Switched Mode Power Conversion

Primitive Converters

Interconnection
of
Switches & Energy Storage Elements
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Interconnection of Switches & Energy Storage Elements

\[ T_1 \quad T_2 \quad L \quad C \]
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Interconnection

of

Switches & Energy Storage Elements
to

Source and Load

\[ V_G \]
\[ I_G \]

\[ T_1 \]
\[ T_2 \]

\[ P \]

\[ L \]

\[ C \]

\[ R \]
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Interconnection Rules

Sources may not be Overloaded
Voltage Sources are not to be Shorted
Current Sources are not to be Opened

Conservation of Energy
Inductor Currents are not to be Interrupted
Capacitor Voltages are not to be Shorted
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Interconnection Rules

Voltage sources may not be connected across PT₁ or PT₂

No Short Circuit of Voltage Sources

Capacitors may not be connected across PT₁ or PT₂

No Disruption of Energy on the Capacitor
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Interconnection Rules

Current sources may not be connected in series with $T_1$ or $T_2$

No Open Circuit of Current Sources

Inductor may not be connected in series with $T_1$ or $T_2$

No Disruption of Energy on the Inductor
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Acceptable Switch-Storage Cells

Two possible switch+storage cells
These are dual of each other
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Primitive Voltage to Current Converter

Input average quantities: $V_G$ and $I_G$
Output average quantities: $I_O$ and $V_O$
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Strategy of Operation & Control

Constant Switching Period

$T_1 P$ ON Time $T_{ON}$ ; $T_2 P$ OFF Time $T_{OFF}$

$T_{ON} + T_{OFF} = T_S$
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Primitive Current to Voltage Converter

Input average quantities: $I_G$ and $V_G$

Output average quantities: $V_O$ and $I_O$
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Primitive Voltage to Current Converter

Ideal Performance Measures
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Primitive Voltage to Current Converter

First Performance Measure
Forward Voltage Conversion Ratio

\[
\frac{V_O}{V_G} = ?
\]
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Primitive Voltage to Current Converter

Performance Measures

Forward Voltage Conversion Ratio

Reverse Current Conversion Ratio
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Forward Voltage Conversion Ratio

Average voltage across inductor in one cycle is zero
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Forward Voltage Conversion Ratio

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

\[\frac{V_O}{V_G} = \frac{T_{ON}}{T_S} = D\]
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Reverse Current Transfer Ratio

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

Reverse Current Conversion Ratio
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Reverse Current Transfer Ratio

\[ I_O T_{ON} - I_G T_S = 0 \]

\[ \frac{I_G}{I_O} \frac{T_{ON}}{T_S} = D \]
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Efficiency of Ideal Converter is Unity

\[
\frac{I_G}{I_O} = ? \quad \text{and} \quad \frac{V_O}{V_G} = ?
\]
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Primitive Voltage to Current Converter

Non-Ideality in the Converter Current $I_O$
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Ripple Current in the Inductor

\[ \Delta I_O = \frac{V_O}{L}(T_S - T_{ON}) = \frac{V_O}{L}(1 - D)T_S \]
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Normalised Ripple Current

\[
\frac{\Delta I_O}{I_O} = \frac{V_O}{I_O L} (1 - D) T_S = \frac{(1 - D) T_S}{L/R}
\]
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Condition for Ripple Current to be Low

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

\[
T_s \geq \frac{L}{R}
\]

Switching Period << Circuit Time Constant
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Primitive Voltage to Current Converter

Non-Ideality in the Switches – Conduction Drop
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Switches are Realised by Real Devices

\[ V_{G} \quad T_{1} \quad P \quad V_{P} \quad T_{2} \quad L \quad V_{O} \]

\[ T_{1P} \text{ Drop is } V_{T}; \quad T_{2P} \text{ Drop is } V_{D} \]
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$T_{1P}$ Drop is $V_T$; $T_{2P}$ Drop is $V_D$

Inductor ON State Voltage is $V_G - V_T - V_O$

Inductor OFF State Voltage is $-V_D - V_O$
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Volt-Sec Balance on the Inductor

\[
(V_G - V_T - V_O)T_{ON} - (V_D + V_O)(T_S - T_{ON}) = 0
\]
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Forward Voltage Transfer Ratio

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

\[ V_O = D V_G \left( 1 - \frac{V_T}{V_G} - \frac{(1-D) V_D}{D V_G} \right) \]
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Reverse Current Transfer Ratio

\[ I_O T_{ON} - I_G T_S = 0 \]

\[ \frac{I_G}{I_O} = \frac{T_{ON}}{T_S} = D \]
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Switch Non-ideality is Series Non-ideality

\[
\frac{I_G}{I_O} = \frac{T_{ON}}{T_S} = D
\]

Switch Non-idealities have no Effect on Current Ratio
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Efficiency

\[ I_G = \frac{T_{ON}}{T_S} = D \]

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

\[ \eta = \frac{V_O I_O}{V_G I_G} = \left( 1 - \frac{V_T}{V_G} - \frac{(1-D)V_D}{DV_G} \right) \]
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Primitive Voltage to Current Converter

Non-Ideality in the Source & Inductor
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Source & Inductor Have Internal Resistances

Source Resistance is $R_S$
Inductor Resistance is $R_L$
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Volt-Sec Balance on the Inductor

\[
\left( V_G - I_O (R_S + R_1) - V_O \right) T_{ON} - \left( I_O R_1 + V_O \right) (T_S - T_{ON}) = 0
\]
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Forward Voltage Transfer Ratio

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

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

\[
(V_G - I_O (R_S + R_1) - V_O) T_{ON} - (I_O R_1 + V_O)(T_S - T_{ON}) = 0
\]
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Reverse Current Transfer Ratio

\[ I_O T_{ON} - I_G T_S = 0 \]

\[ \frac{I_G}{I_O} = \frac{T_{ON}}{T_S} = D \]
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Efficiency

\[
\frac{I_G}{I_O} = \frac{T_{ON}}{T_S} = D
\]

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

\[
\eta = \frac{V_O I_O}{V_G I_G} = \left( \frac{1}{1 + \frac{DR_S + R_1}{R}} \right)
\]
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Efficiency with Switch/Source/Inductor Drops

\[ \eta = \frac{V_O I_O}{V_G I_G} = \left( \frac{1 - \frac{V_T}{V_G} - \frac{(1-D)V_D}{D V_G}}{1 + \frac{D R_s}{R} + \frac{R_i}{R}} \right) \]
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Guidelines for Good Efficiency

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

\[ V_T \square V_G ; V_D \square V_O \]

\[ R_S \square R ; R_1 \square R \]
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Non-ideality Related to Output Voltage

Output Voltage Ripple is a Function of the Load
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Evaluation of the Output Voltage Ripple

Capacitor Supported Load is Common
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Inductor Current & Output Voltage Ripple

Output Voltage Ripple is $\Delta V_O$
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Inductor Current & Output Voltage Ripple

\[ \Delta I_o = \frac{V_o}{L} (1 - D) T_s \]

Charge causing voltage ripple
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Inductor Current & Output Voltage Ripple

Charge causing voltage ripple

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

\[ \Delta V_o = \frac{\Delta I_o}{2} \frac{1}{T_S} \frac{1}{2} \frac{1}{C} \]
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Inductor Current & Output Voltage Ripple

\[ \Delta I_o = \frac{V_o}{L} (1 - D) T_s \]

\[ \Delta V_o = \frac{V_o (1 - D) T_s}{2L} \left( \frac{1}{2} \frac{T_s}{2} \frac{1}{C} \right) = \frac{V_o (1 - D) T_s^2}{8LC} \]

\[ \frac{\Delta V_o}{V_o} = \frac{(1 - D) T_s^2}{8LC} \]
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Guidelines for Low Output Ripple

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

Switching Period \(<<\) Natural Frequency

\[ T_s \ll \frac{1}{\sqrt{LC}} \]
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Summary of Steady State Performance

Voltage Gain $V_O/V_G$

Current Gain $I_O/I_G$

Current Ripple $\Delta I_O/I_O$

Voltage Ripple $\Delta V_O/V_O$

Switch Non-ideality

Source Non-ideality

Storage Non-ideality

Efficiency
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Summary of Steady State Performance

Inductor Volt-sec Balance: $V_o/V_G$

Current Averaging: $I_o/I_G$

Inductor Volt-sec in Sub-period: $\Delta I_o/I_o$

Capacitor Charge in Sub-period: $\Delta V_o/V_o$

Inductor Volt-sec Balance with Non-ideality: $\eta$
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Transistor Amplifiers

Transistor Amplifier Variants
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Buck, Boost & Buck-Boost Variants
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Buck, Boost & Buck-Boost Variants