Switched Mode Power Conversion
Converters in Canonical Form

The SPDT Supports Unidirectional Current
Switched Mode Power Conversion

Operating Modes – CCM and DCM

Inductor Current Cannot Reverse Direction
Switched Mode Power Conversion

Buck Converter – Inductor Current

Inductor Current is Positive and Continuous
Switched Mode Power Conversion

Buck Converter – Inductor Current

Inductor $L_2 < L_1$
Switched Mode Power Conversion

Buck Converter – Inductor Current

Inductor Current is Positive and Continuous
Switched Mode Power Conversion
Buck Converter – Inductor Current

Frequency $F_{S2} < F_{S1}$ ; $T_{S1} < T_{S2}$
Switched Mode Power Conversion

Buck Converter – Inductor Current

Inductor Current is Positive and Continuous
Switched Mode Power Conversion

Buck Converter – Inductor Current

Load Current $I_{L1}(av) > I_{L2}(av)$
Switched Mode Power Conversion

Buck Converter – Inductor Current

$L, T_S, R$
Switched Mode Power Conversion

Buck Converter – DCM

Third State: Transistor & Diode Both are OFF
Switched Mode Power Conversion

Buck Converter – DCM

T₁ Transistor ON Time
Switched Mode Power Conversion

Buck Converter – DCM

$T_2$ Diode ON Time
Swiched Mode Power Conversion

**Buck Converter – DCM**

T₃ Transistor & Diode are Both OFF
Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

Inductor Volt-Sec Balance
Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \]

\[ \frac{T_2}{T_S} = d_2 \]

\[(V_G - V_O)T_1 - V_O T_2 = 0\]

\[dV_G = (d + d_2) V_O\]

\[\frac{V_O}{V_G} = M = \frac{d}{d + d_2}\]

Voltage Conversion Ratio
Switched Mode Power Conversion
Buck Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \]

\[ \frac{T_2}{T_S} = d_2 \]

Resolving \( d_2 \) as a function of \( d \)
Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

\[
\frac{T_1}{T_S} = d
\]

\[
\frac{T_2}{T_S} = d_2
\]

\[
I_p = d_2 V_O T_S / L
\]

\[
I_o = \frac{V_O}{R} = \frac{1}{2} I_p (d + d_2) = \frac{1}{2} (d + d_2) \frac{d_2 T_S V_O}{L}
\]

Resolving \( d_2 \) as a function of \( d \)
Switched Mode Power Conversion
Buck Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \]

\[ \frac{T_2}{T_S} = d_2 \]

\[ I_O = \frac{V_O}{R} = \frac{1}{2} I_P (d + d_2) = \frac{1}{2} (d + d_2) \frac{d_2 T_S V_O}{L} \]

\[ d_2 (d + d_2) = \frac{2L}{R T_S} = K \]

\[ d \text{ and } d_2 \text{ are related through Conduction Parameter } K \]
Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

\[
\frac{T_1}{T_S} = d
\]

\[
\frac{T_2}{T_S} = d_2
\]

\[
d_2 \left( d + d_2 \right) = \frac{2L}{RT_S} = K
\]

\[
d_2 = \frac{-d + d\sqrt{1 + \left(\frac{4K}{d^2}\right)}}{2}
\]

*d and \(d_2\) are related through Conduction Parameter \(K\)*
Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \]

\[ \frac{T_2}{T_S} = d_2 \]

\[ d_2 = \frac{-d + d\sqrt{1 + \left(\frac{4K}{d^2}\right)}}{2} \]

\[ M = \frac{V_O}{V_G} = \frac{2}{1 + \sqrt{1 + \left(\frac{4K}{d^2}\right)}} \]

Conversion Factor is a Function of d and K
Switched Mode Power Conversion
Buck Converter – DCM Conversion Ratio

\[
\frac{T_1}{T_S} = d \\
\frac{T_2}{T_S} = d_2
\]

\[
M = \frac{d}{d + d_2} > d \quad (\therefore (d + d_2) < 1)
\]

Conversion Factor in DCM is More
Switched Mode Power Conversion

Buck Converter – Border Between DCM & CCM

\[ \frac{T_1}{T_s} = d \]
\[ \frac{T_2}{T_s} = d_2 \]

\[ d_2 (d + d_2) = (1 - d) = \frac{2L}{RT_s} = K \]

\[ \frac{2L}{RT_s} > (1 - d) \Rightarrow \text{Op. Mode is CCM} \]
\[ \frac{2L}{RT_s} < (1 - d) \Rightarrow \text{Op. Mode is CCM} \]

Border of DCM and CCM
Switched Mode Power Conversion

Buck Converter – Border Between DCM & CCM

\[
\frac{T_1}{T_S} = d \\
\frac{T_2}{T_S} = d_2
\]

Define \( K_{cri} = (1-d) \)

\( K > K_{cri} : \text{CCM Operation} \quad \text{or} \quad K < K_{cri} : \text{CCM Operation} \)}

Border of DCM and CCM
Switched Mode Power Conversion

Buck Converter – Border Between DCM & CCM

Graphical Determination of DCM and CCM

\[ \frac{2L}{\text{RT}_s} < (1 - D) \quad \text{DCM} \]

\[ \frac{2L}{\text{RT}_s} > (1 - D) \quad \text{CCM} \]
Switched Mode Power Conversion

Buck Converter

\[
\frac{2L}{RT_s} < (1 - D)
\]

DCM

CCM

\[
\frac{2L}{RT_s} > (1 - D)
\]

Gain is More in DCM
Switched Mode Power Conversion

DCM Operation – Salient Features

- Zero (Low) Turn-on Loss
- Soft Diode Recovery
- Low Circuit Inductance
- High Inductor Ripple

Inductor Current
Switched Mode Power Conversion

Boost Converter – Inductor Current

\[ V_G \rightarrow L \rightarrow V_D \rightarrow V_T \rightarrow V_O \]

\[ I_L(t) \]

Inductor Current
Switched Mode Power Conversion
Boost Converter – DCM Conversion Ratio

Inductor Volt-Sec Balance
Switched Mode Power Conversion

Boost Converter – DCM Conversion Ratio

\[
\frac{T_1}{T_S} = d \quad \frac{T_2}{T_S} = d_2
\]

\[
V_G T_1 + (V_G - V_O) T_2 = 0 \quad (d + d_2) V_G = d_2 V_O
\]

\[
\frac{V_O}{V_G} = M = \frac{d + d_2}{d_2}
\]

Voltage Conversion Ratio
Switched Mode Power Conversion
Boost Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \]
\[ \frac{T_2}{T_S} = d_2 \]

Resolving \( d_2 \) as a function of \( d \)
Switched Mode Power Conversion

Boost Converter – DCM Conversion Ratio

\[
\frac{T_1}{T_S} = d
\]

\[
\frac{T_2}{T_S} = d_2
\]

\[
I_p = dV_G T_S / L
\]

\[
I_o = \frac{V_o}{R} = \frac{1}{2} I_p d_2 = \frac{1}{2} d_2 \frac{dT_S V_G}{L}
\]

Resolving \(d_2\) as a function of \(d\)
Switched Mode Power Conversion
Boost Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \]

\[ \frac{T_2}{T_S} = d_2 \]

\[ I_O = \frac{V_O}{R} = \frac{1}{2} I_P d_2 = \frac{1}{2} d_2 \] \frac{dT_S V_G}{L} \]

\[ K(d + d_2) = dd_2 \]

\[ K = \frac{2L}{RT_S} \]

d and \( d_2 \) are related through Conduction Parameter \( K \)
Switched Mode Power Conversion
Boost Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \quad \frac{T_2}{T_S} = d_2 \]

\[ K(d + d_2) = dd_2^2 \]

\[ d_2 = \frac{K}{d} \left\{ \frac{1 + \sqrt{1 + \left( \frac{4d^2}{K} \right)}}{2} \right\} \]

\( d \) and \( d_2 \) are related through Conduction Parameter \( K \).
Switched Mode Power Conversion
Boost Converter – DCM Conversion Ratio

\[
\frac{T_1}{T_S} = d \quad \quad \frac{T_2}{T_S} = \frac{d_2}{d_2}
\]

\[
\frac{V_O}{V_G} = \frac{d + d_2}{d_2} = \frac{d}{K}
\]

\[
\frac{V_O}{V_G} = \left\{ 1 + \sqrt{1 + \left( \frac{4d^2}{K} \right) \right\} \right/ 2
\]

\text{d and d}_2 \text{ are related through Conduction Parameter K}
Switched Mode Power Conversion

Boost Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \]

\[ \frac{T_2}{T_S} = d_2 \]

\[ M = \frac{d + d_2}{d_2} > \frac{1}{(1-d)} \quad (\because (d + d_2) < 1) \]

Conversion Factor in DCM is More
Switched Mode Power Conversion
Boost Converter – Border Between DCM & CCM

\[ \frac{T_1}{T_S} = d \]

\[ \frac{T_2}{T_S} = d_2 \]

\[ K(d + d_2) = dd_2^2 \]

\[ K_{cri} = d(1 - d)^2 \]

Border of DCM and CCM
Switched Mode Power Conversion
Boost Converter – Border Between DCM & CCM

\[ \frac{T_1}{T_S} = d \]

\[ \frac{T_2}{T_S} = d_2 \]

Define \( K_{cri} = d(1-d)^2 \)

\( K > K_{cri} : \) CCM Operation \hspace{1cm} \( K < K_{cri} : \) CCM Operation

Border of DCM and CCM
Switched Mode Power Conversion
Boost Converter – Border Between DCM & CCM

Graphical Determination of DCM and CCM
Switched Mode Power Conversion

Boost Converter – Border Between DCM & CCM

Graphical Determination of DCM and CCM

\[ K_{\text{cri}} = d(1 - d)^2 \]

CCM

DCM

CCM

0 \quad 1/3 \quad d \quad 1

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

Graphical Determination of DCM and CCM
Switched Mode Power Conversion

Boost Converter – DCM & CCM

Graphical Determination of DCM and CCM

\[ K_{\text{cri}} = d(1 - d)^2 \]

CCM

DCM

CCM

\[ \frac{V_O}{V_G} \]
Switched Mode Power Conversion
Boost Converter – DCM & CCM

Gain in DCM is More than Gain in CCM

$K_{cri} \approx \frac{4}{27} \text{ and } K_{cri} = d(1 - d)^2$
Switched Mode Power Conversion

Flyback Converter – Inductor Current

Inductor Current

\[ I_L(t) \]

\[ T_{ON} \quad T \quad T_{OFF} \]

\[ V_G \quad T_1 \quad T_2 \quad V_O \]

\[ L \]
Switched Mode Power Conversion
Flyback Converter – DCM Conversion Ratio

Inductor Volt-Sec Balance
Switched Mode Power Conversion
Flyback Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_s} = d \]

\[ \frac{T_2}{T_s} = d_2 \]

\[ V_G T_1 + V_O T_2 = 0 \]

\[ dV_G = -d_2 V_O \]

\[ \frac{V_O}{V_G} = M = -\frac{d}{d_2} \]

Voltage Conversion Ratio
Switched Mode Power Conversion
Flyback Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \]

\[ \frac{T_2}{T_S} = d_2 \]

Resolving \( d_2 \) as a function of \( d \)
Switched Mode Power Conversion
Flyback Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \]

\[ T_{ON} \quad T_{OFF} \]

\[ \frac{T_2}{T_S} = d_2 \]

\[ I_P = dV_G T_S / L \]

\[ I_O = \frac{V_O}{R} = \frac{1}{2} I_P d_2 = \frac{1}{2} d_2 \frac{dT_S V_G}{L} \]

Resolving \( d_2 \) as a function of \( d \)
Switched Mode Power Conversion
Flyback Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \]

\[ \frac{T_2}{T_S} = d_2 \]

\[ I_0 = \frac{V_O}{R} = \frac{1}{2} I_P d_2 = \frac{1}{2} d_2 \frac{dT_S V_G}{L} \]

\[ K = d_2^2 \; ; \; K = \frac{2L}{RT_S} \]

d and \( d_2 \) are related through Conduction Parameter \( K \)
Switched Mode Power Conversion

Flyback Converter – DCM Conversion Ratio

\[ \frac{T_1}{T_S} = d \]

\[ \frac{V_O}{V_G} = \frac{d}{d_2} \]

\[ \frac{T_2}{T_S} = d_2 \]

\[ d_2^2 = K \]

\[ \frac{V_O}{V_G} = \frac{d}{\sqrt{K}} \]

\[ d \text{ and } d_2 \text{ are related through Conduction Parameter } K \]
Switched Mode Power Conversion

Flyback Converter – DCM Conversion Ratio

\[
\frac{T_1}{T_S} = d \quad \text{and} \quad \frac{T_2}{T_S} = d_2
\]

\[
|M| = \frac{d}{d_2} > \frac{d}{(1-d)} \quad (\because (d + d_2) < 1)
\]

Conversion Factor in DCM is More
Switched Mode Power Conversion
Flyback Converter – Border Between DCM & CCM

\[ \frac{T_1}{T_S} = d \]

\[ \frac{T_2}{T_S} = d_2 \]

\[ K = d_2^2 \]

\[ K_{cri} = (1 - d)^2 \]

Border of DCM and CCM
Switched Mode Power Conversion
Flyback Converter – Border Between DCM & CCM

\[
\frac{T_1}{T_S} = d
\]

\[
\frac{T_2}{T_S} = d_2
\]

Define \( K_{cri} = (1-d)^2 \)

\( K > K_{cri} : \) CCM Operation

\( K < K_{cri} : \) CCM Operation

Border of DCM and CCM
Switched Mode Power Conversion
Flyback Converter – Border Between DCM & CCM

Graphical Determination of DCM and CCM

\[ K_{cri} = (1 - d)^2 \]

- For DCM: \[ 2 \frac{L}{RT_s} < (1 - d)^2 \]
- For CCM: \[ 2 \frac{L}{RT_s} > (1 - d)^2 \]
Switched Mode Power Conversion
Flyback Converter – Border Between DCM & CCM

\[ K_{\text{cri}} = (1 - d)^2 \]

Graphical Determination of DCM and CCM
Switched Mode Power Conversion
Flyback Converter – Border Between DCM & CCM

Graphical Determination of DCM and CCM

\[ K_{cri} = (1 - d)^2 \]
Switched Mode Power Conversion

DCM Operation – Salient Features

- Zero (Low) Turn-on Loss
- Soft Diode Recovery
- Low Circuit Inductance
- High Inductor Ripple

Inductor Current

$I_L(t)$