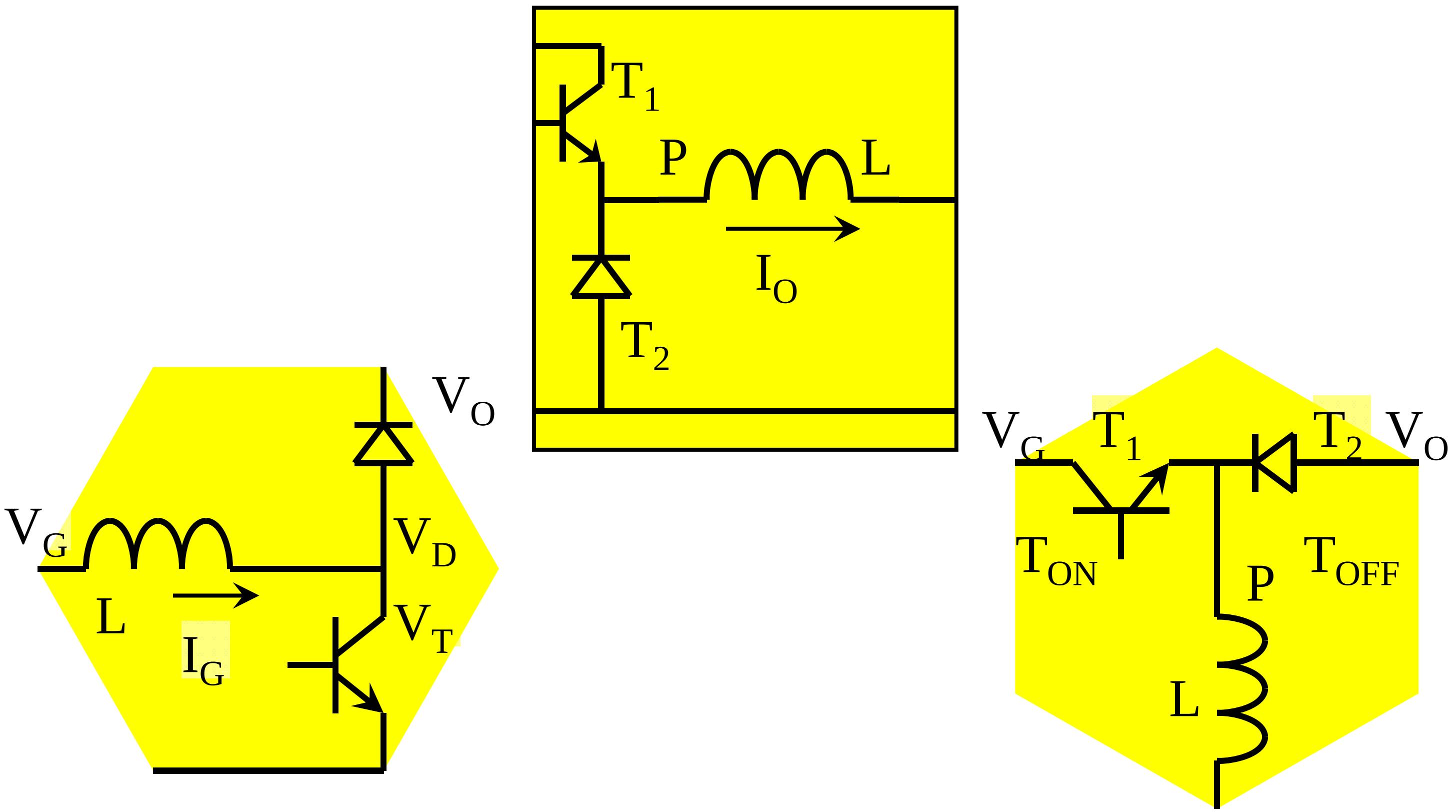
Switched Mode Power Conversion

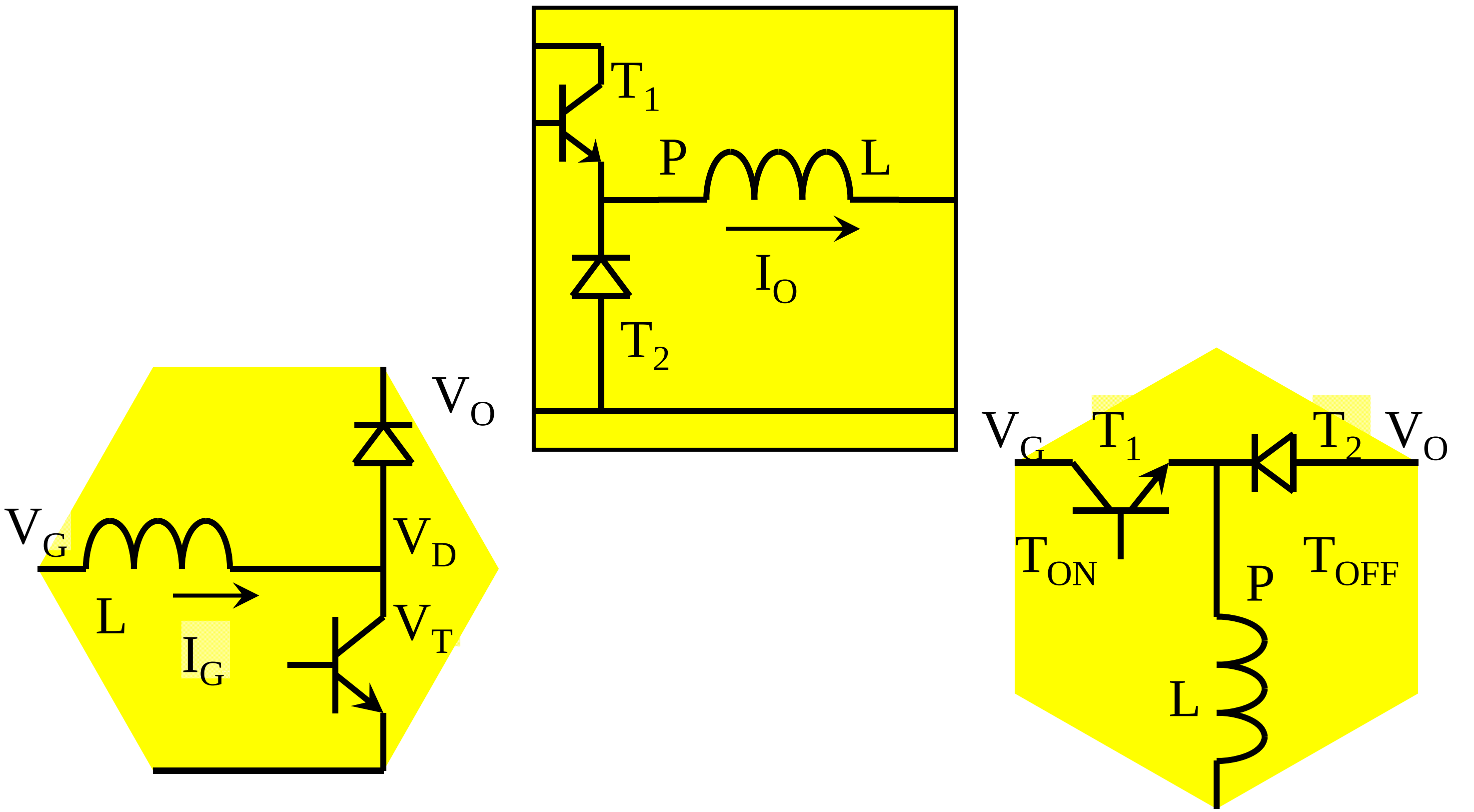
Converters in Canonical Form



The SPDT Supports Unidirectional Current

Switched Mode Power Conversion

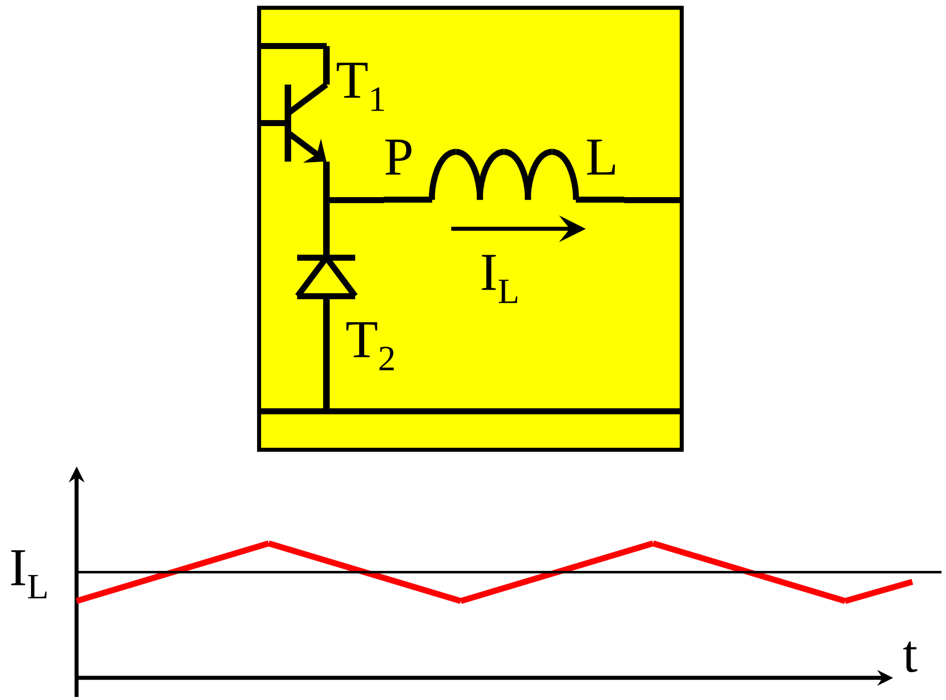
Operating Modes – CCM and DCM



Inductor Current Cannot Reverse Direction

Switched Mode Power Conversion

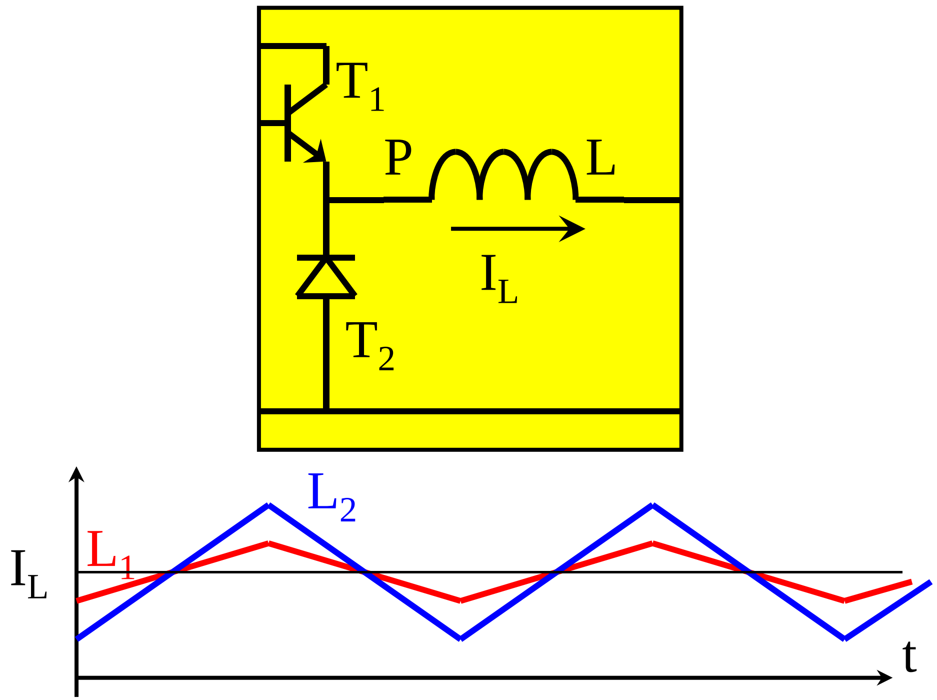
Buck Converter – Inductor Current



Inductor Current is Positive and Continuous

Switched Mode Power Conversion

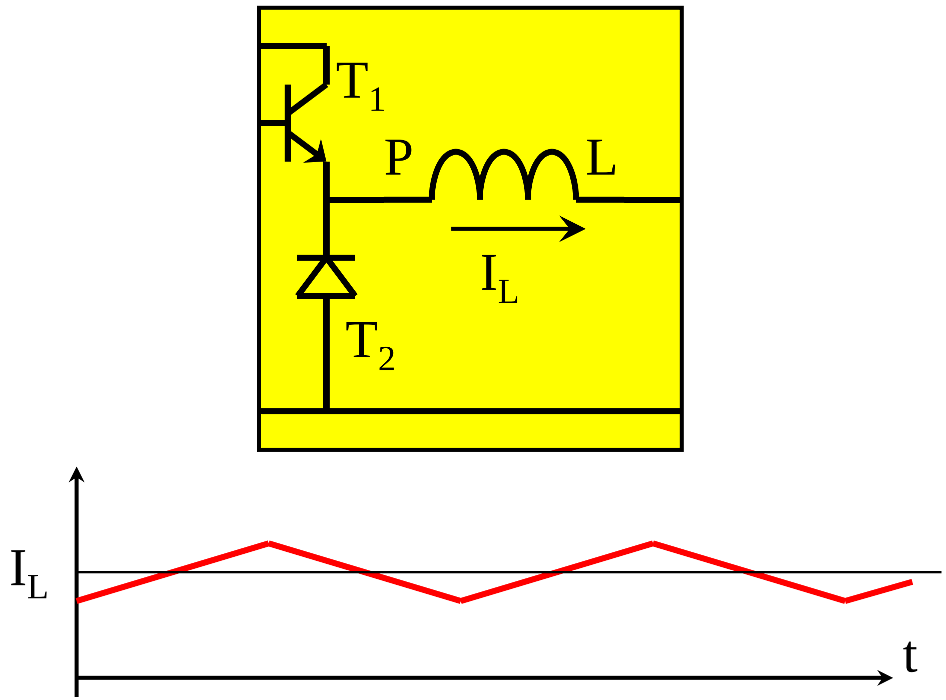
Buck Converter – Inductor Current



Inductor $L_2 < L_1$

Switched Mode Power Conversion

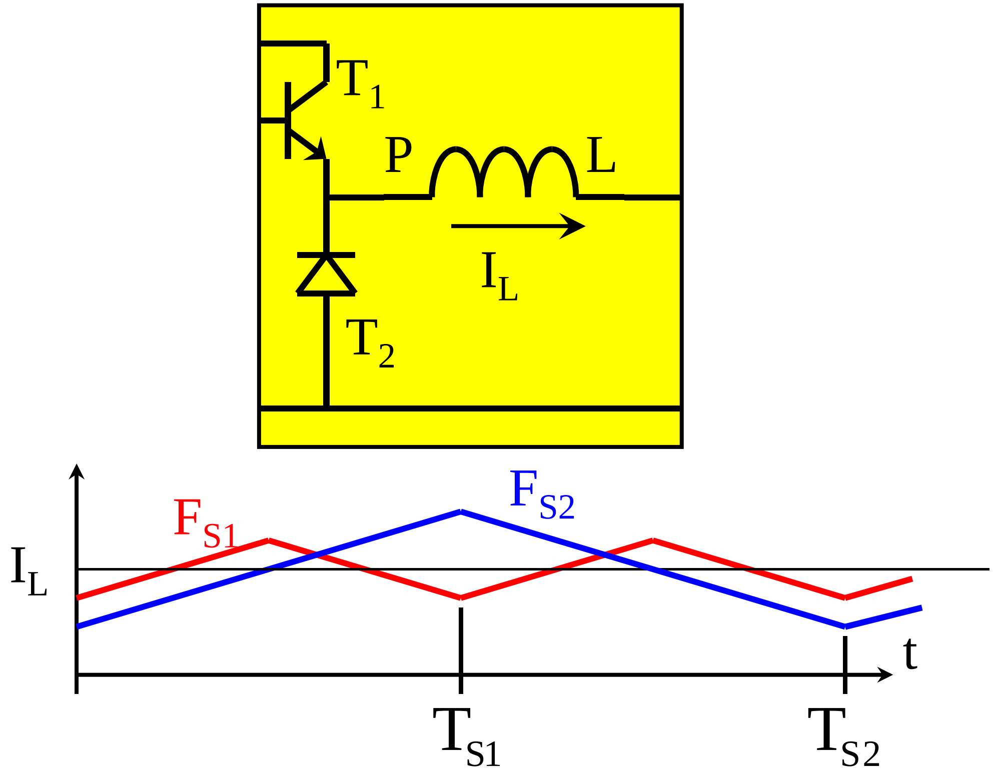
Buck Converter – Inductor Current



Inductor Current is Positive and Continuous

Switched Mode Power Conversion

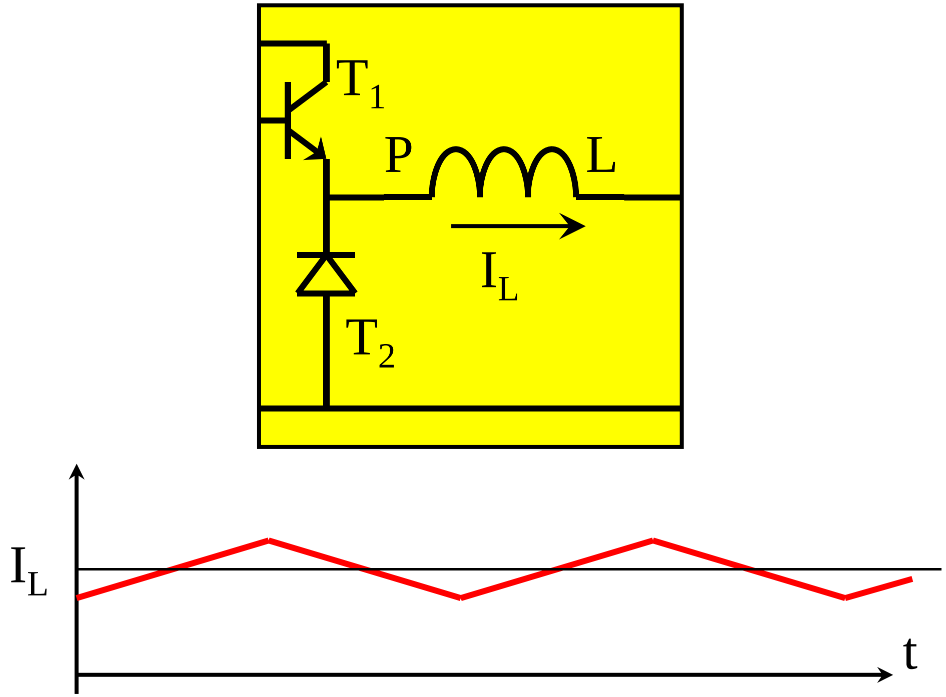
Buck Converter – Inductor Current



Frequency $F_{S2} < F_{S1}$; $T_{S1} < T_{S2}$

Switched Mode Power Conversion

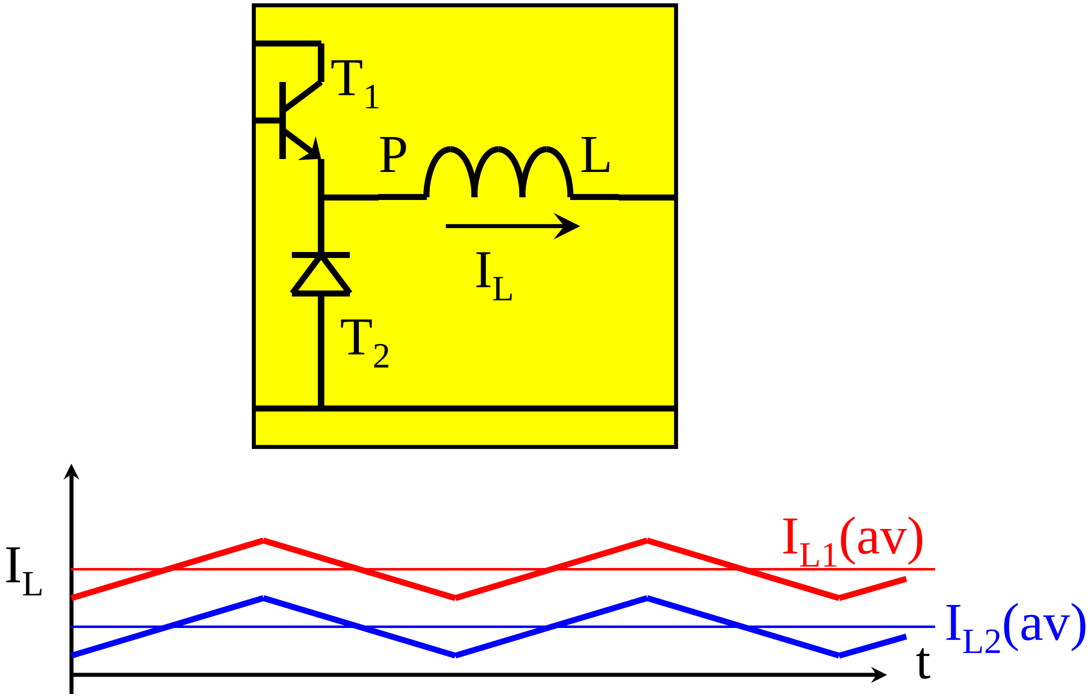
Buck Converter – Inductor Current



Inductor Current is Positive and Continuous

Switched Mode Power Conversion

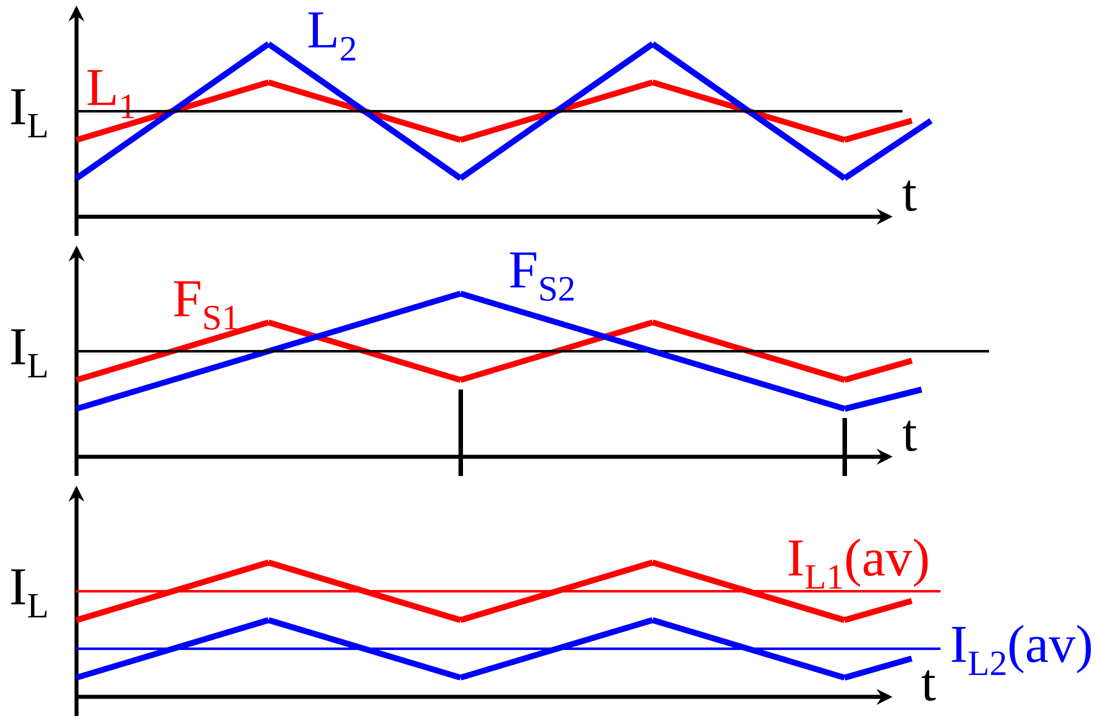
Buck Converter – Inductor Current



Load Current $I_{L1}(av) > I_{L2}(av)$

Switched Mode Power Conversion

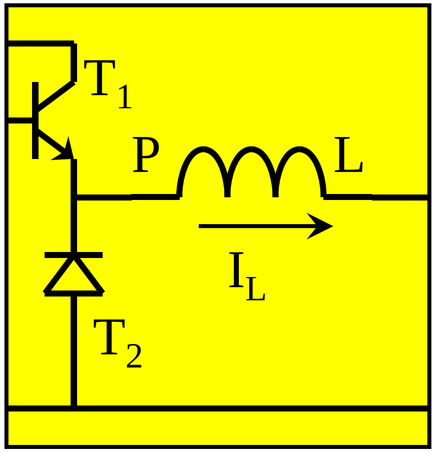
Buck Converter – Inductor Current

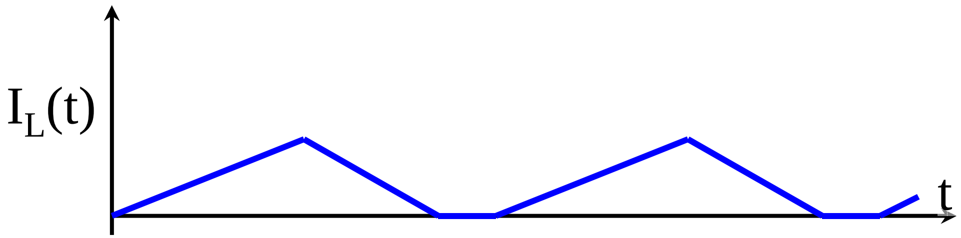


L, T_S, R

Switched Mode Power Conversion

Buck Converter – DCM

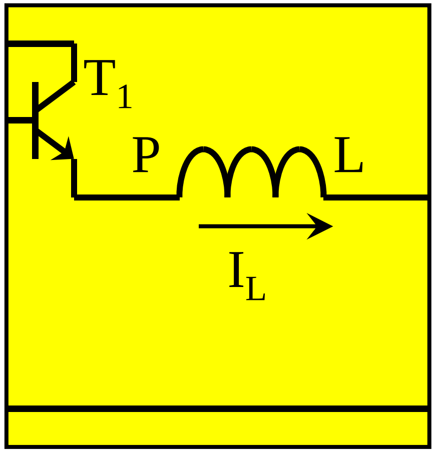


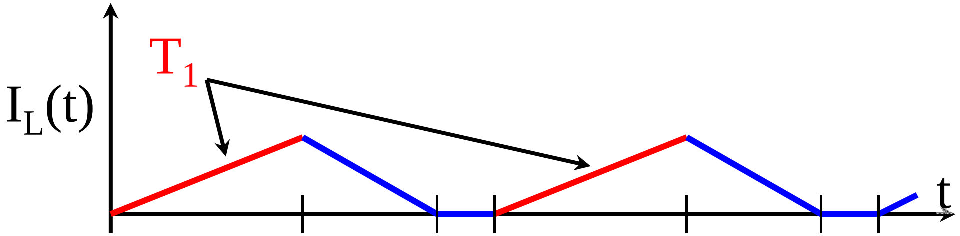


Third State: Transistor & Diode Both are OFF

Switched Mode Power Conversion

Buck Converter – DCM

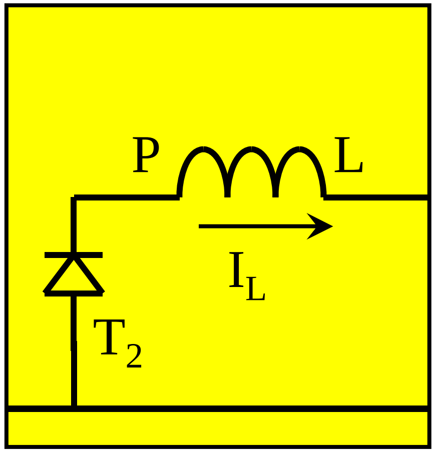


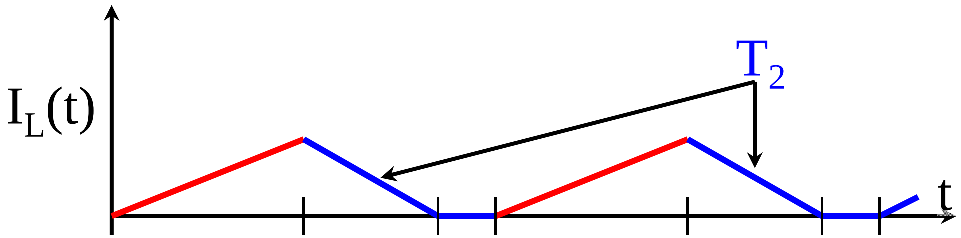


T_1 Transistor ON Time

Switched Mode Power Conversion

Buck Converter – DCM

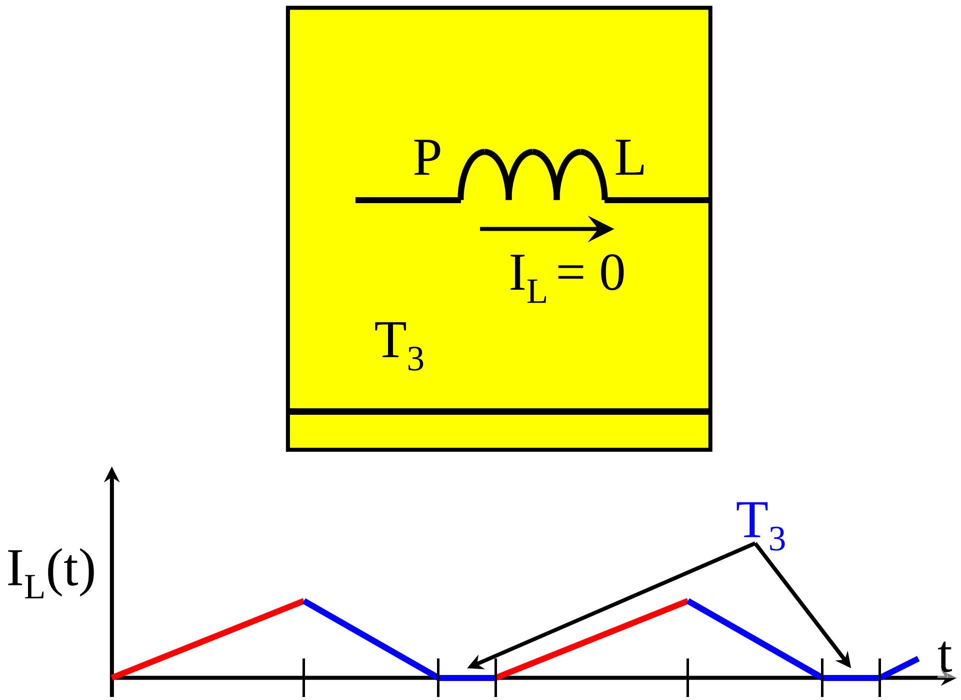




T_2 Diode ON Time

Switched Mode Power Conversion

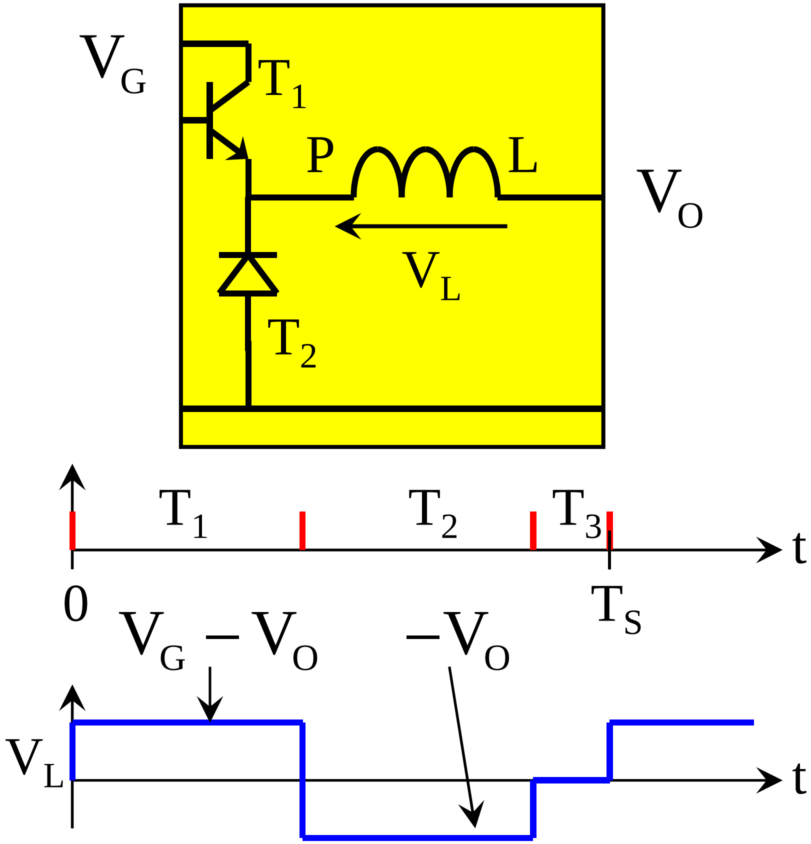
Buck Converter – DCM



T_3 Transistor & Diode are Both OFF

Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

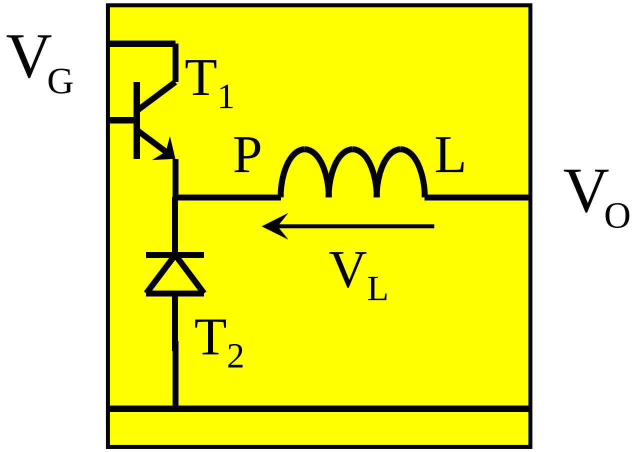


Inductor Volt-Sec Balance

Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$(V_G - V_O)T_1 - V_O T_2 = 0$$

$$dV_G = (d + d_2)V_O$$

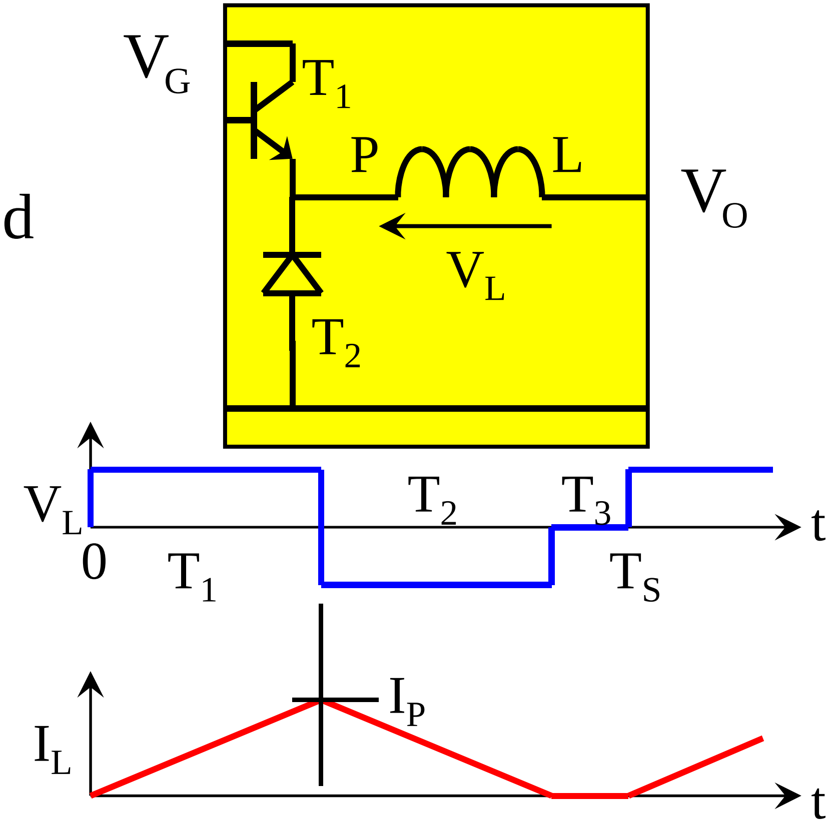
$$\frac{V_O}{V_G} = M = \frac{d}{d + d_2}$$

Voltage Conversion Ratio

Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



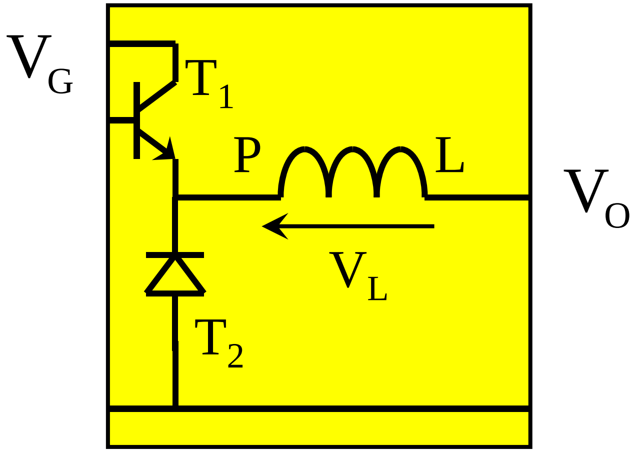
$$\frac{T_2}{T_S} = d_2$$

Resolving d_2 as a function of d

Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$I_P = d_2 V_O T_S / L$$

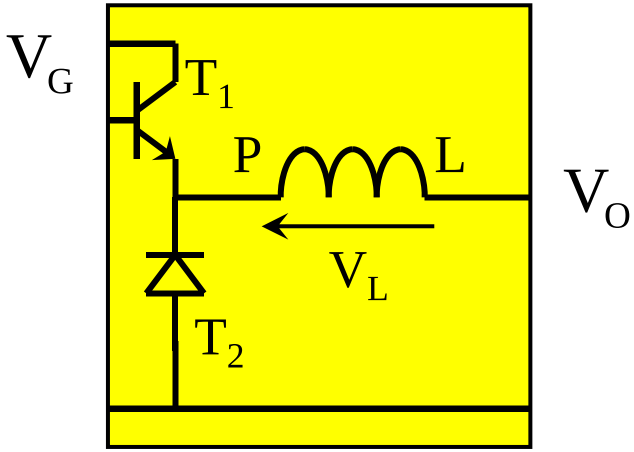
$$I_O = \frac{V_O}{R} = \frac{1}{2} I_P \left(d + d_2 \right) = \frac{1}{2} \left(d + d_2 \right) \frac{d_2 T_S V_O}{L}$$

Resolving d_2 as a function of d

Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$I_O = \frac{V_O}{R} = \frac{1}{2} I_P \left(d + d_2\right) = \frac{1}{2}\left(d + d_2\right) \frac{d_2 T_S V_O}{L}$$

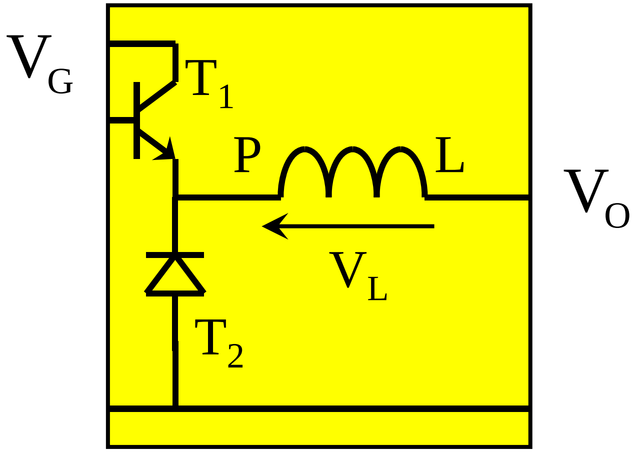
$$d_2\left(d + d_2\right) = \frac{2L}{RT_S} = K$$

d and d_2 are related through Conduction Parameter K

Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

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

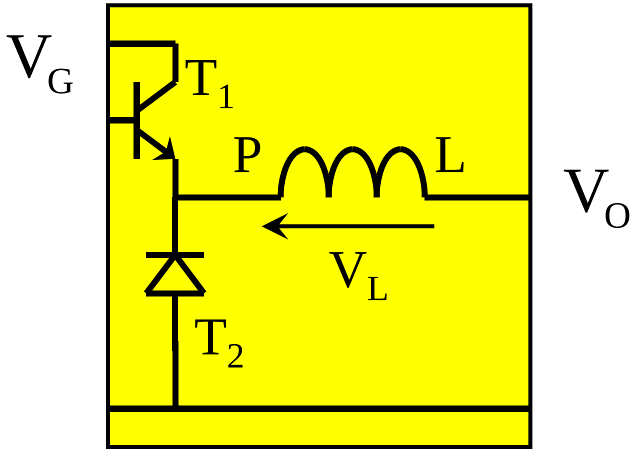
$$d_2 = \frac{-d + d\sqrt{1 + \left(4K/d^2\right)}}{2}$$

d and d_2 are related through Conduction Parameter K

Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

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

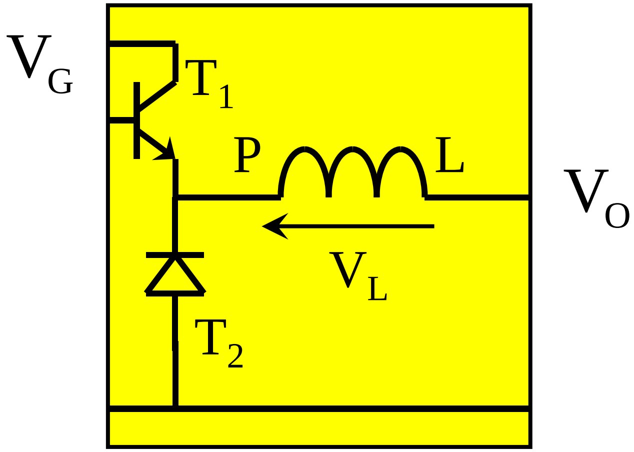
$$M = \frac{V_O}{V_G} = \frac{2}{1 + \sqrt{1 + \left(4K/d^2\right)}}$$

Conversion Factor is a Function of d and K

Switched Mode Power Conversion

Buck Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

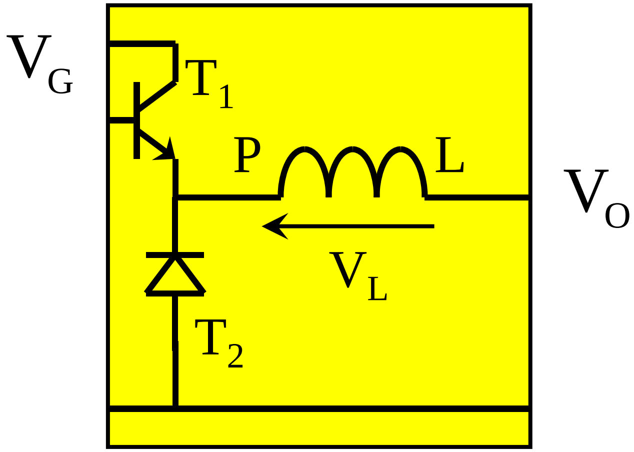
$$M = \frac{d}{d + d_2} > d \quad \left(\because (d + d_2) < 1\right)$$

Conversion Factor in DCM is More

Switched Mode Power Conversion

Buck Converter – Border Between DCM & CCM

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$d_2\left(d + d_2\right) = \left(1 - d\right) = \frac{2L}{RT_S} = K$$

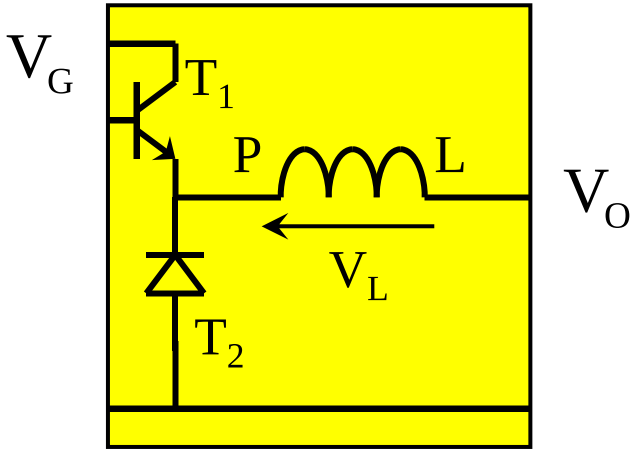
$$\frac{2L}{RT_S} > (1-d) \Rightarrow \text{ Op.Mode is CCM} \qquad \frac{2L}{RT_S} < (1-d) \Rightarrow \text{ Op.Mode is CCM}$$

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)

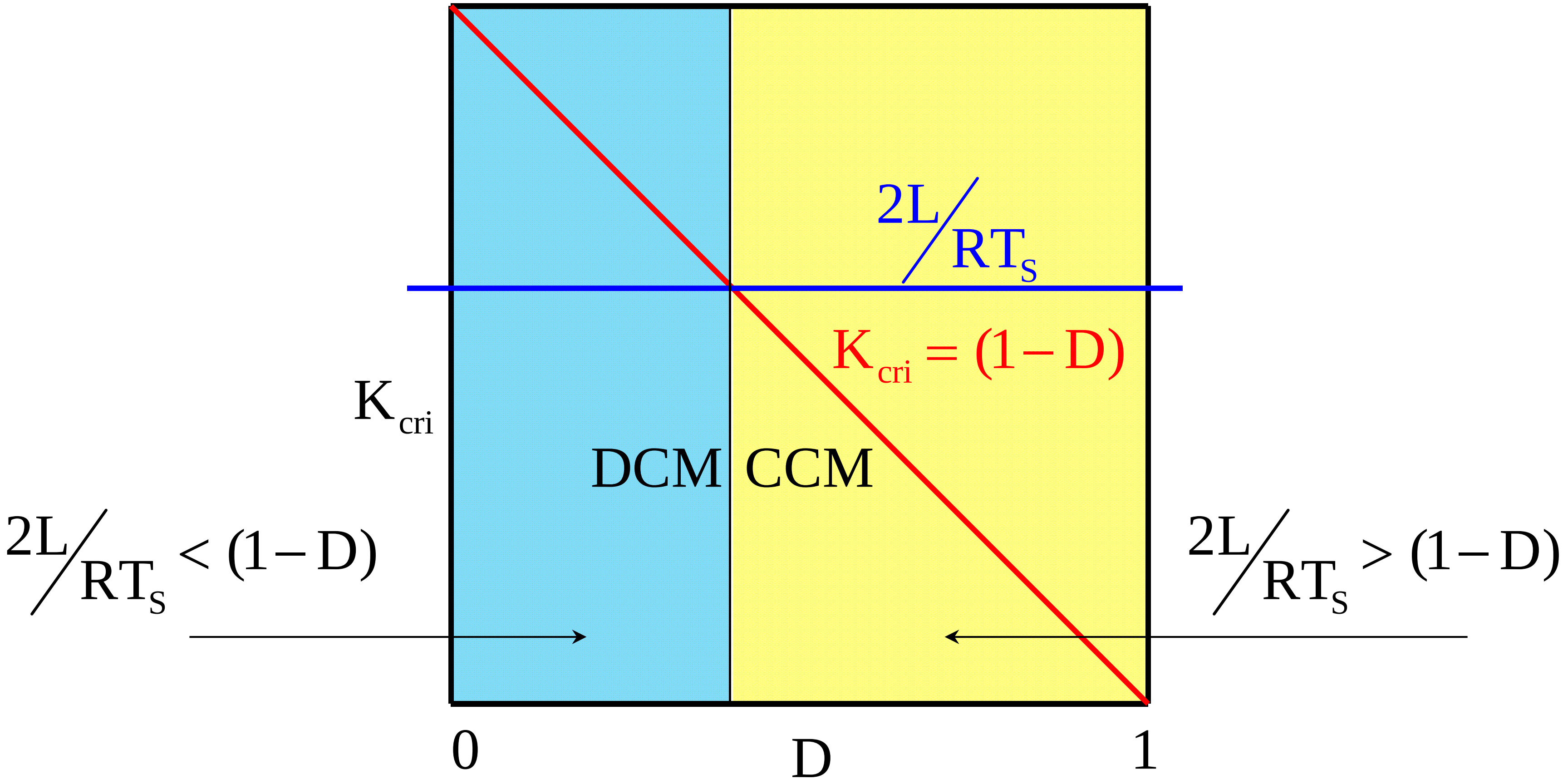
$K > K_{cri}$: CCM Operation

$K < K_{cri}$: CCM Operation

Border of DCM and CCM

Switched Mode Power Conversion

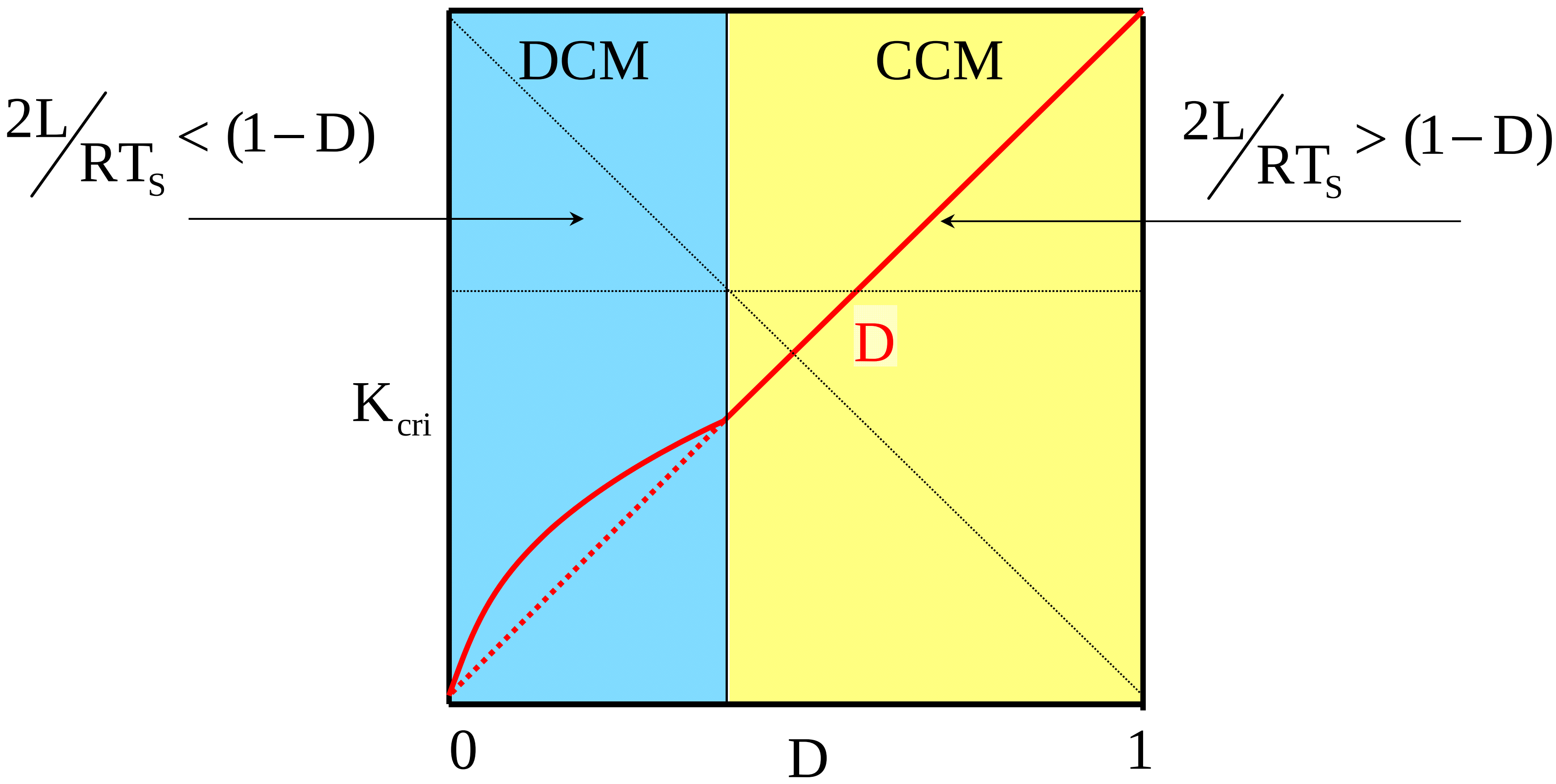
Buck Converter – Border Between DCM & CCM



Graphical Determination of DCM and CCM

Switched Mode Power Conversion

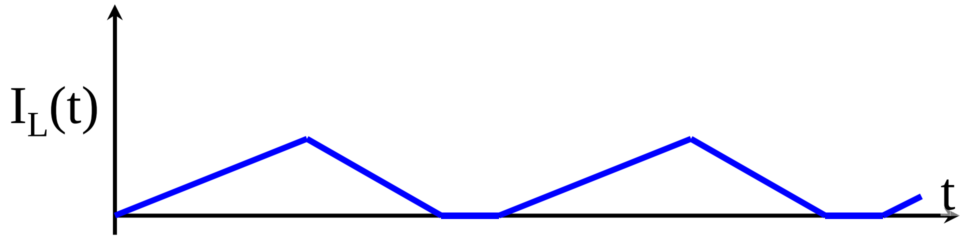
Buck Converter



Gain is More in DCM

Switched Mode Power Conversion

DCM Operation – Salient Features



Zero (Low) Turn-on Loss

Soft Diode Recovery

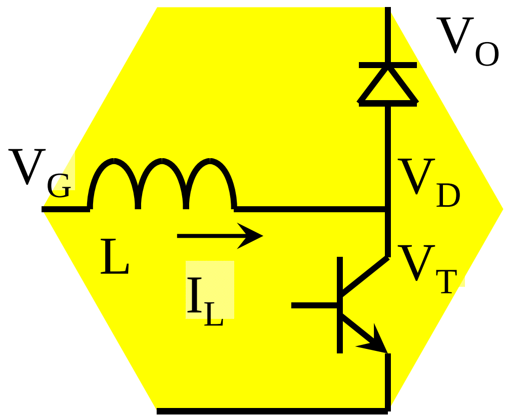
Low Circuit Inductance

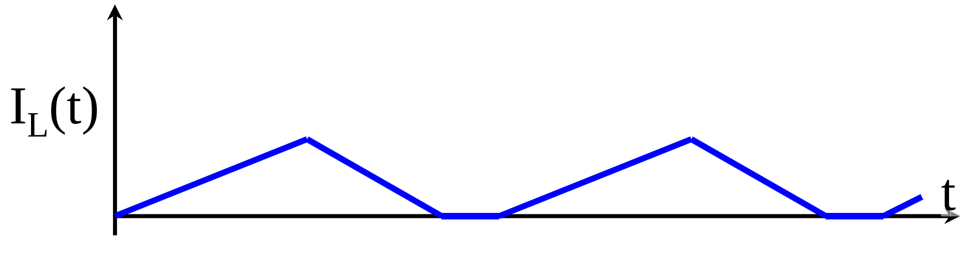
High Inductor Ripple

Inductor Current

Switched Mode Power Conversion

Boost Converter – Inductor Current

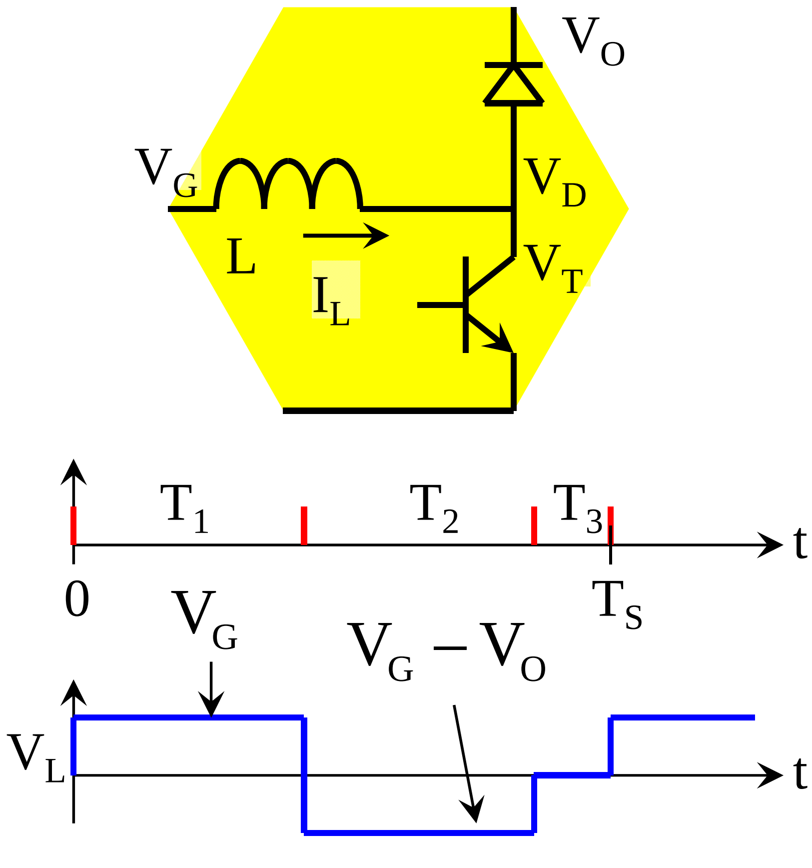




Inductor Current

Switched Mode Power Conversion

Boost Converter – DCM Conversion Ratio

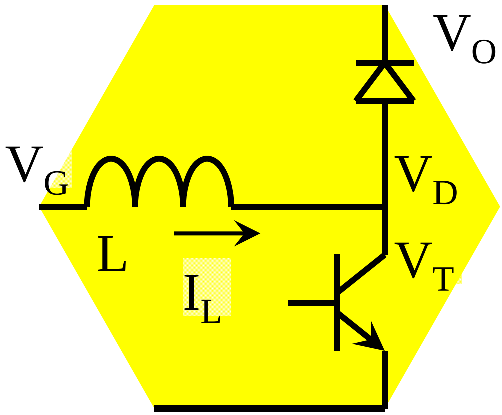


Inductor Volt-Sec Balance

Switched Mode Power Conversion

Boost Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$V_G T_1 + \left(V_G - V_O\right) T_2 = 0$$

$$\left(d + d_2\right) V_G = d_2 V_O$$

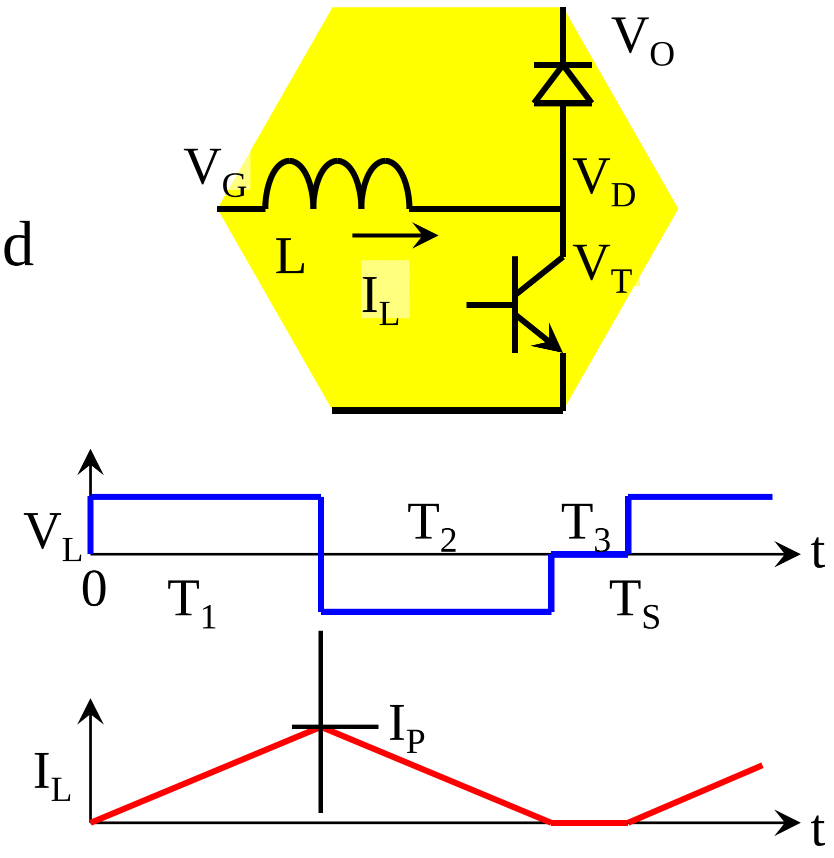
$$\frac{V_O}{V_G} = M = \frac{d + d_2}{d_2}$$

Voltage Conversion Ratio

Switched Mode Power Conversion

Boost Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



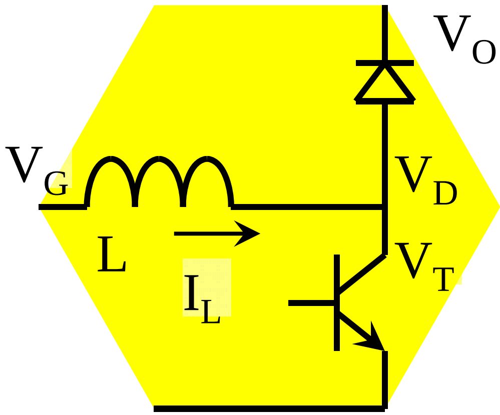
$$\frac{T_2}{T_S} = d_2$$

Resolving d_2 as a function of d

Switched Mode Power Conversion

Boost Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$I_P = dV_G T_S / L$$

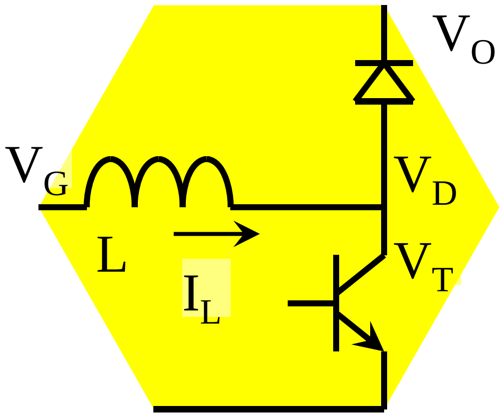
$$I_O = \frac{V_O}{R} = \frac{1}{2} I_P\, d_2 = \frac{1}{2} d_2 \frac{dT_S V_G}{L}$$

Resolving d_2 as a function of d

Switched Mode Power Conversion

Boost Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$I_O = \frac{V_O}{R} = \frac{1}{2} I_P\, d_2 = \frac{1}{2} d_2 \frac{dT_S V_G}{L}$$

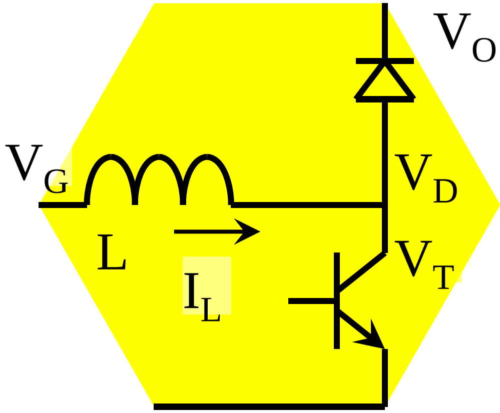
$$K\left(d + d_2\right) = dd_2^2 \;\; ; K = \frac{2L}{RT_S}$$

d and d_2 are related through Conduction Parameter K

Switched Mode Power Conversion

Boost Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$K\left(d + d_2\right) = d d_2^2$$

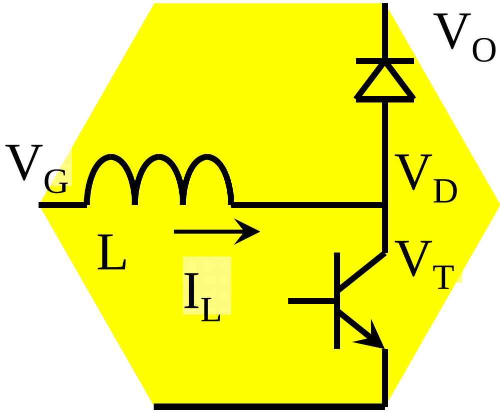
$$d_2 = \frac{K}{d}\frac{\left\{1 + \sqrt{1 + \left(4d^2/K\right)}\right\}}{2}$$

d and d_2 are related through Conduction Parameter K

Switched Mode Power Conversion

Boost Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$\frac{V_O}{V_G} = \frac{d + d_2}{d_2} = \frac{d}{K} d_2$$

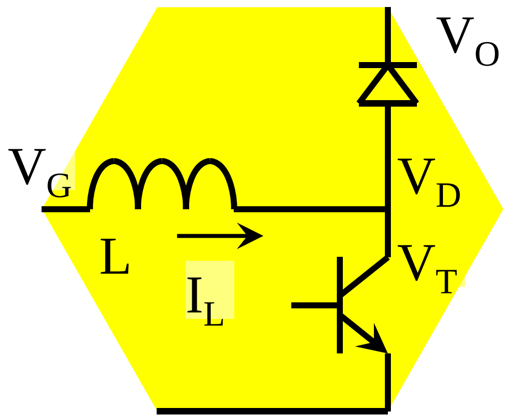
$$\frac{V_O}{V_G} = \frac{\left\{1 + \sqrt{1 + \left(4d^2 / K\right)}\right\}}{2}$$

d and d_2 are related through Conduction Parameter K

Switched Mode Power Conversion

Boost Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

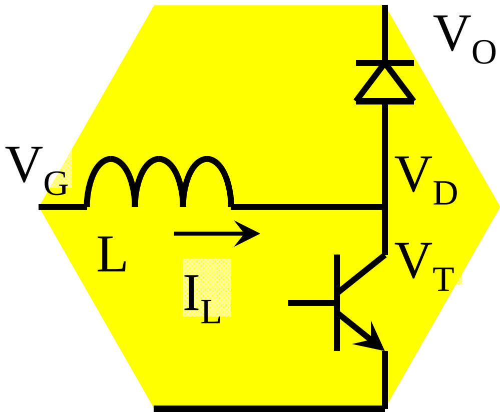
$$M = \frac{d + d_2}{d_2} > \frac{1}{(1-d)} \quad \left(\because (d + d_2) < 1\right)$$

Conversion Factor in DCM is More

Switched Mode Power Conversion

Boost Converter – Border Between DCM & CCM

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$K\left(d + d_2\right) = d d_2^2$$

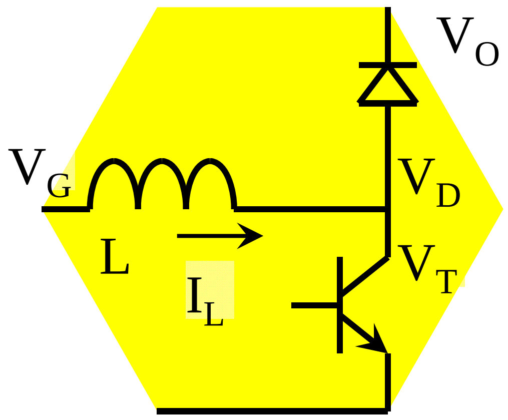
$$K_{cri} = d\left(1 - d\right)^2$$

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

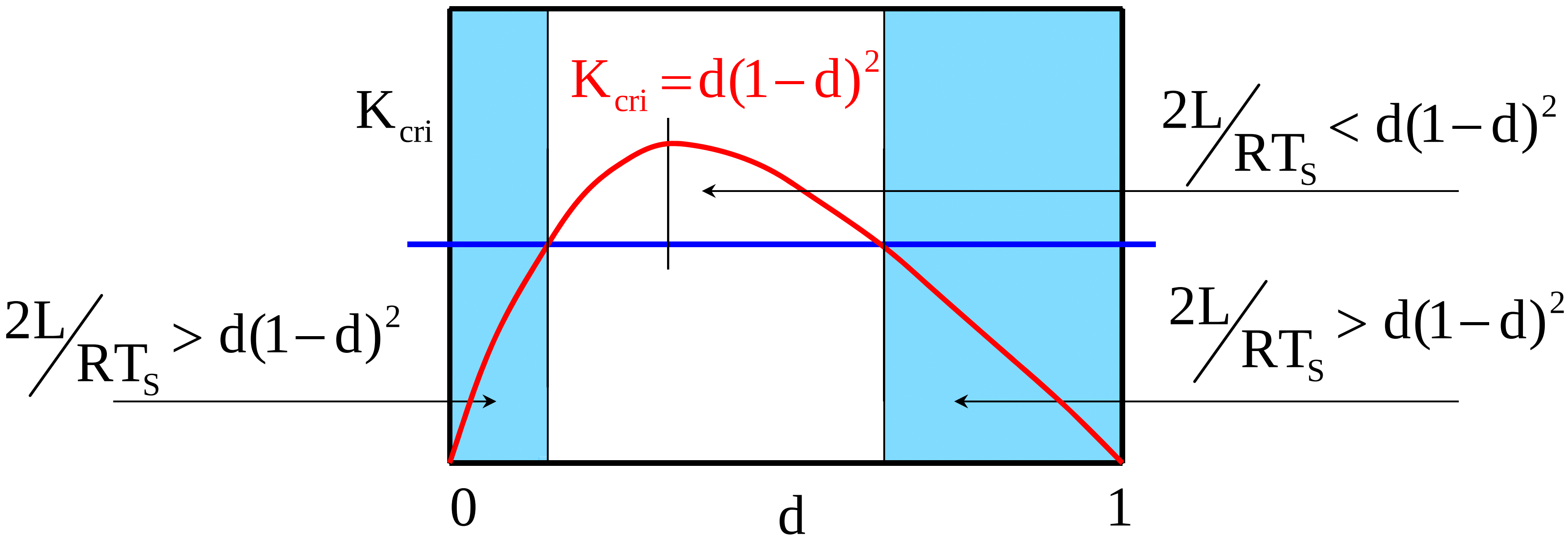
$K > K_{cri}$: CCM Operation

$K < K_{cri}$: CCM Operation

Border of DCM and CCM

Switched Mode Power Conversion

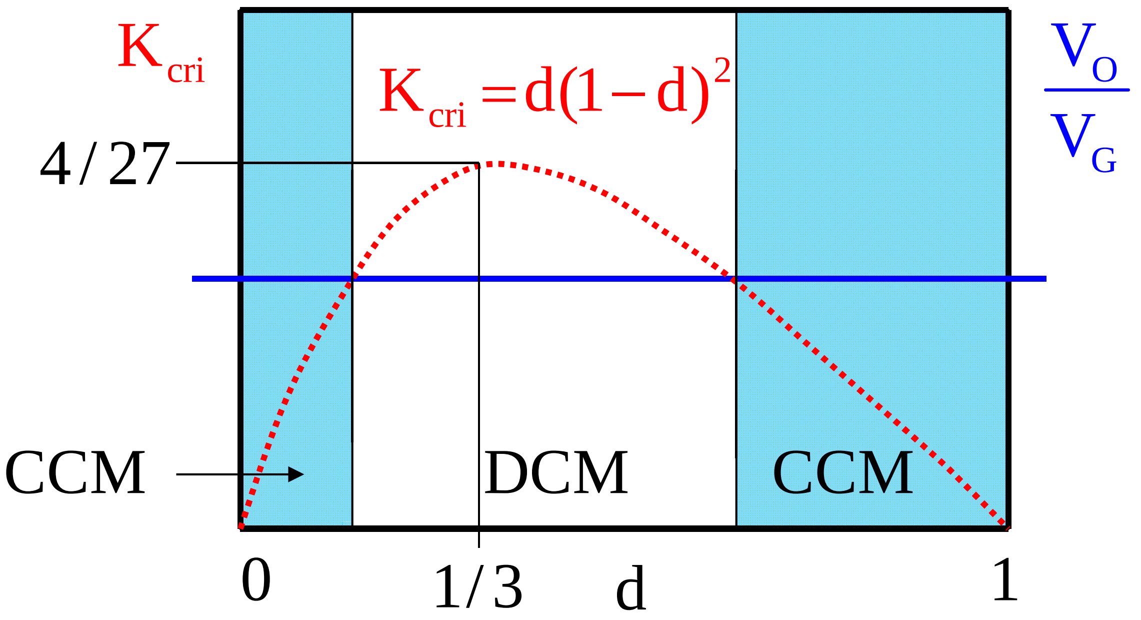
Boost Converter – Border Between DCM & CCM



Graphical Determination of DCM and CCM

Switched Mode Power Conversion

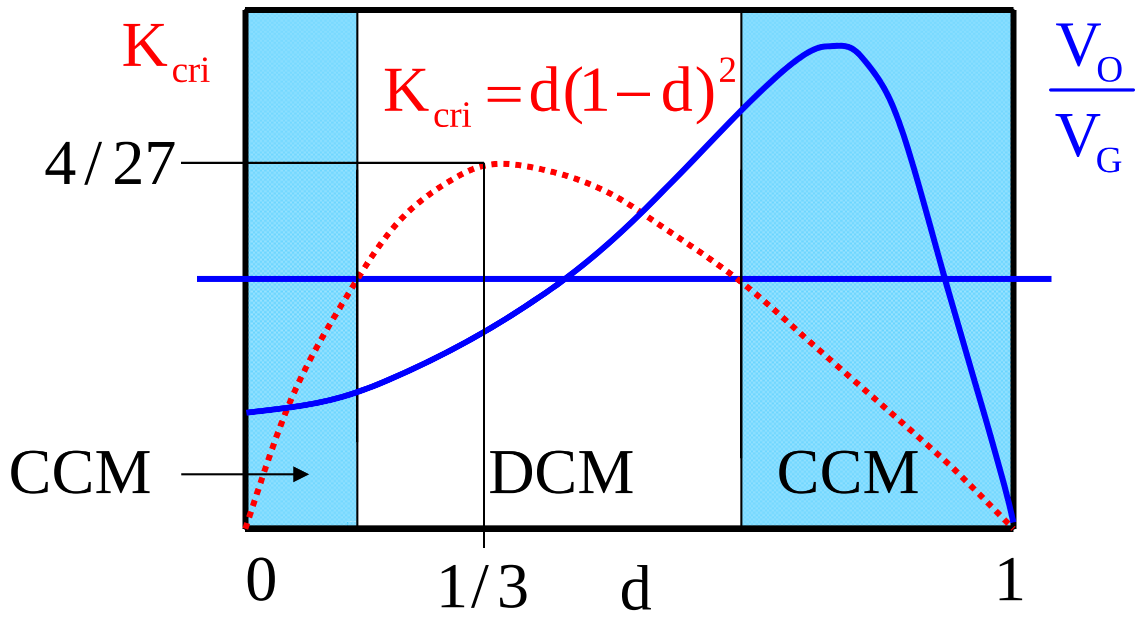
Boost Converter – Border Between DCM & CCM



Graphical Determination of DCM and CCM

Switched Mode Power Conversion

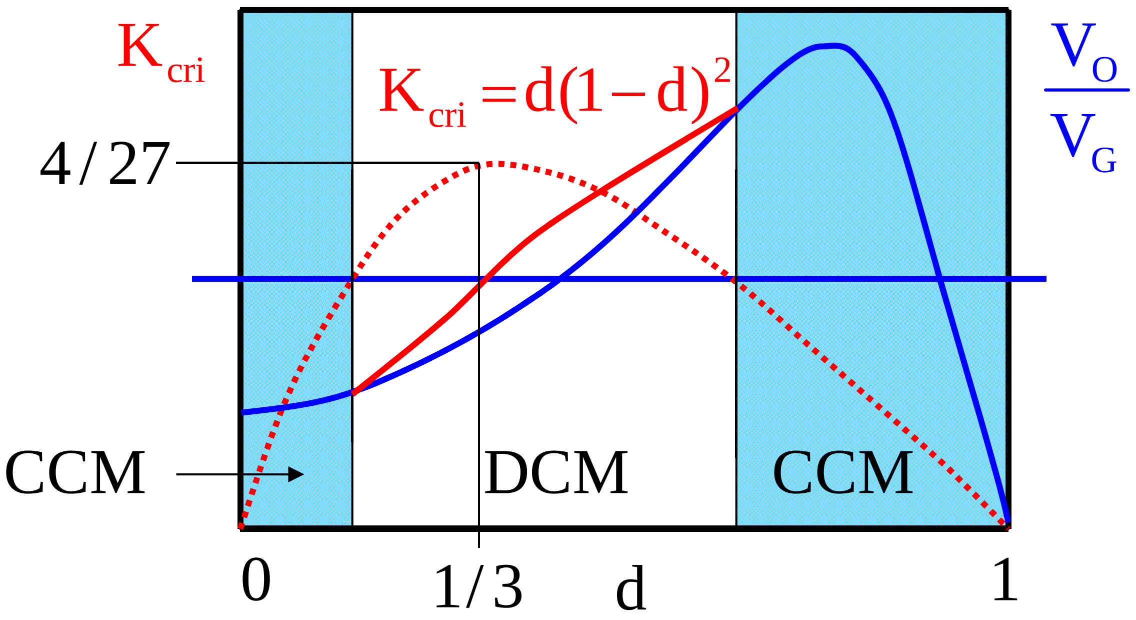
Boost Converter – DCM & CCM



Graphical Determination of DCM and CCM

Switched Mode Power Conversion

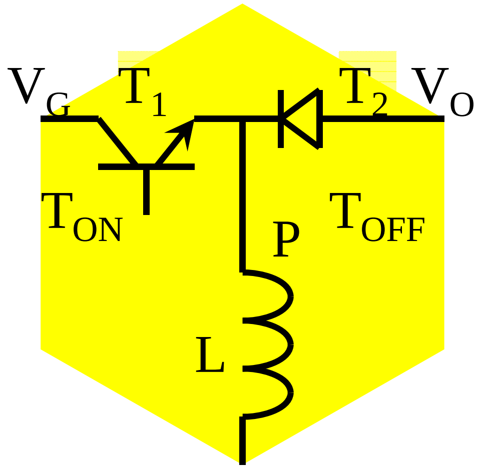
Boost Converter – DCM & CCM

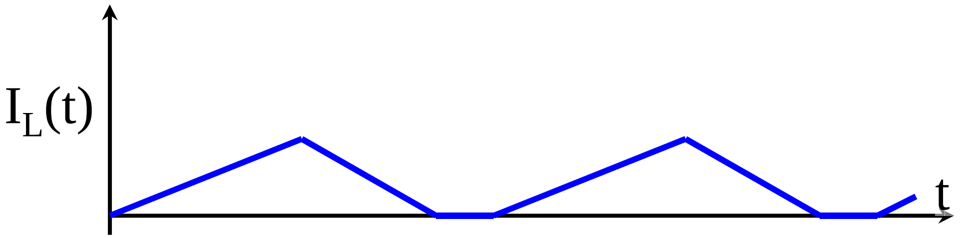


Gain in DCM is More than Gain in CCM

Switched Mode Power Conversion

Flyback Converter – Inductor Current

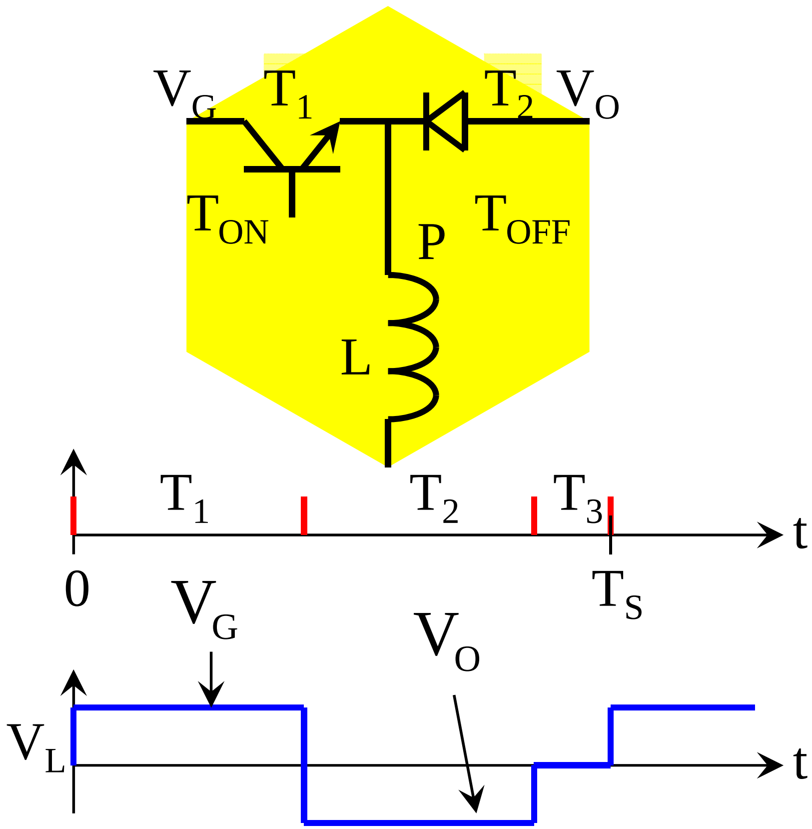




Inductor Current

Switched Mode Power Conversion

Flyback Converter – DCM Conversion Ratio

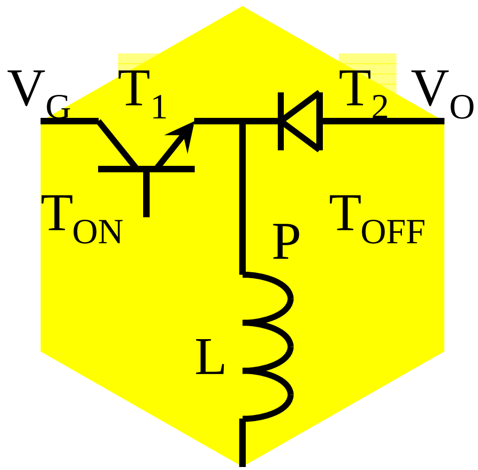


Inductor Volt-Sec Balance

Switched Mode Power Conversion

Flyback Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$V_G T_1 + V_O T_2 = 0$$

$$dV_G = -d_2 V_O$$

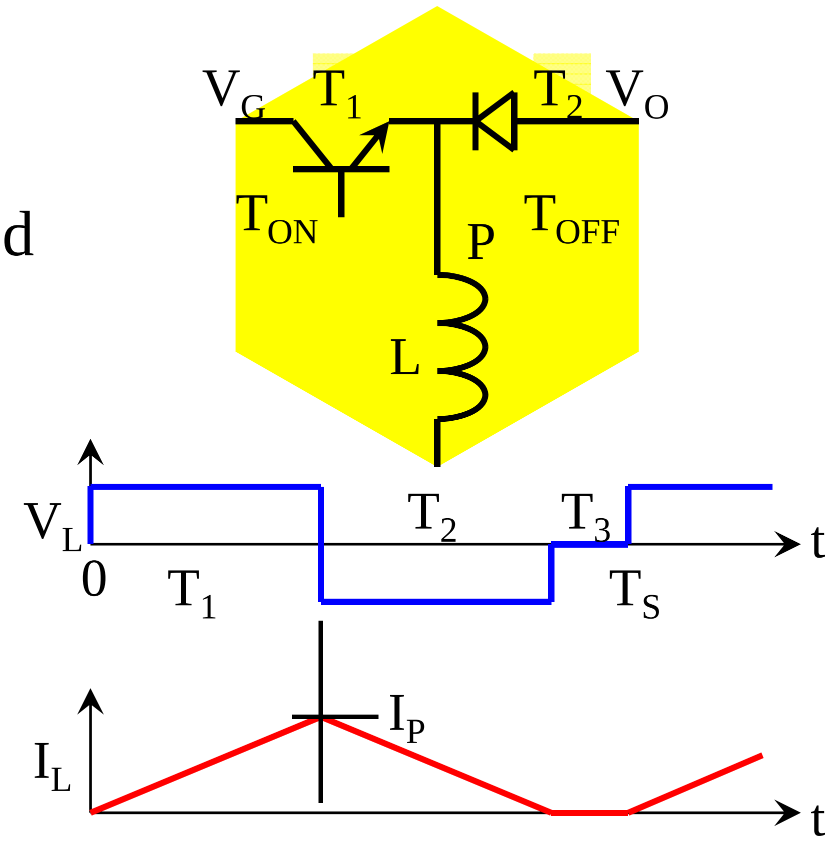
$$\frac{V_O}{V_G} = M = -\frac{d}{d_2}$$

Voltage Conversion Ratio

Switched Mode Power Conversion

Flyback Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



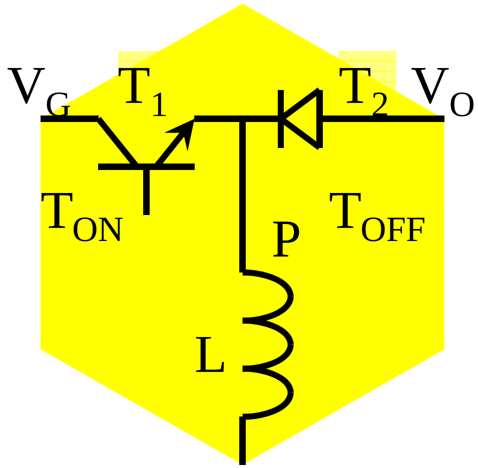
$$\frac{T_2}{T_S} = d_2$$

Resolving d_2 as a function of d

Switched Mode Power Conversion

Flyback Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$I_P = dV_G T_S / L$$

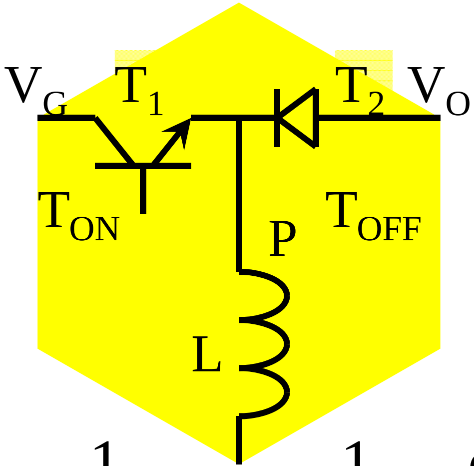
$$I_O = \frac{V_O}{R} = \frac{1}{2} I_P d_2 = \frac{1}{2} d_2 \frac{dT_S V_G}{L}$$

Resolving d_2 as a function of d

Switched Mode Power Conversion

Flyback Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

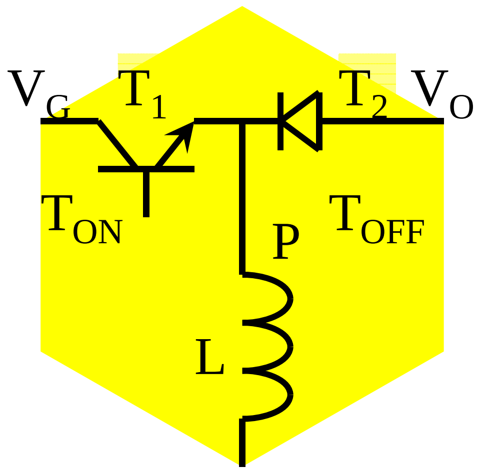
$$I_O = \frac{V_O}{R} = \frac{1}{2} I_P\, d_2 = \frac{1}{2} d_2 \; \frac{dT_S V_G}{L}$$

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

d and d_2 are related through Conduction Parameter K

Switched Mode Power Conversion

Flyback Converter – DCM Conversion Ratio



$$\frac{T_1}{T_S} = d \qquad \frac{T_2}{T_S} = d_2$$

$$\frac{V_O}{V_G} = \frac{d}{d_2} \qquad d_2^2 = K$$

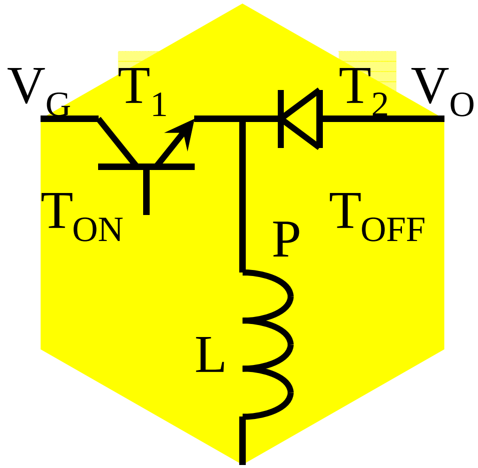
$$\frac{V_O}{V_G} = \frac{d}{\sqrt{K}}$$

d and d_2 are related through Conduction Parameter K

Switched Mode Power Conversion

Flyback Converter – DCM Conversion Ratio

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

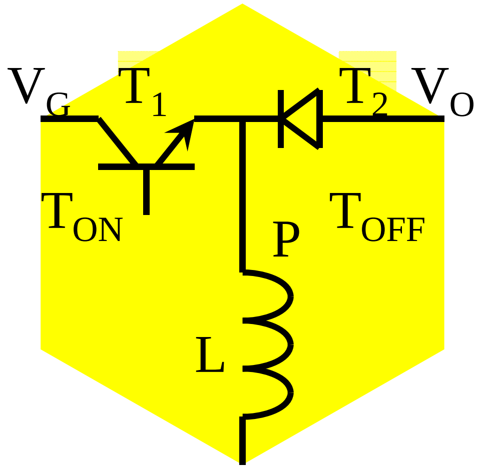
$$|M| = \frac{d}{d_2} > \frac{d}{(1-d)} \quad \left(\because (d + d_2) < 1\right)$$

Conversion Factor in DCM is More

Switched Mode Power Conversion

Flyback Converter – Border Between DCM & CCM

$$\frac{T_1}{T_S} = d$$



$$\frac{T_2}{T_S} = d_2$$

$$K = d_2^2$$

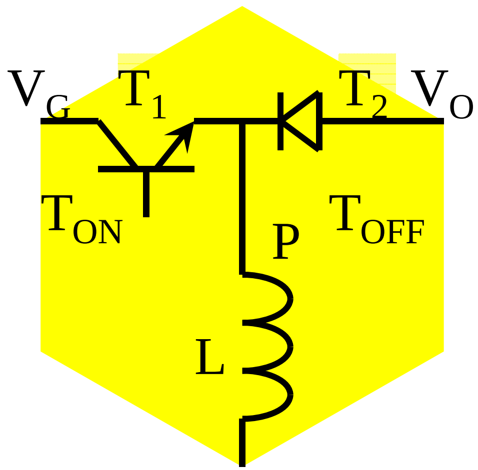
$$K_{cri} = (1-d)^2$$

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

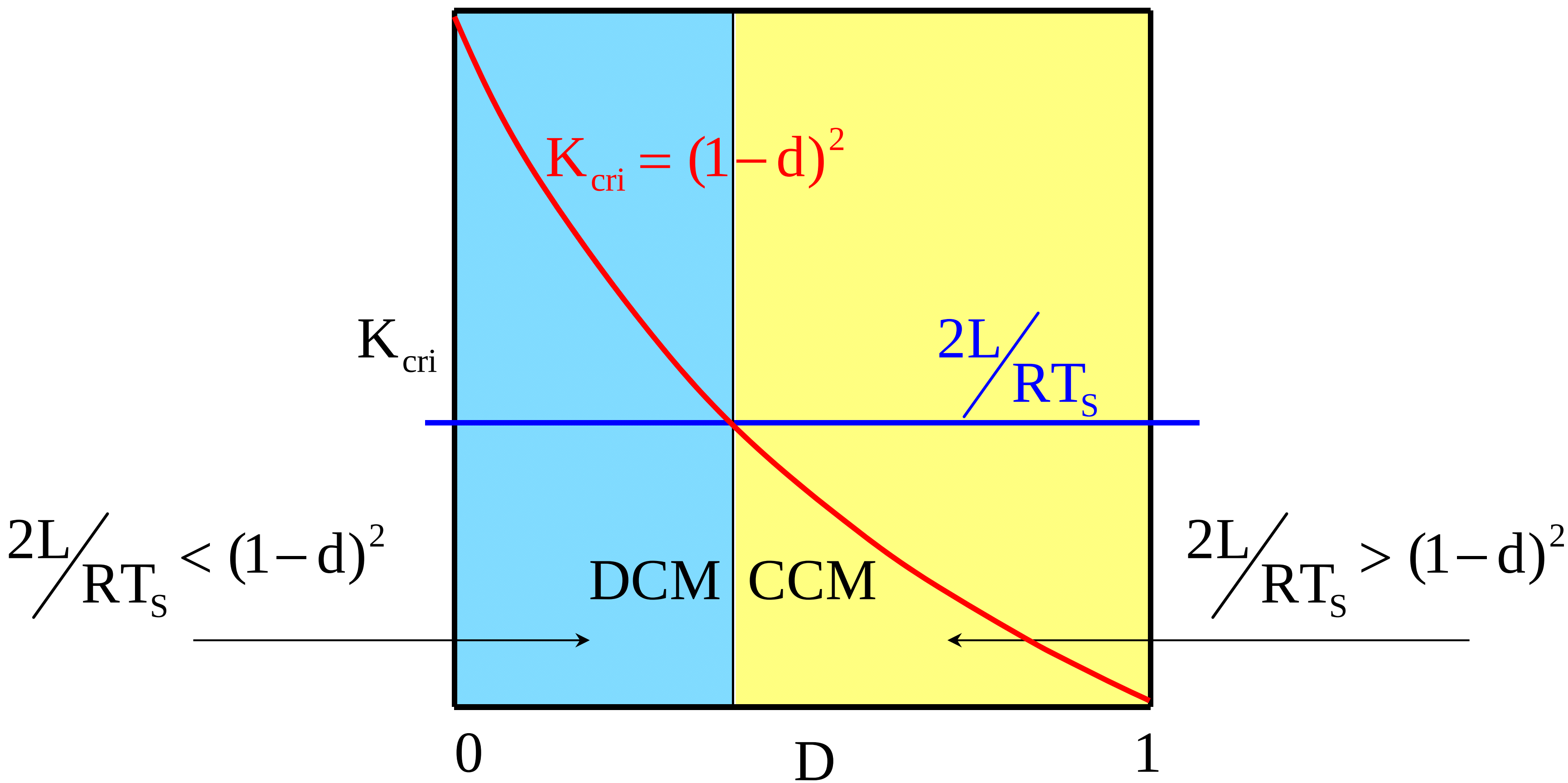
$K > K_{cri}$: CCM Operation

$K < K_{cri}$: CCM Operation

Border of DCM and CCM

Switched Mode Power Conversion

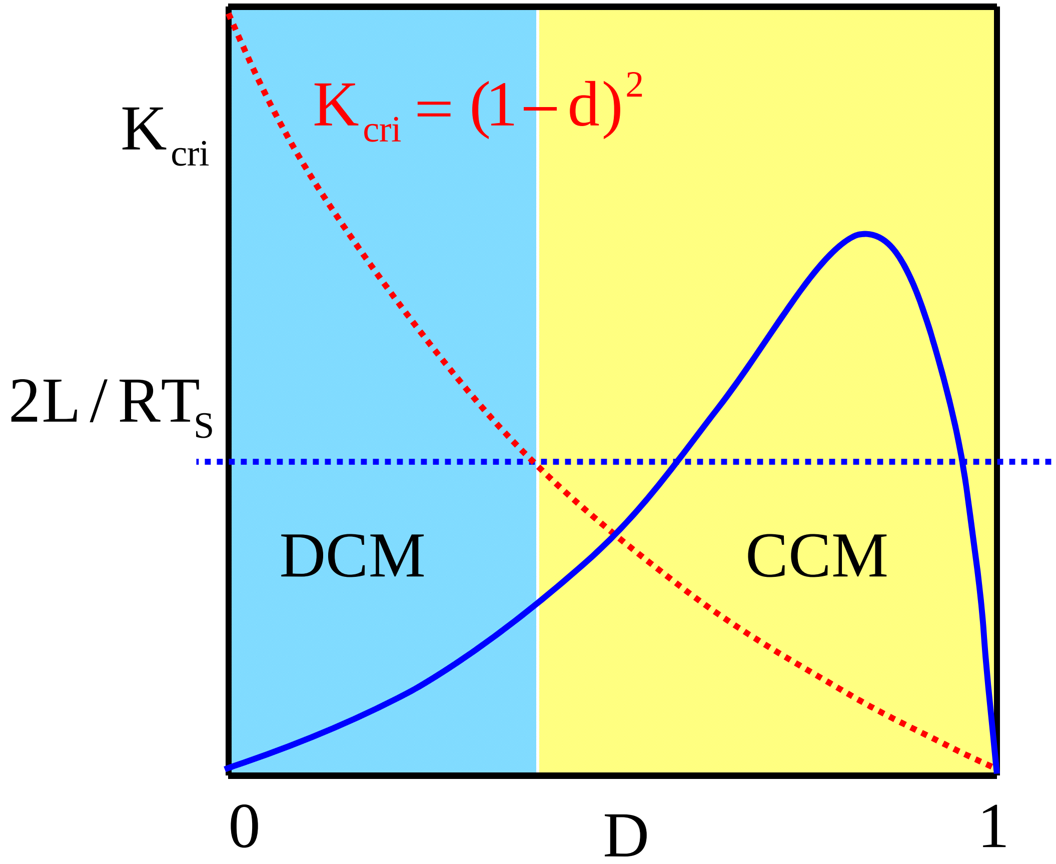
Flyback Converter – Border Between DCM & CCM



Graphical Determination of DCM and CCM

Switched Mode Power Conversion

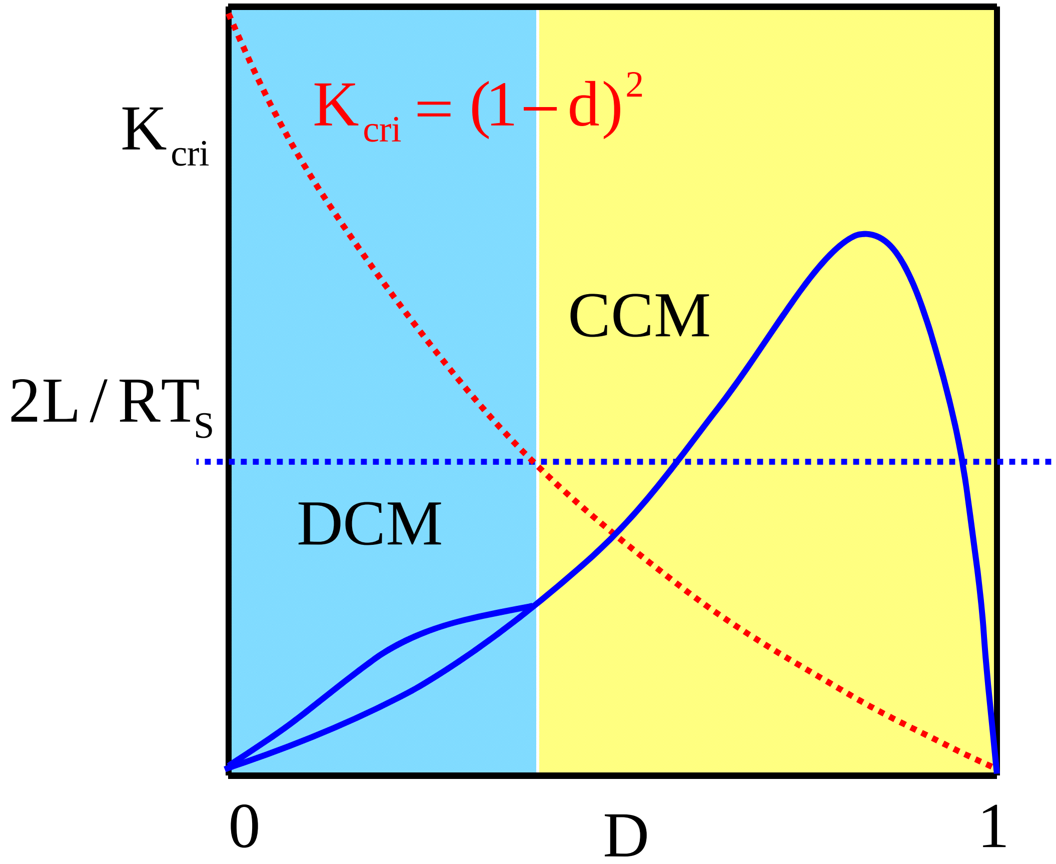
Flyback Converter – Border Between DCM & CCM



Graphical Determination of DCM and CCM

Switched Mode Power Conversion

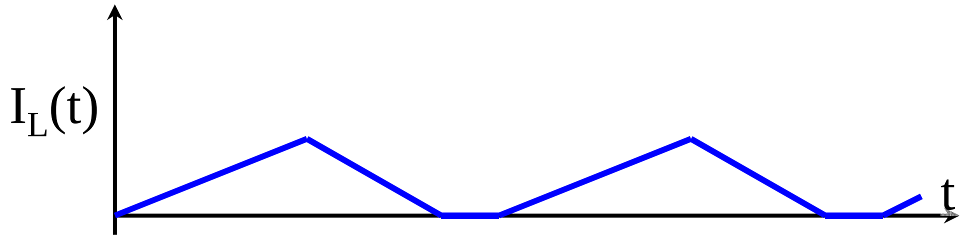
Flyback Converter – Border Between DCM & CCM



Graphical Determination of DCM and CCM

Switched Mode Power Conversion

DCM Operation – Salient Features



Zero (Low) Turn-on Loss

Soft Diode Recovery

Low Circuit Inductance

High Inductor Ripple

Inductor Current