

Gain: \( 1 - \sqrt{\alpha} \)

Gain: \( D \)

Gain: \( 1 \)

Gain: \( 0 \)

Gain: \( 0.5 \)
Switched Mode Power Conversion

Boost Converter

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

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

Preferred Range of Duty Ratio

Efficiency Gain

Preferred Operating Region

Preferred Range of Duty Ratio
Switched Mode Power Conversion

Boost Converter

Output Voltage Ripple
Switched Mode Power Conversion

Boost Converter

Capacitor Charge Balance
Switched Mode Power Conversion

Boost Converter

I_o(t)

0 T_{ON} T_S t

V_o(t)

\Delta V_o

Capacitor Charge Balance
Switched Mode Power Conversion

Boost 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

Boost Converter

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

Design Guideline: \( T_s \ll RC \)

Capacitor Charge Balance
Switched Mode Power Conversion

Boost Converter

Ideal Voltage Gain

\[
\frac{V_O}{V_G} = \frac{T_S}{T_{OFF}} = \frac{1}{1 - D}
\]
Switched Mode Power Conversion

Boost Converter

Ideal Voltage Gain

Ideal Current Gain

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

Boost Converter

Ideal Voltage Gain

Ideal Current Gain

Current Ripple

\[
\frac{\Delta I_L}{I_L} = \frac{(1-D)^2}{(L/R)} DT_s
\]
Switched Mode Power Conversion

Boost Converter

Ideal Voltage Gain
Ideal Current Gain
Current Ripple
Voltage Ripple

\[
\frac{\Delta V_o}{V_o} = \frac{D T_s}{R C}
\]
Switched Mode Power Conversion

Boost Converter

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

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

\[
\frac{V_O}{V_G} = \frac{1}{1-D} \left( 1 - \frac{D V_T}{V_G} - \frac{(1-D)V_D}{V_G} \right)
\]
Switched Mode Power Conversion

Boost Converter

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

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

**Boost Converter**

- **Ideal Voltage Gain**
- **Ideal Current Gain**
- **Current Ripple**
- **Voltage Ripple**
- **Real Voltage Gain**
- **Real Current Gain**
- **Efficiency**

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

\[
\eta = \left(1 - \frac{D V_T}{V_G} - \frac{(1-D)V_D}{V_G}\right)
\]
Switched Mode Power Conversion

Boost 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