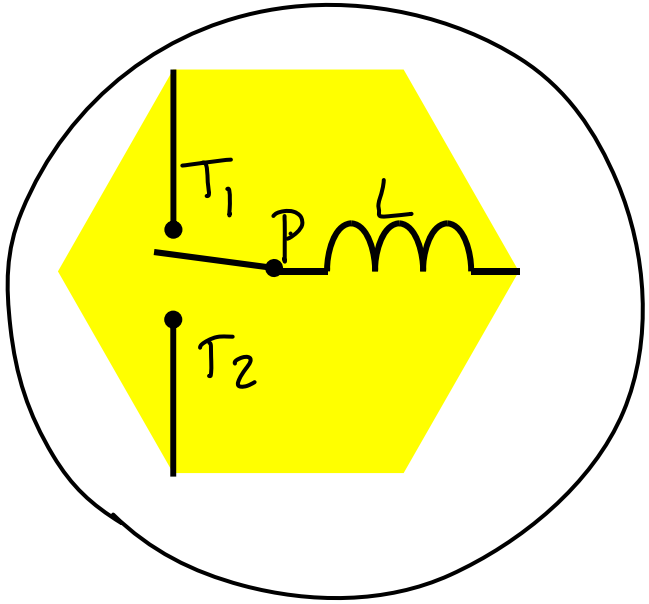
Switched Mode Power Conversion

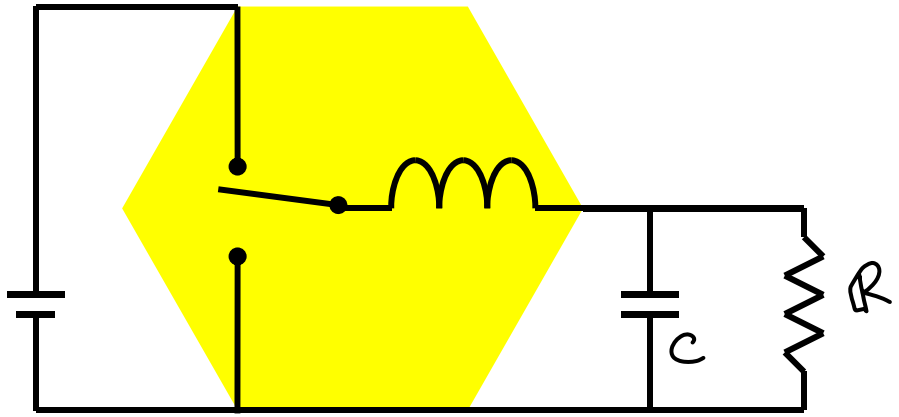
Non-Isolated Converters



Basic Converter Cell

Switched Mode Power Conversion

Non-Isolated Converters



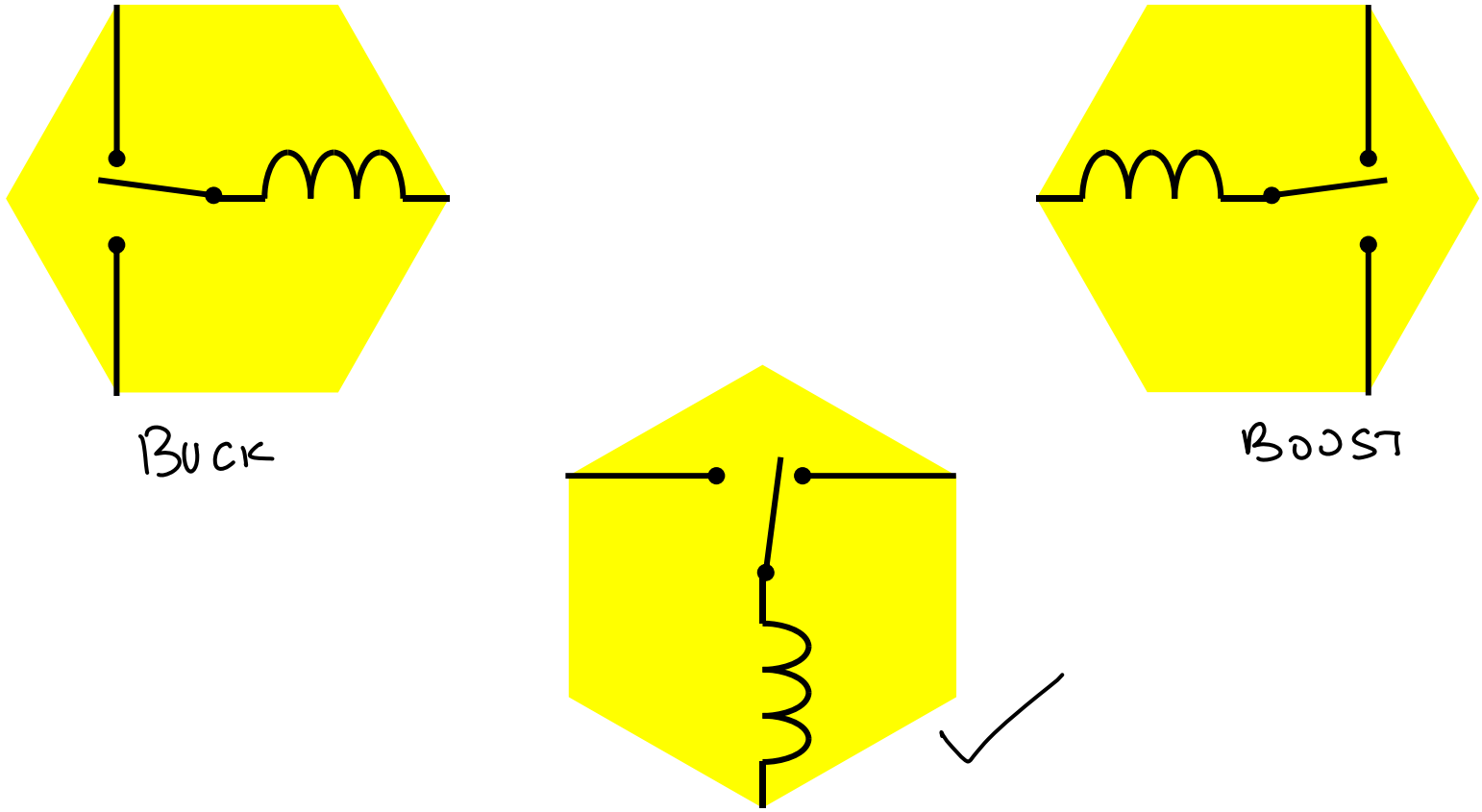
$V_0 = DV_g$

$0 < D < 1$

Buck Converter

Switched Mode Power Conversion

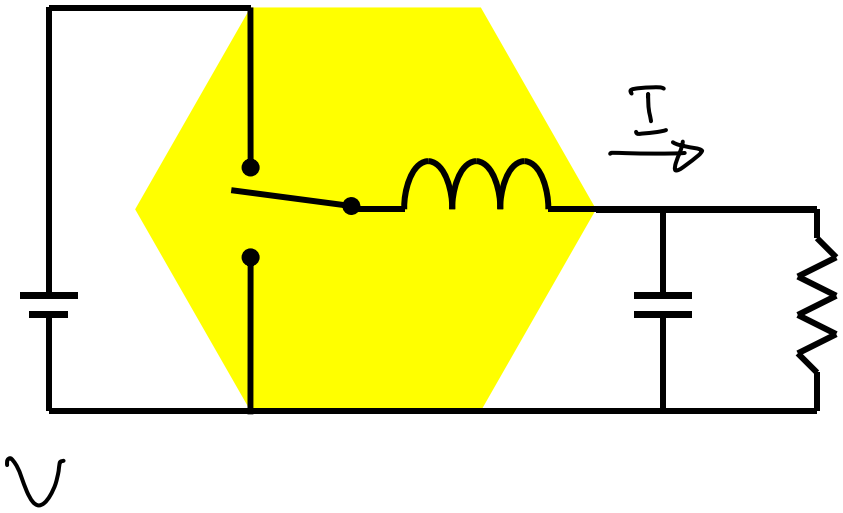
Basic Converter Cell



Three Variants of the Switch-Inductor Cell

Switched Mode Power Conversion

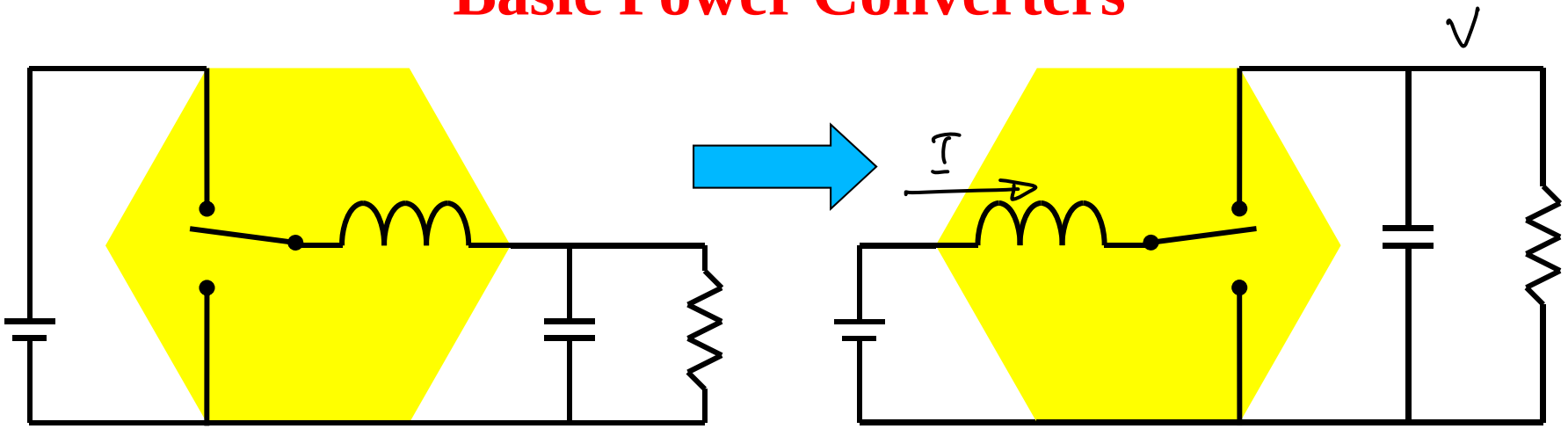
Buck Converter



Voltage Input Current Output Converter

Switched Mode Power Conversion

Basic Power Converters



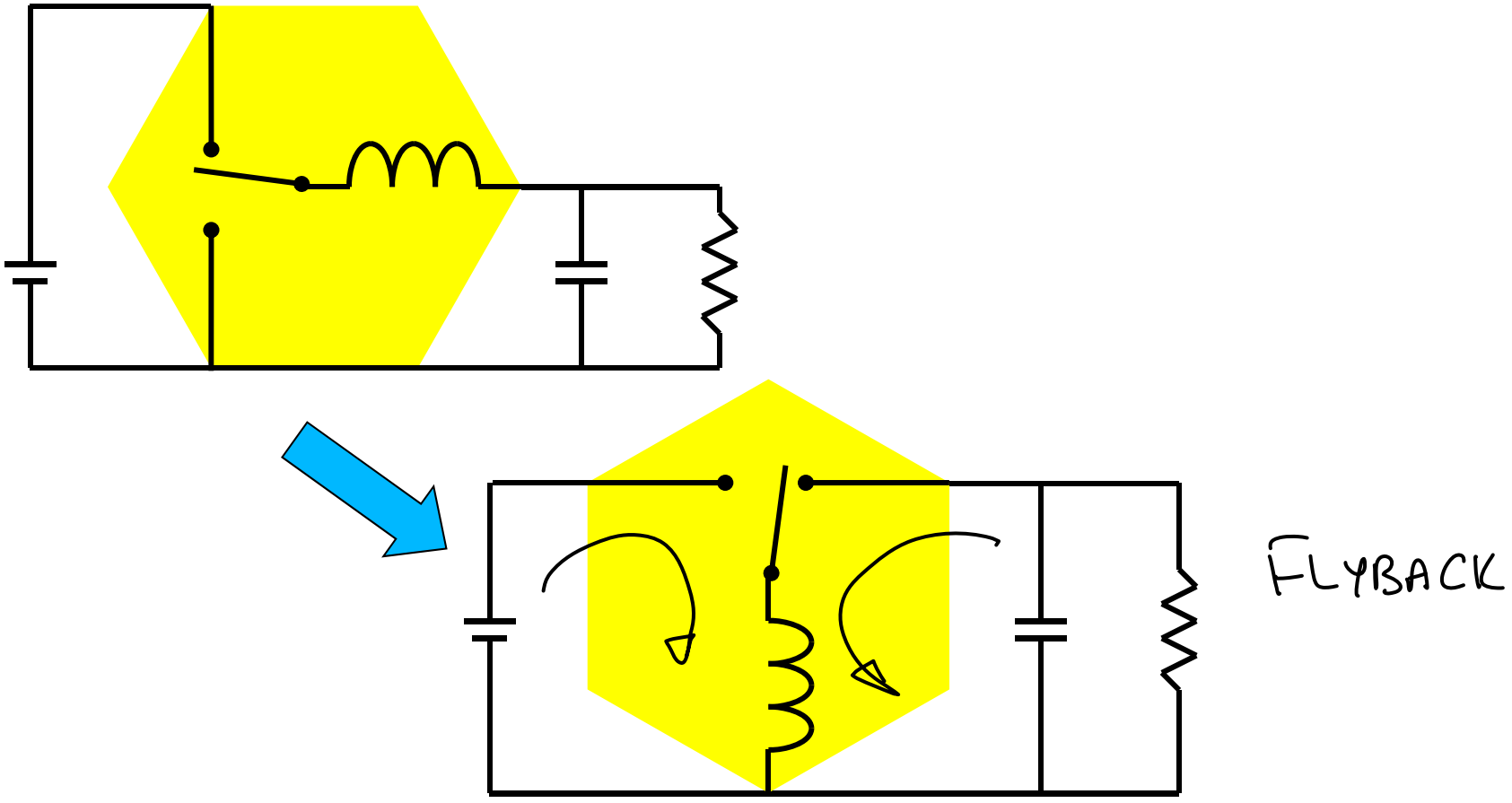
$$V_o = \frac{V_g}{1-D}$$

$$0 < D < 1$$

Current Input Voltage Output Variant

Switched Mode Power Conversion

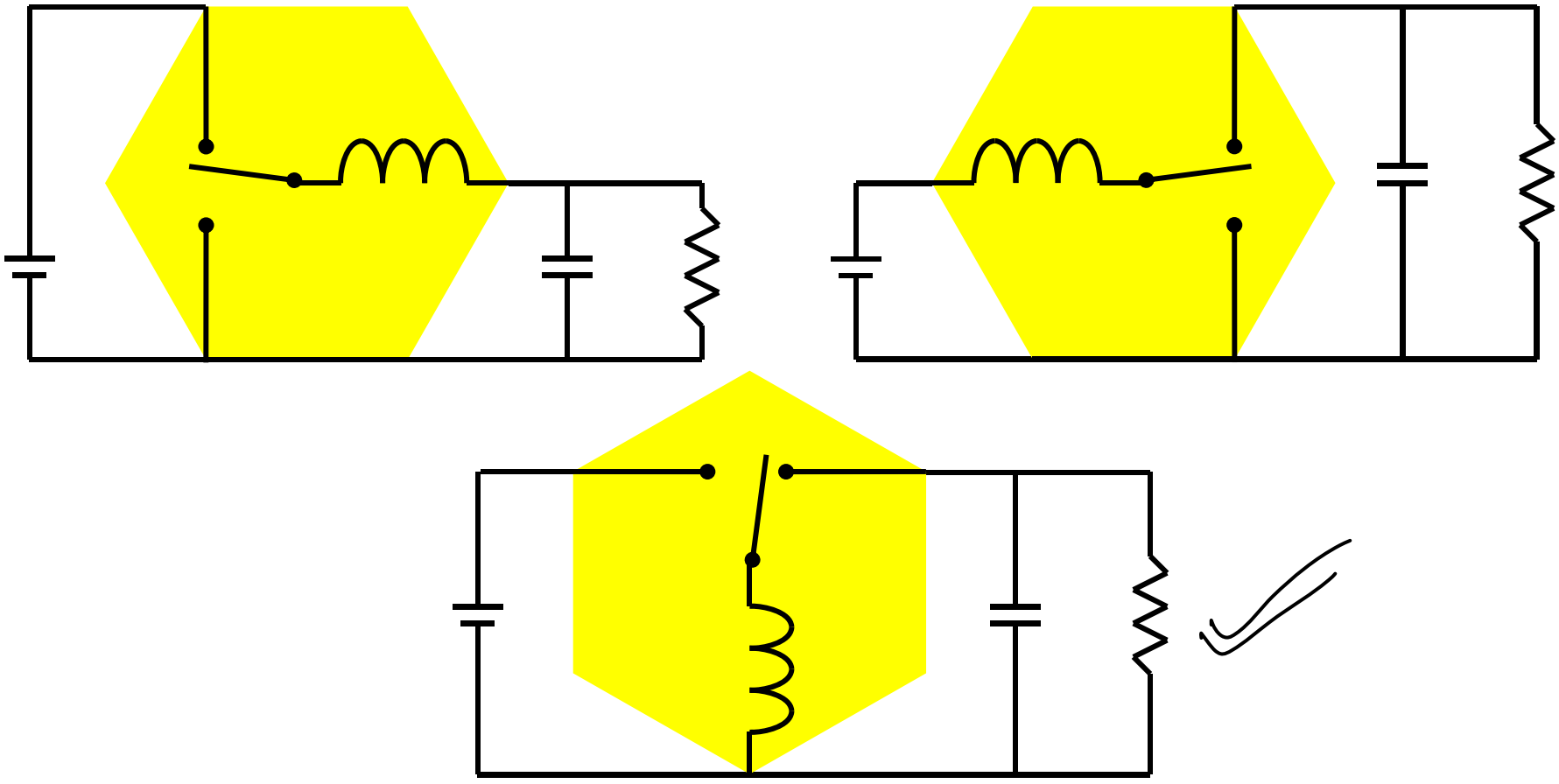
Basic Power Converters



Current Input Current Output Variant

Switched Mode Power Conversion

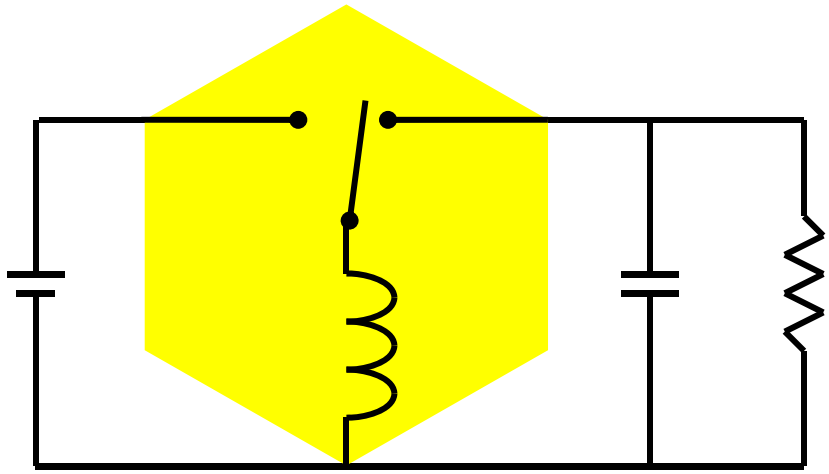
Basic Power Converters



Buck, Boost & Flyback Variants

Switched Mode Power Conversion

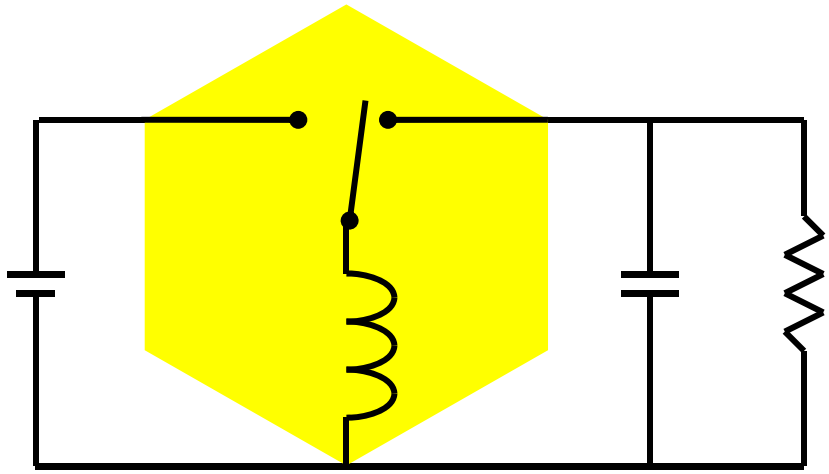
Analysis of Flyback Converters



Flyback Converter

Switched Mode Power Conversion

Analysis of Flyback Converters



1) **Voltage Gain V_O/V_G** = $f(D)$

(2) **Current Gain I_O/I_G** = $g(D)$

* **Current Ripple $\Delta I_O/I_O$** $\Delta I/I$

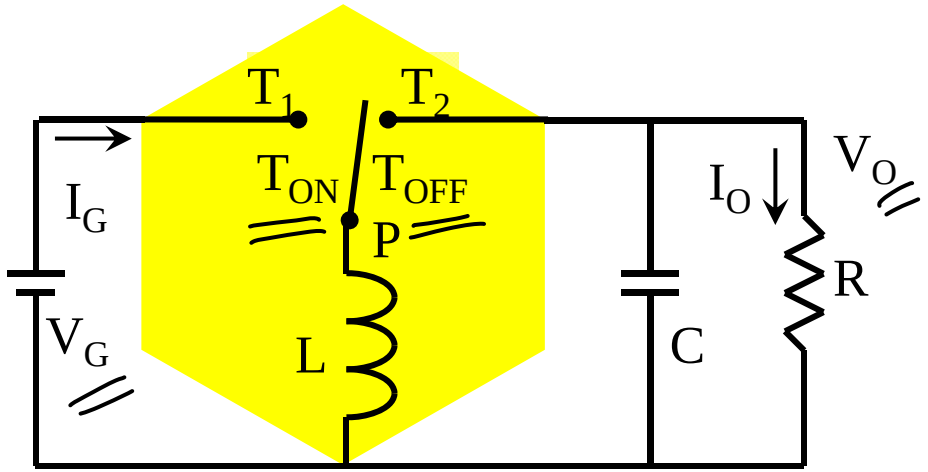
* **Voltage Ripple $\Delta V_O/V_O$** $\Delta V/V$

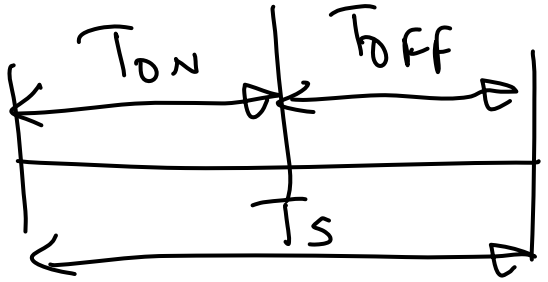
Switch, Source, Storage Non-ideality

Efficiency $\eta = P_o/P_i$

Switched Mode Power Conversion

Flyback Converter



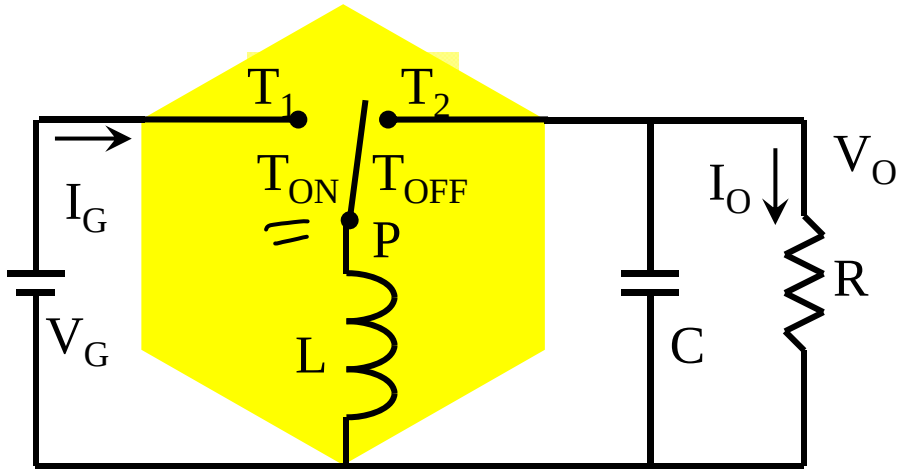


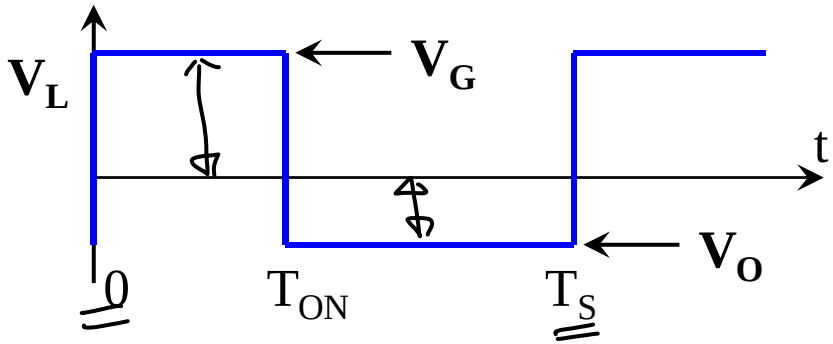
$$\frac{V_O}{V_G} = ?$$

Voltage Conversion Ratio

Switched Mode Power Conversion

Flyback Converter

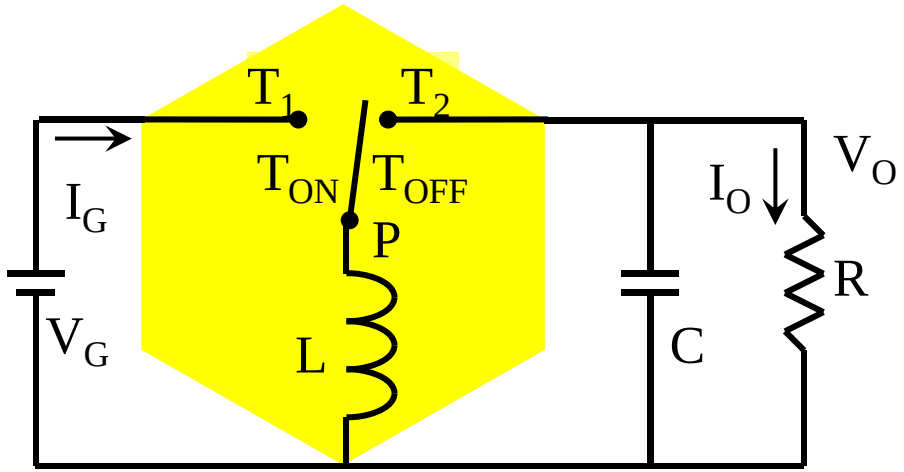


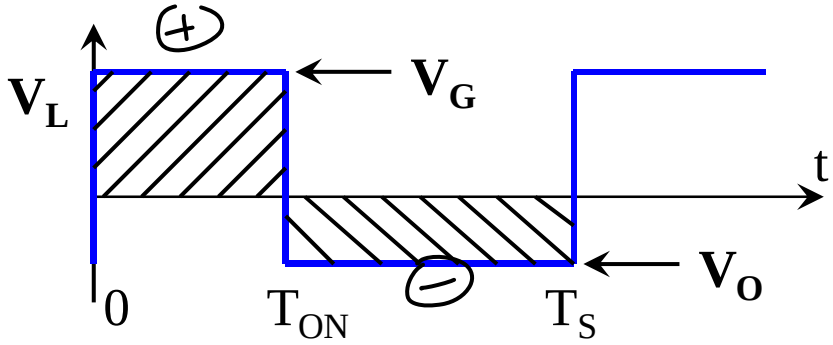


Inductor Volt-Sec Balance

Switched Mode Power Conversion

Flyback Converter

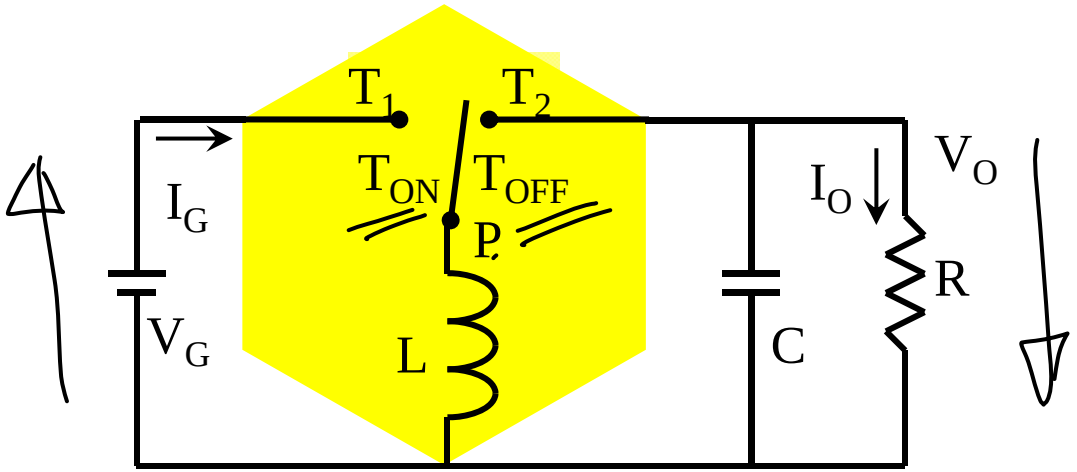




Inductor Volt-Sec Balance

Switched Mode Power Conversion

Flyback Converter



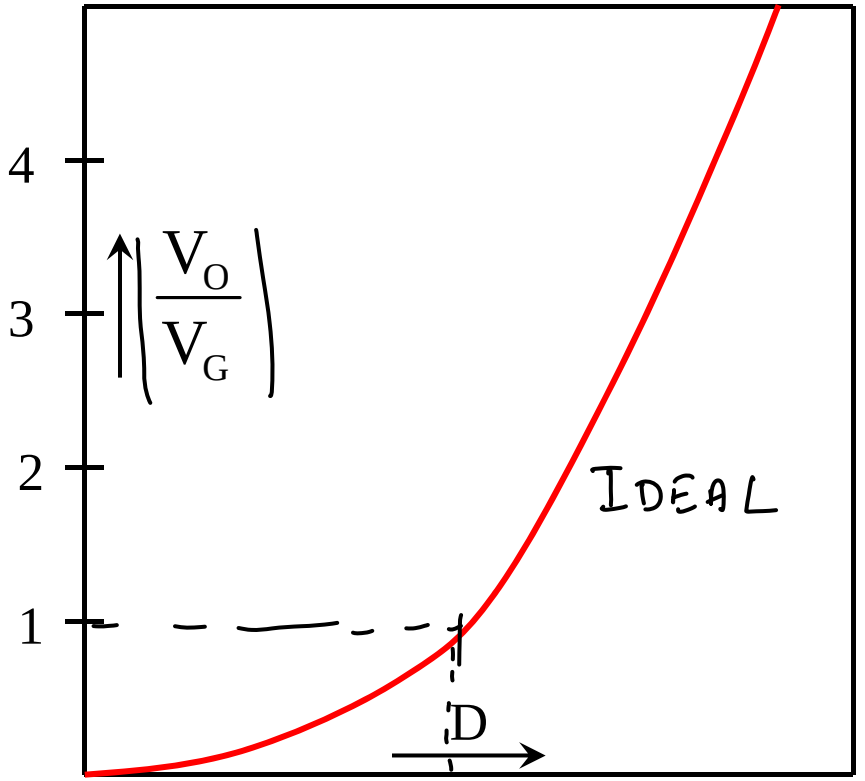
$$(V_G)T_{ON} + (V_O)T_{OFF} = 0$$

$$\frac{V_O}{V_G} = -\frac{T_{ON}}{T_{OFF}} = -\frac{D}{1-D}$$

$$-\frac{D}{1-D}$$

Switched Mode Power Conversion

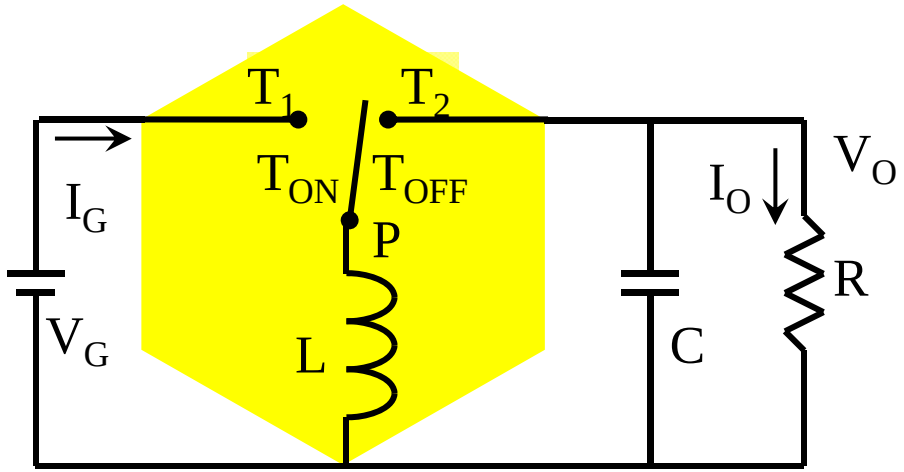
Flyback Converter



$$\frac{V_O}{V_G} = -\frac{T_{ON}}{T_{OFF}} = -\frac{D}{1-D}$$

Switched Mode Power Conversion

Flyback Converter

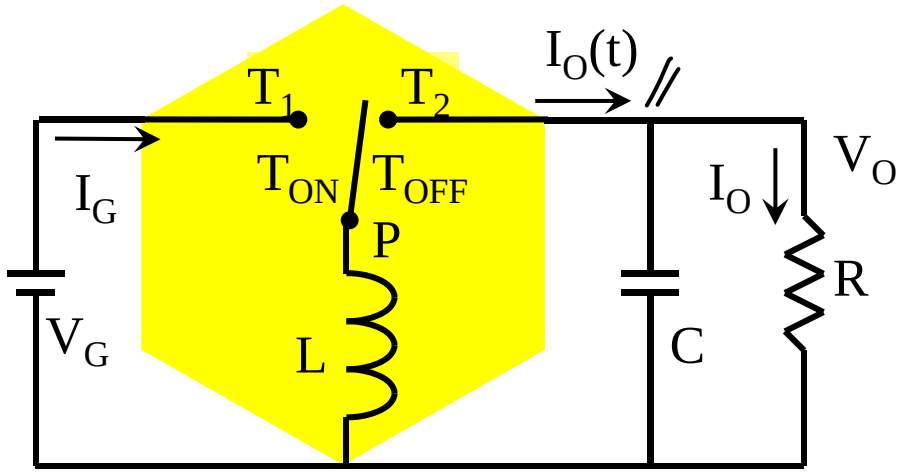


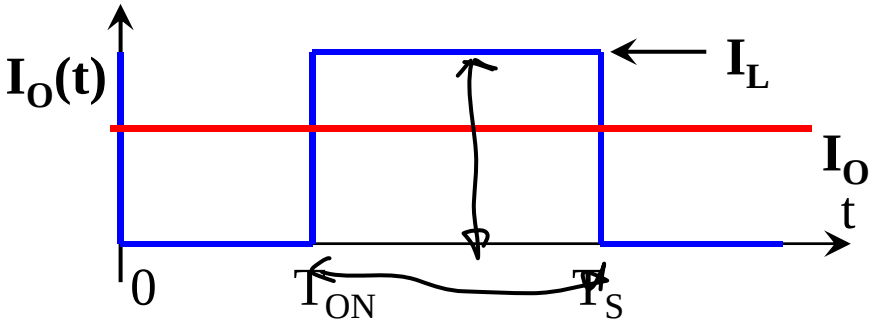
$$\frac{I_G}{I_O} = ?$$

Current Conversion Ratio

Switched Mode Power Conversion

Flyback Converter



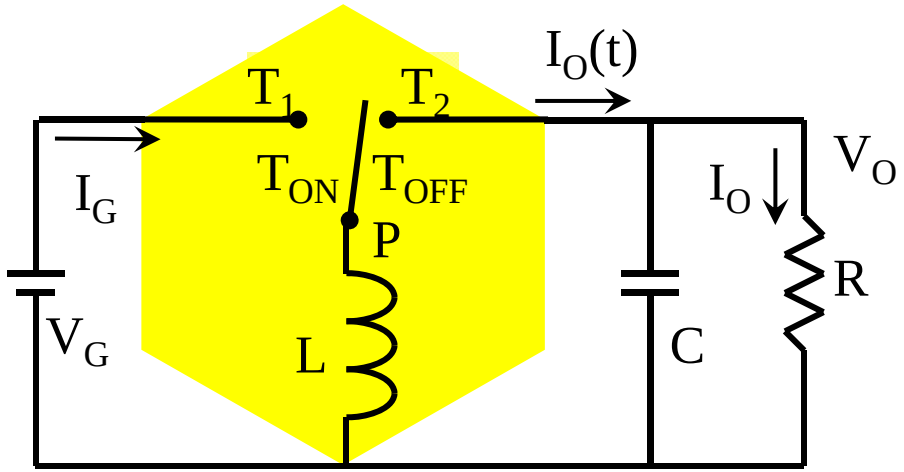


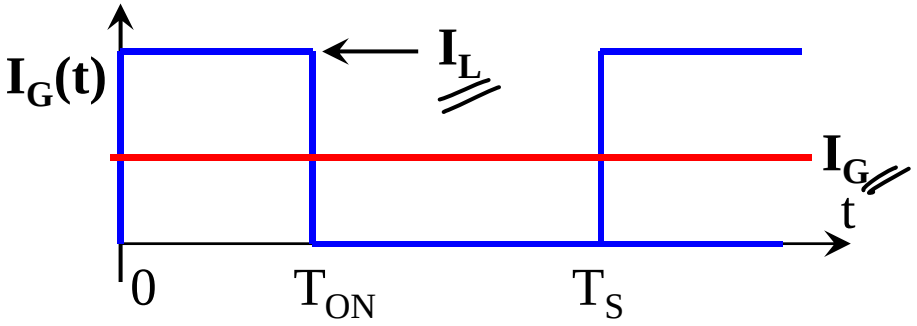
$$I_L \, T_{OFF} = I_O \, T_S$$

Average Output Current

Switched Mode Power Conversion

Flyback Converter



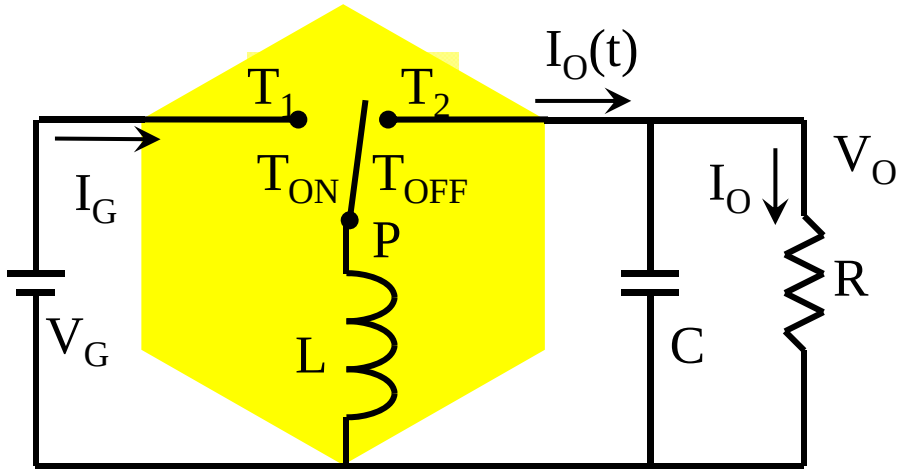


$$I_L \, T_{ON} = I_G \, T_S$$

Average Input Current

Switched Mode Power Conversion

Flyback Converter



$$I_G / T_{ON} = -I_O / T_{OFF}$$

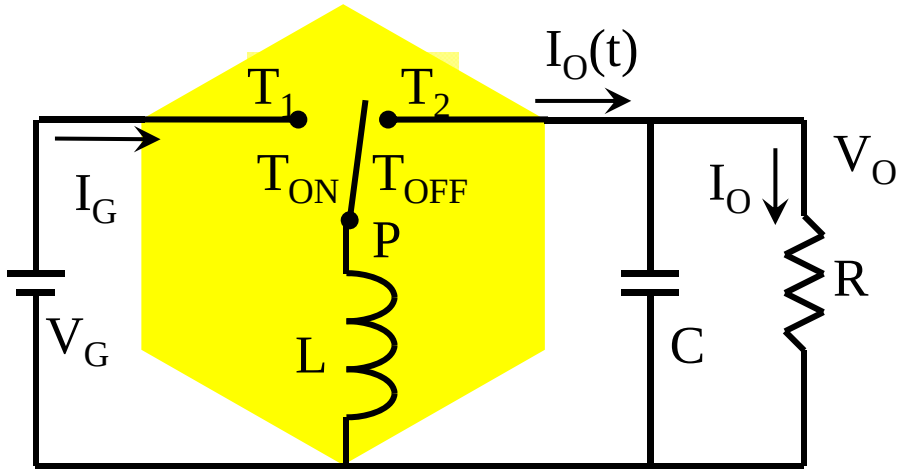
$$\frac{I_G}{I_O} = -\frac{T_{ON}}{T_{OFF}} = -\frac{D}{1-D}$$

$$\frac{V_O I_O}{V_G I_G} = 1$$

Current Conversion Ratio

Switched Mode Power Conversion

Flyback Converter

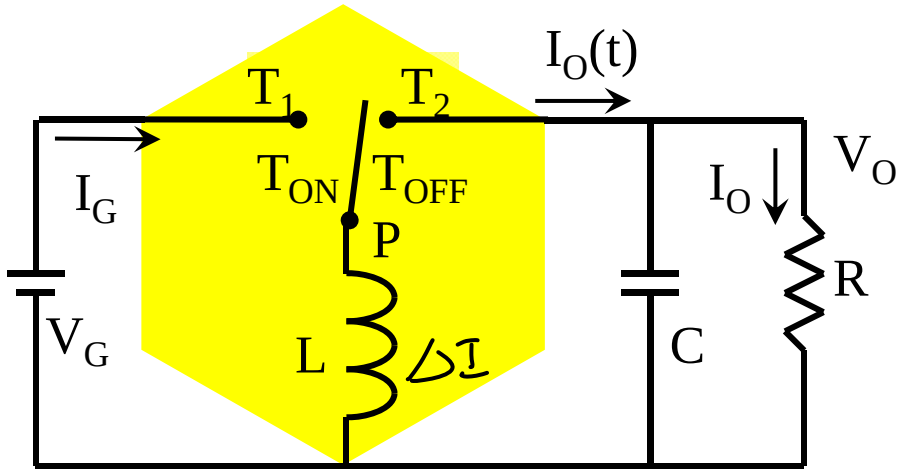


$$\frac{V_O}{V_G}\frac{I_O}{I_G} = \frac{D}{1-D}\frac{1-D}{D} = 1$$

Ideal Efficiency is Unity

Switched Mode Power Conversion

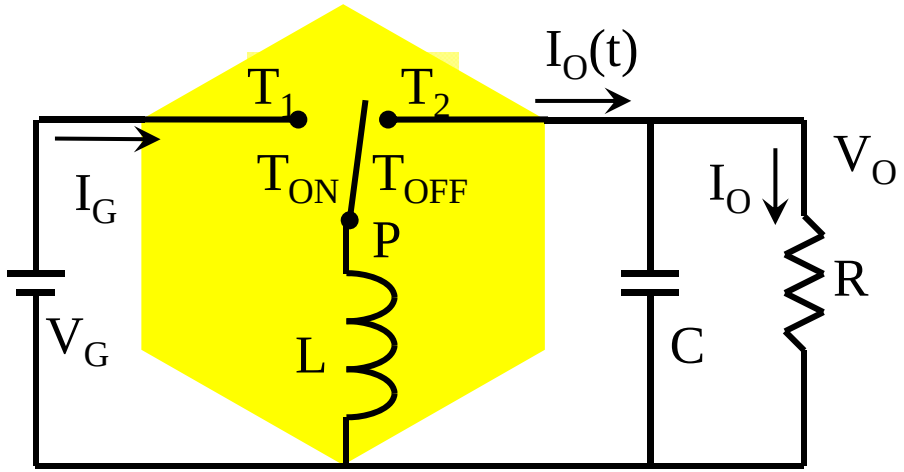
Flyback Converter

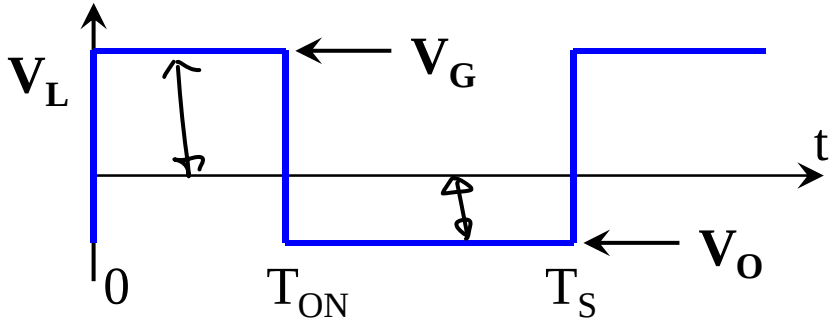


Non-Ideality in the Inductor Current

Switched Mode Power Conversion

Flyback Converter

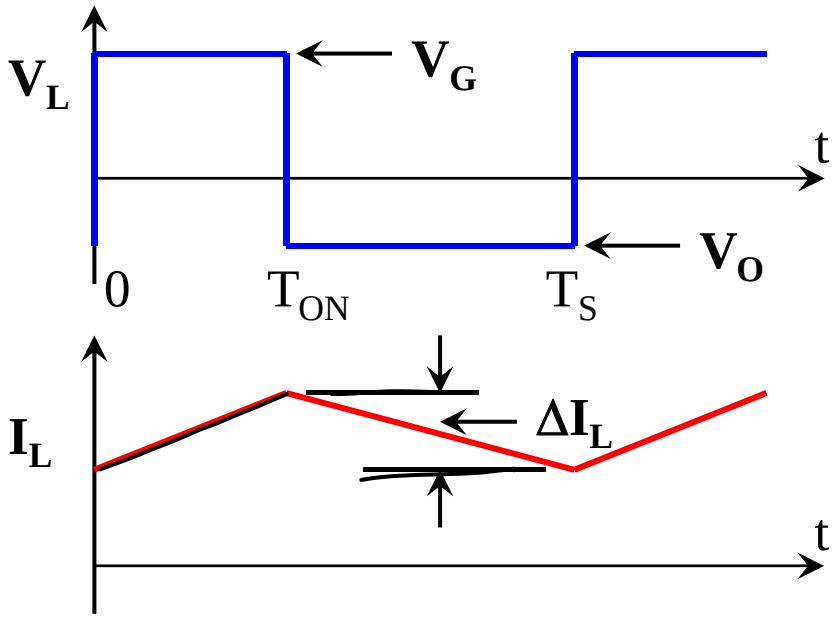




Inductor Current Ripple – Integral of Inductor Voltage

Switched Mode Power Conversion

Flyback Converter

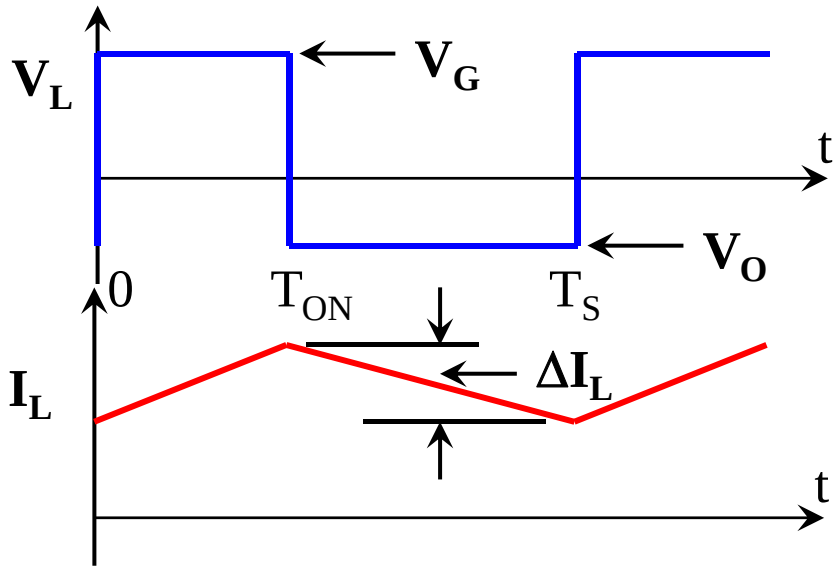


$$\Delta I_L = \frac{V_G}{L} D T_S$$

Inductor Current Ripple – Integral of Inductor Voltage

Switched Mode Power Conversion

Flyback Converter



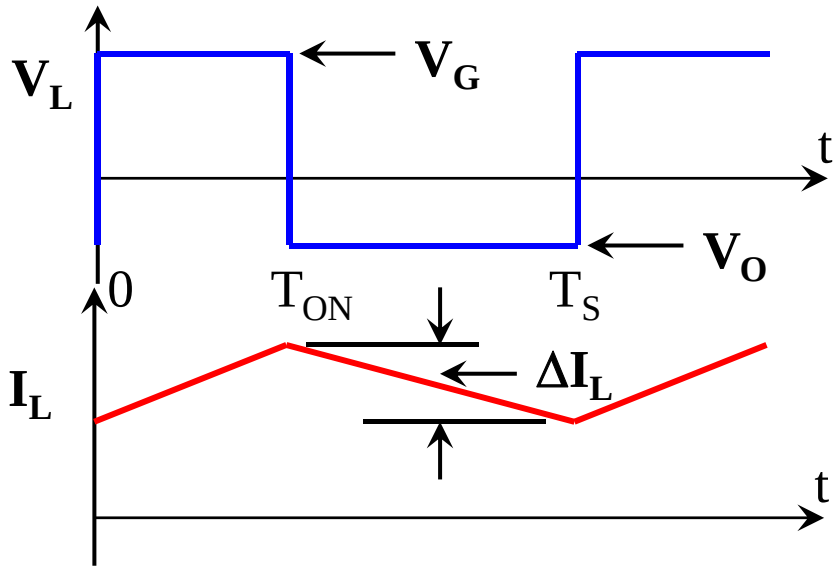
$$\Delta I_L = \frac{V_O(1-D)}{DL} DT_S = \frac{V_O(1-D)}{L} T_S$$

$$I_L = \frac{I_O}{1-D} = \frac{V_O}{R(1-D)}$$

Inductor Current Ripple – Integral of Inductor Voltage

Switched Mode Power Conversion

Flyback Converter

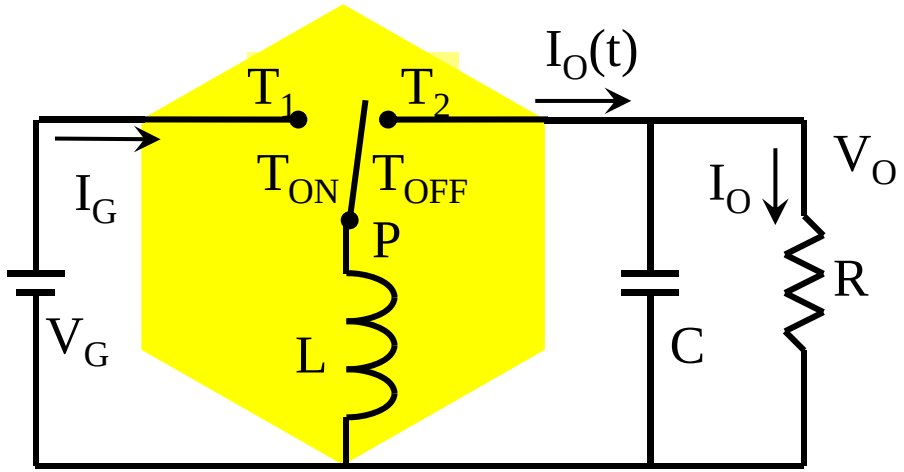


$$\frac{\Delta I_L}{I_L} = \frac{(1-D)^2 T_S}{(L/R)}$$

Inductor Current Ripple – Integral of Inductor Voltage

Switched Mode Power Conversion

Flyback Converter



$$\frac{\Delta I_L}{I_L} = \frac{(1-D)^2}{(L/R)} T_S$$

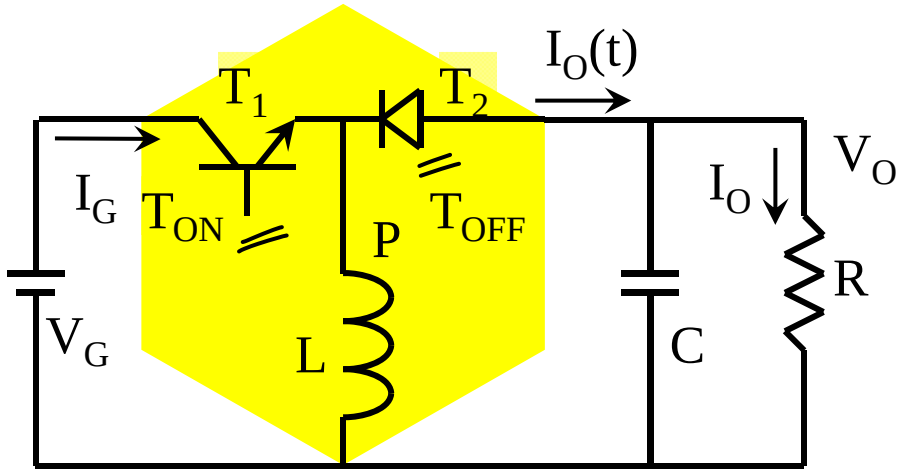
$$T_S \ll \frac{L}{R}$$

Condition for Low Ripple Current

Switching Period T_S << Circuit Time Constant (L/R)

Switched Mode Power Conversion

Flyback Converter

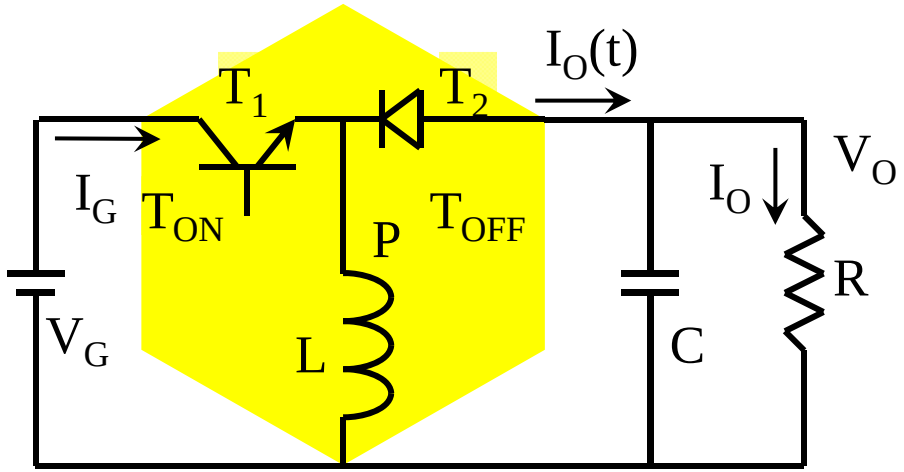


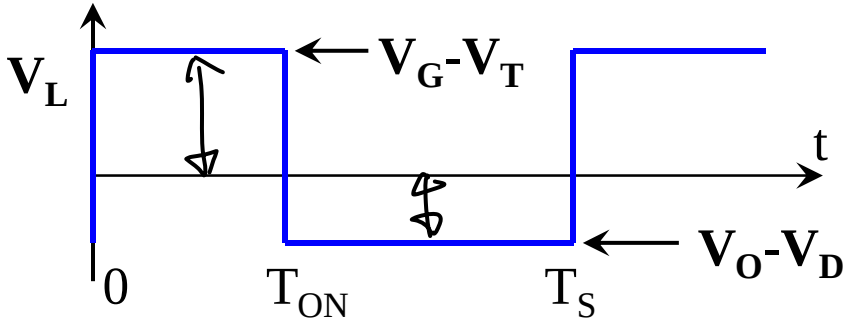
$$\frac{V_O}{V_G} = ?$$

Non-Ideality of the Switches

Switched Mode Power Conversion

Flyback Converter

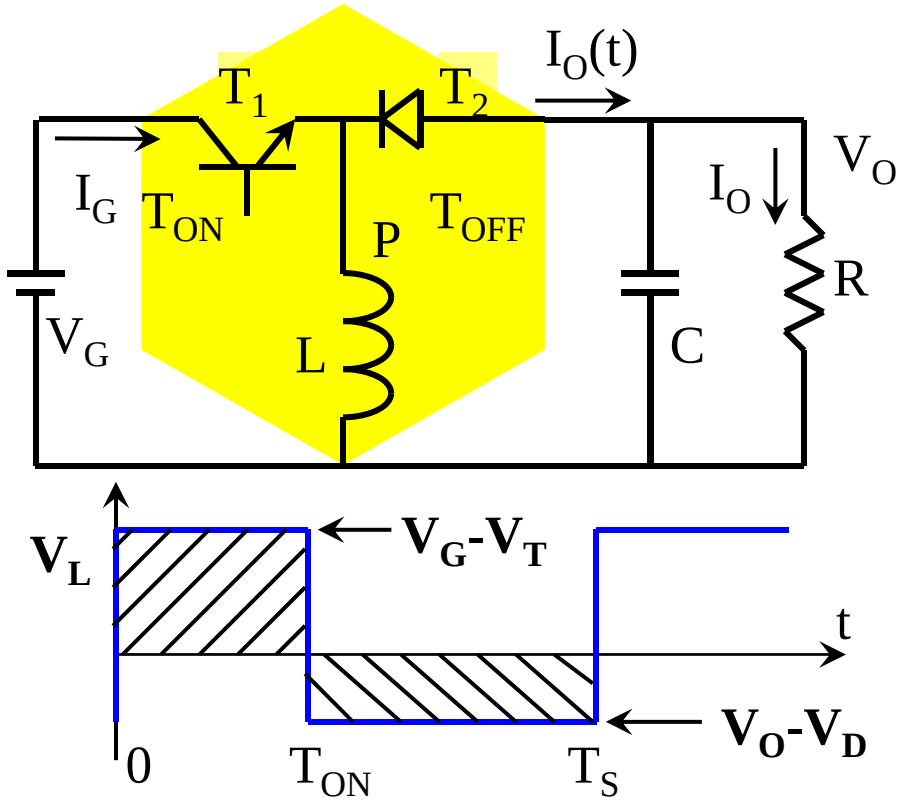




Volt-Sec Balance on Inductor

Switched Mode Power Conversion

Flyback Converter

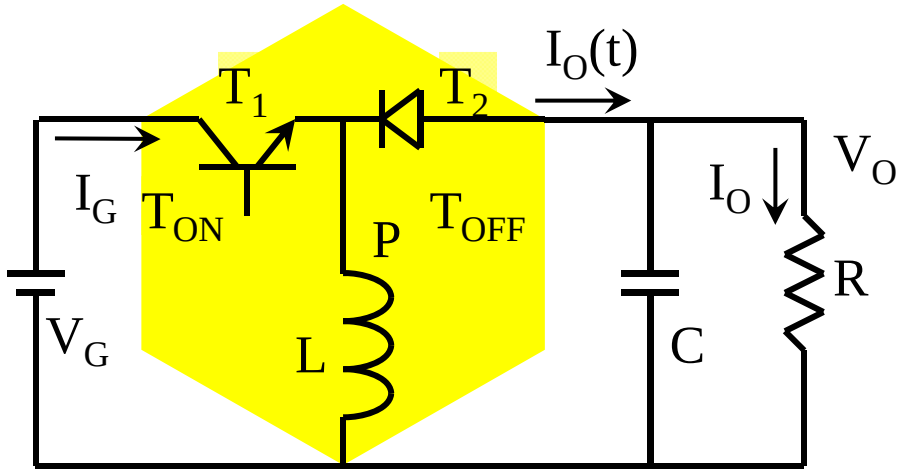


$$(V_G - V_T)T_{ON} + (V_O + V_D)T_{OFF} = 0$$

Volt-Sec Balance on Inductor

Switched Mode Power Conversion

Flyback Converter



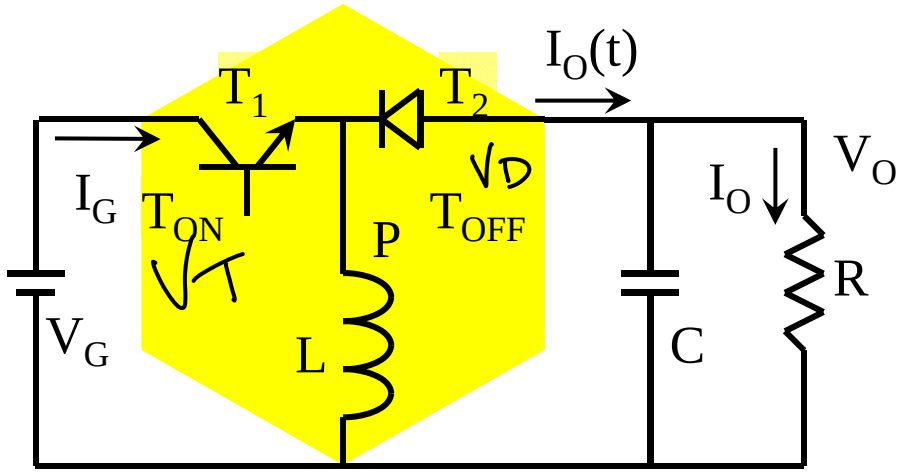
$$\frac{V_O}{V_G} = -\frac{D}{1-D}\cdot\frac{\left(1-\frac{V_T}{V_G}\right)}{\left(1+\frac{V_D}{V_O}\right)}$$

$$\eta = \frac{\left(1-\frac{V_T}{V_G}\right)}{\left(1+\frac{V_D}{V_O}\right)}$$

Volt-Sec Balance on Inductor

Switched Mode Power Conversion

Flyback Converter

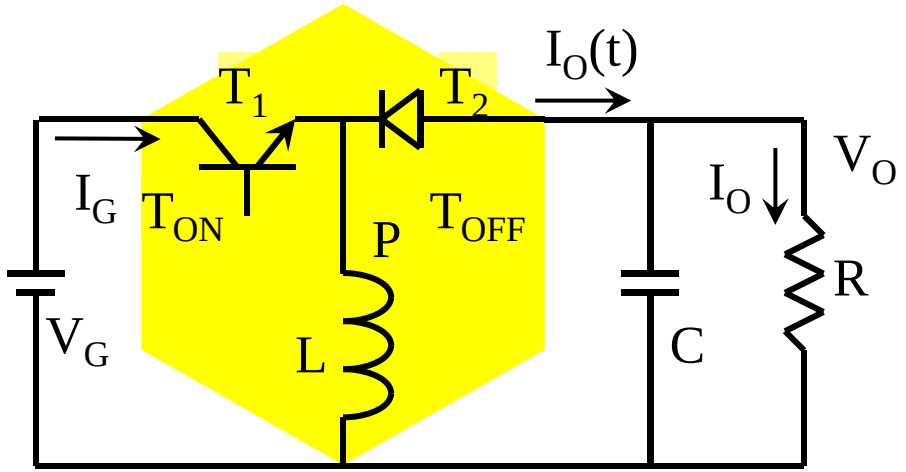


$$\frac{I_G}{I_O} = -\frac{D}{1-D}$$

Current Averaging

Switched Mode Power Conversion

Flyback Converter



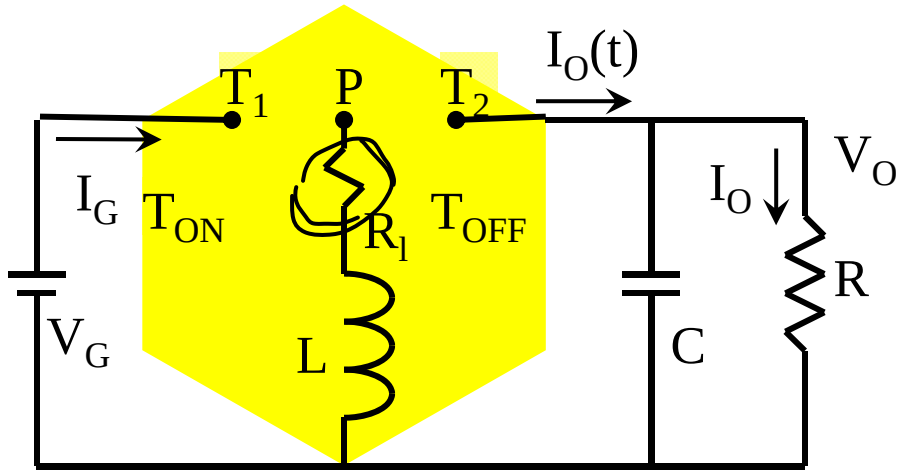
$$\frac{V_O I_O}{V_G I_G} = -\frac{D}{1-D}\frac{\left(1-\frac{V_T}{V_G}\right)}{\left(1+\frac{V_D}{V_O}\right)}\left(-\frac{1-D}{D}\right)$$

$$\eta = \frac{\left(1-\frac{V_T}{V_G}\right)}{\left(1+\frac{V_D}{V_O}\right)}$$

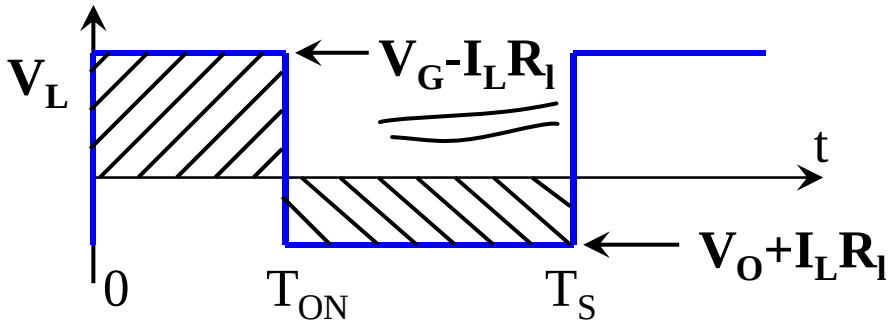
Efficiency of Power Conversion

Switched Mode Power Conversion

Flyback Converter



$\frac{V_0}{V_G}$



Non-Ideality of the Inductor

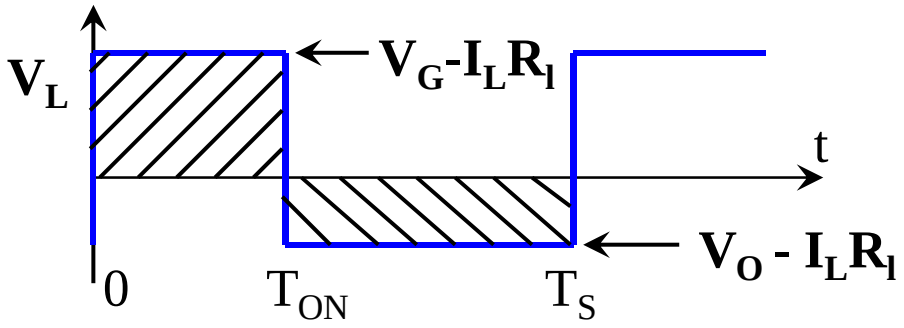
Switched Mode Power Conversion

Flyback Converter

$$\left(V_G - I_L R_l\right)T_{on} + \left(V_O - I_L R_l\right)T_{OFF} = 0$$

$$V_G D = -V_O(1-D) + I_L R_l = -V_O(1-D) - \frac{I_O}{(1-D)} R_l$$

$$DV_G = -V_O(1-D) - \frac{V_O}{(1-D)} \frac{R_l}{R}$$



Volt-Second Balance

Switched Mode Power Conversion

Flyback Converter

$$DV_G = -V_O(1-D) - \frac{V_O}{(1-D)}\frac{R_l}{R}$$

Define : $\alpha = \frac{R_l}{R}$

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

Voltage Conversion Ratio

Switched Mode Power Conversion

Flyback Converter

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

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

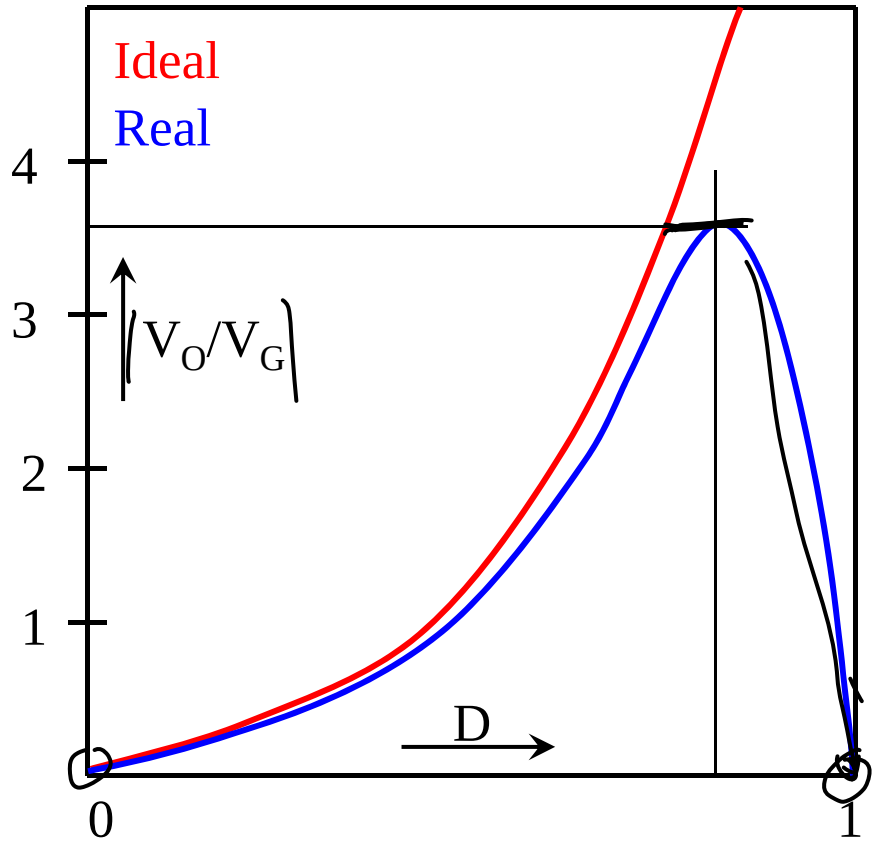
$$\eta = \frac{V_O I_O}{V_G I_G} = \frac{1}{\left(1+\frac{\alpha}{(1-D)^2}\right)} \quad //$$

Efficiency of Power Conversion

Switched Mode Power Conversion

Flyback Converter

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

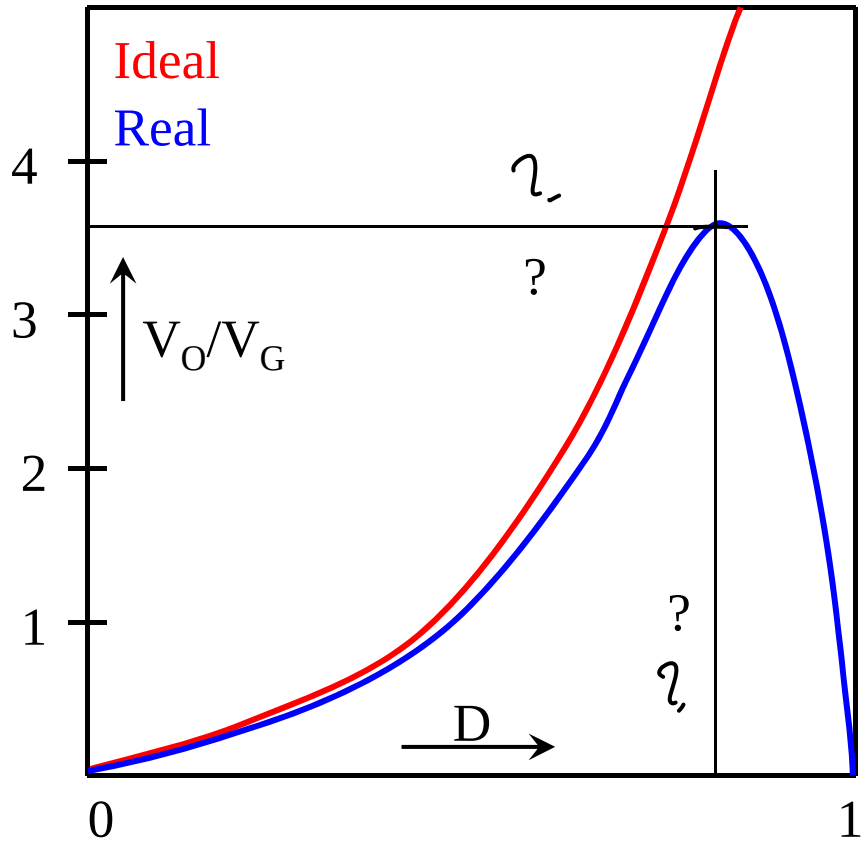


Real Forward Voltage Gain

Switched Mode Power Conversion

Flyback Converter

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



Real Forward Voltage Gain

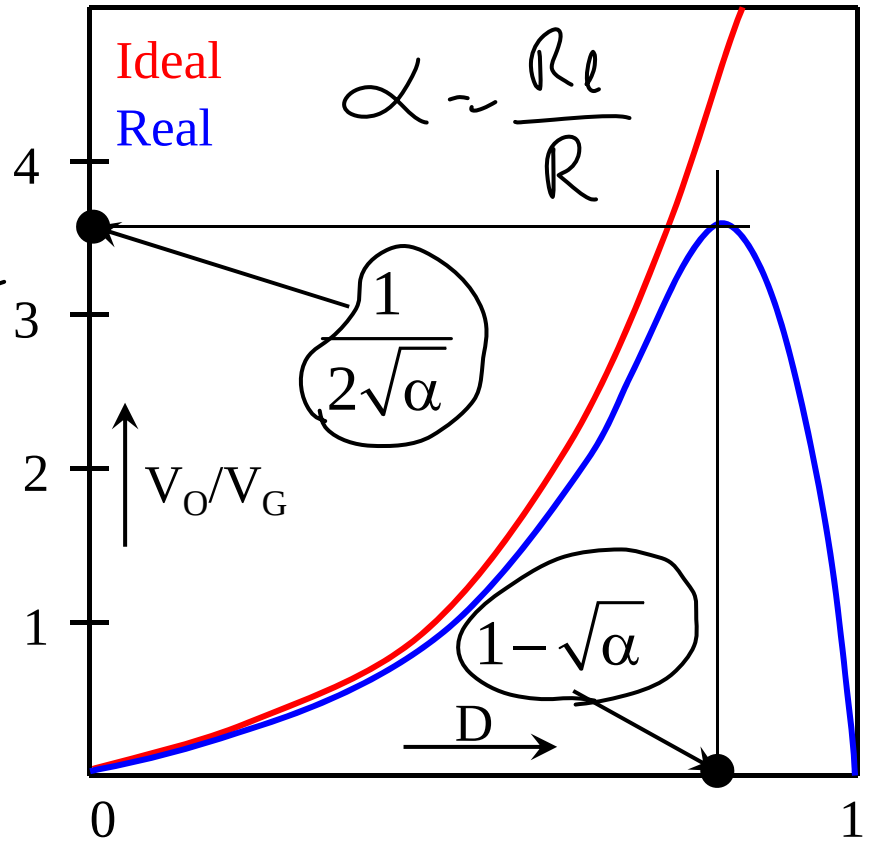
Switched Mode Power Conversion

Flyback Converter

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

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

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



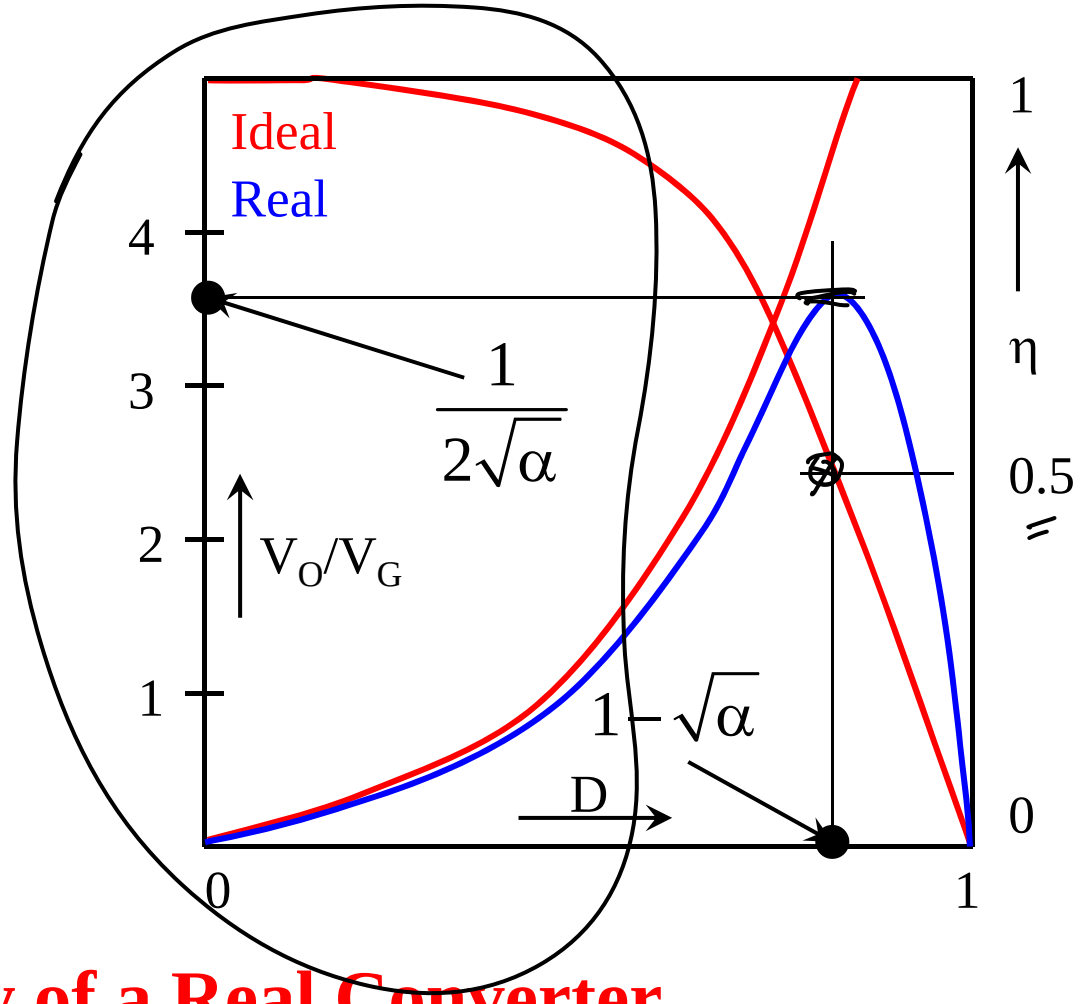
Real Forward Voltage Gain

Switched Mode Power Conversion

Flyback Converter

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

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



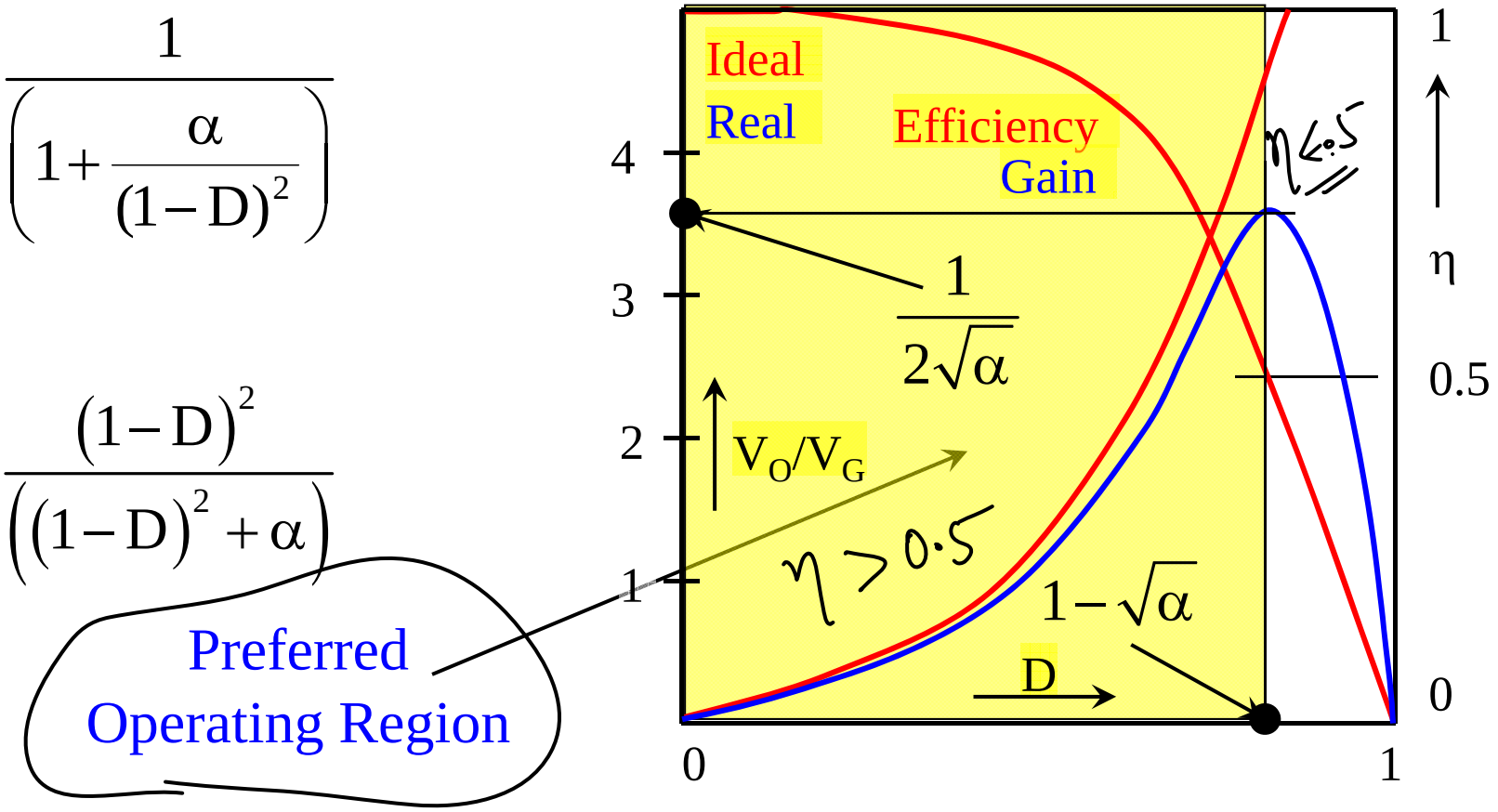
Efficiency of a Real Converter

Switched Mode Power Conversion

Flyback Converter

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

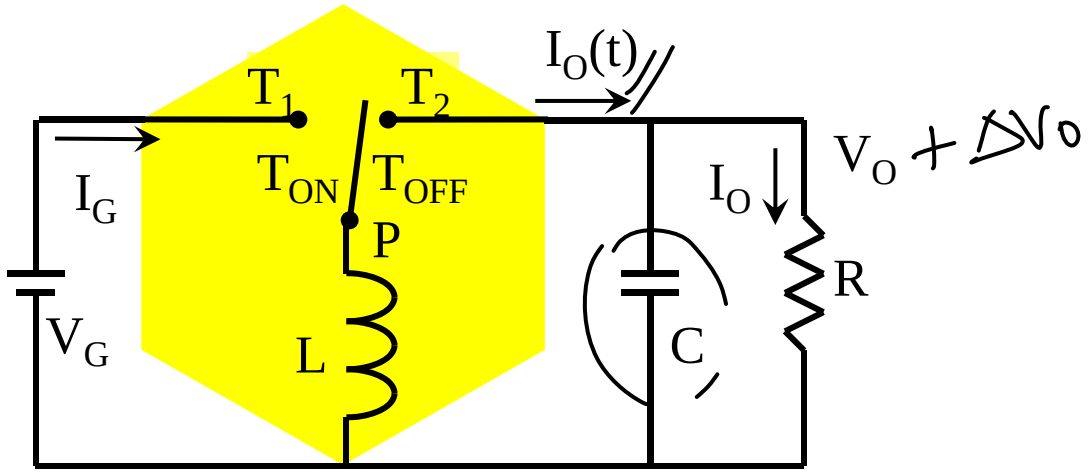
$$\eta = \frac{(1-D)^2}{\left((1-D)^2 + \alpha\right)}$$

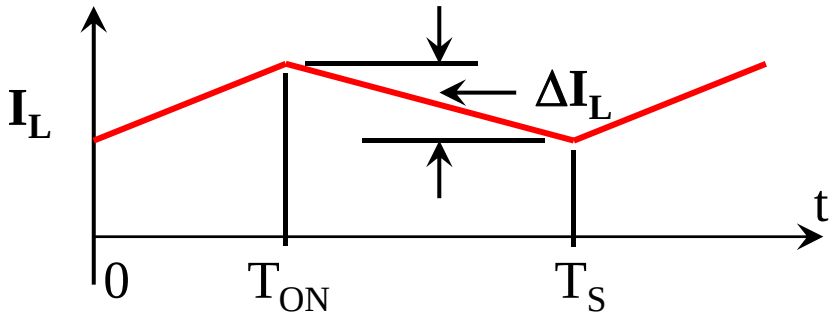


Preferred Range of Duty Ratio

Switched Mode Power Conversion

Flyback Converter

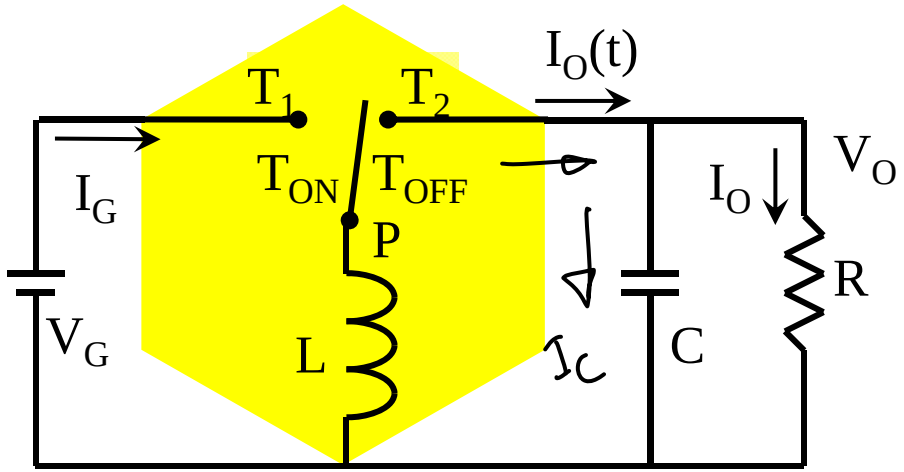


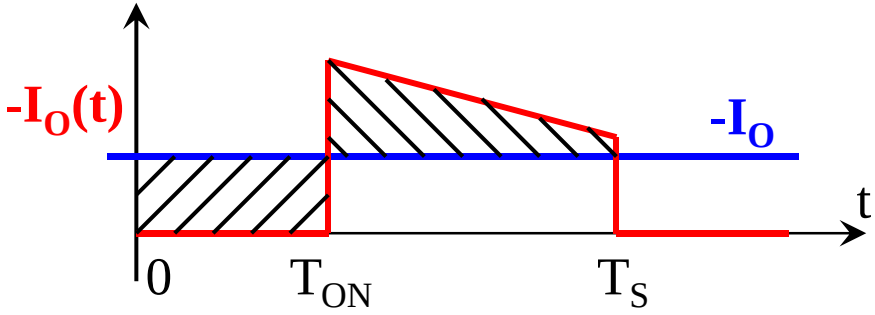


Output Voltage Ripple

Switched Mode Power Conversion

Flyback Converter

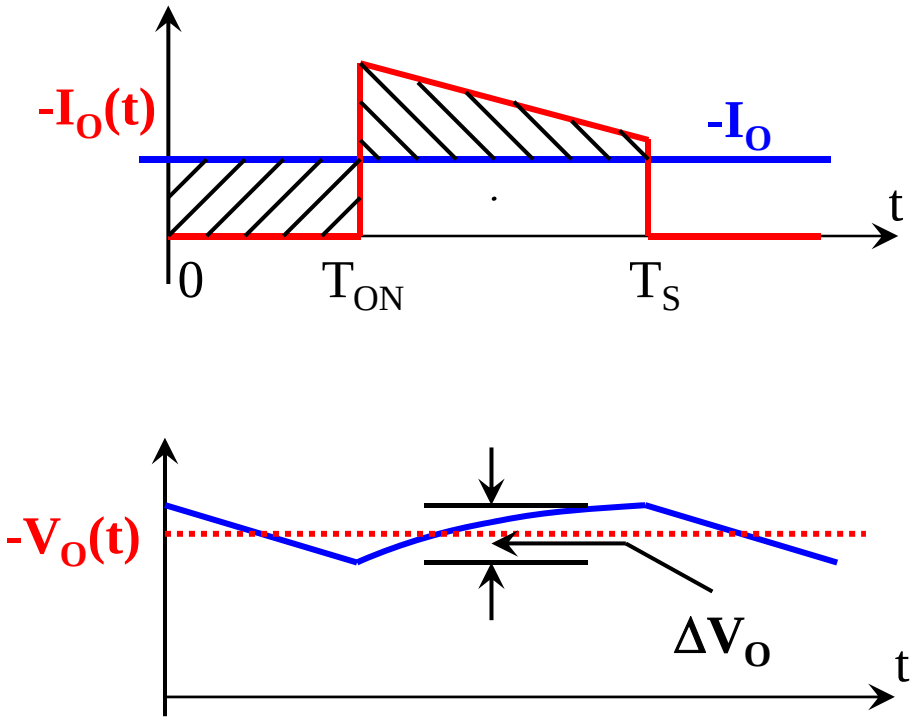




Capacitor Charge Balance

Switched Mode Power Conversion

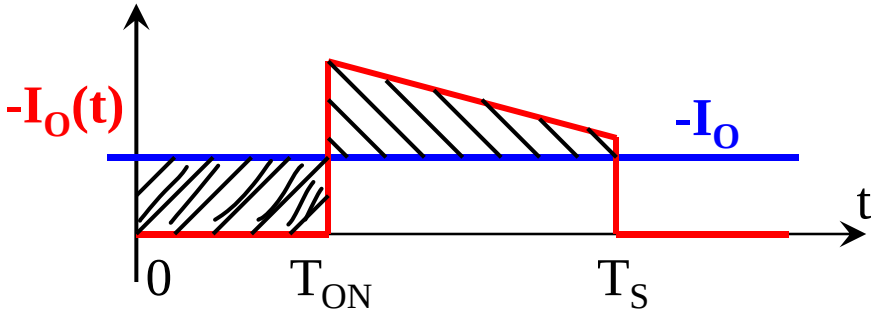
Flyback Converter



Capacitor Charge Balance

Switched Mode Power Conversion

Flyback Converter

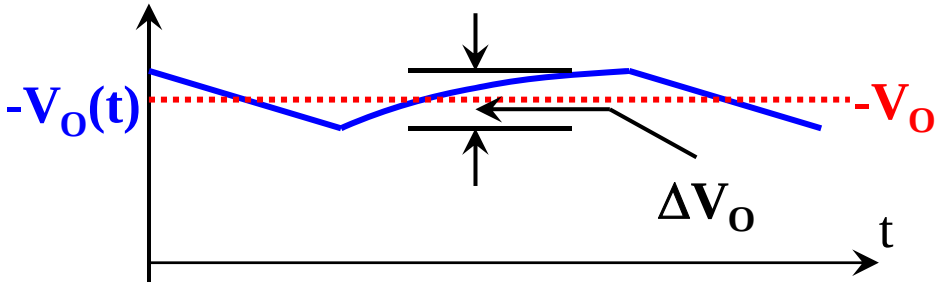


$$\Delta V_O = \frac{I_O D T_S}{C} = \frac{V_O D T_S}{R C}$$

Capacitor Charge Balance

Switched Mode Power Conversion

Flyback Converter



$$\frac{\Delta V_O}{V_O} = \frac{D T_S}{RC}$$

Design Guideline: $T_S << RC$

Capacitor Charge Balance

Switched Mode Power Conversion

Flyback Converter

Ideal Voltage Gain

$$\frac{V_O}{V_G} = -\frac{T_{ON}}{T_{OFF}} = -\frac{D}{1-D}$$

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

$$\frac{\Delta I_L}{I_L} = \frac{(1-D)^2}{(L/R)} T_S$$

$(1-D)^2 \frac{T_S}{4R}$

$T_S << L/R$

Switched Mode Power Conversion

Flyback Converter

Ideal Voltage Gain

Ideal Current Gain

Current Ripple

Voltage Ripple

$$\frac{\Delta V_O}{V_O} = \frac{D T_S}{R C}$$

Switched Mode Power Conversion

Flyback Converter

Ideal Voltage Gain

Ideal Current Gain

Current Ripple

Voltage Ripple

Real Voltage Gain

$$\frac{V_O}{V_G} = -\frac{D}{(1-D)}\frac{1}{\left(1+\frac{\alpha /\!/}{(1-D)^2}\right)}$$

$$\frac{V_O}{V_G} = -\frac{D}{1-D}\frac{\left(1-\frac{V_T}{V_G}\right)/\!/}{\left(1+\frac{V_D}{V_O}\right)}$$

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

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

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

Switched Mode Power Conversion

Flyback Converter

Ideal Voltage Gain

Ideal Current Gain

Current Ripple

Voltage Ripple

Real Voltage Gain

Real Current Gain

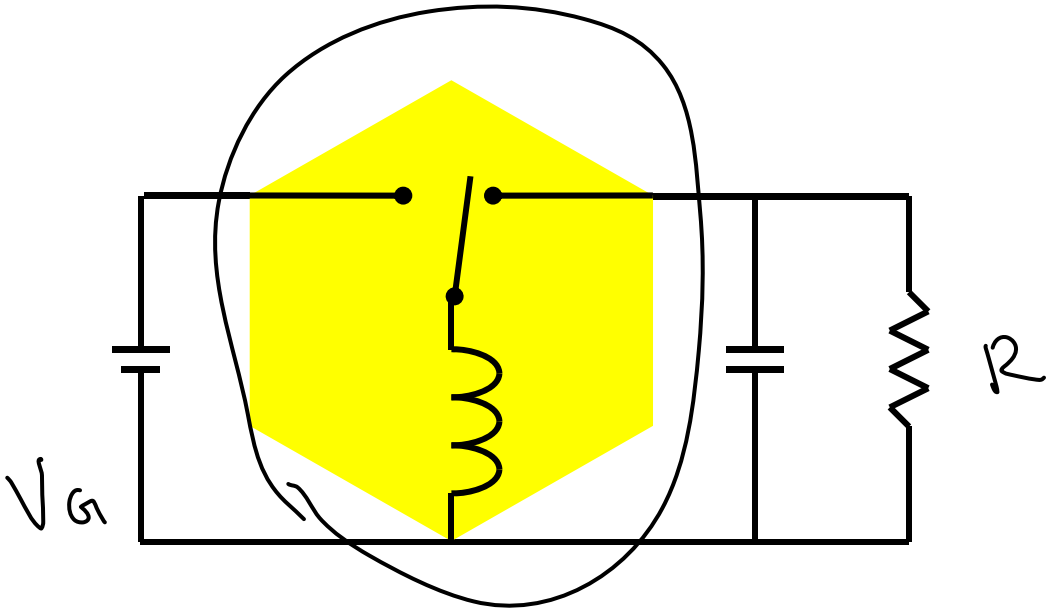
Efficiency

Preferred Operating Range

$$0 \le D \le \left(1-\sqrt{\alpha}\right); \qquad \alpha = R_1 / R$$

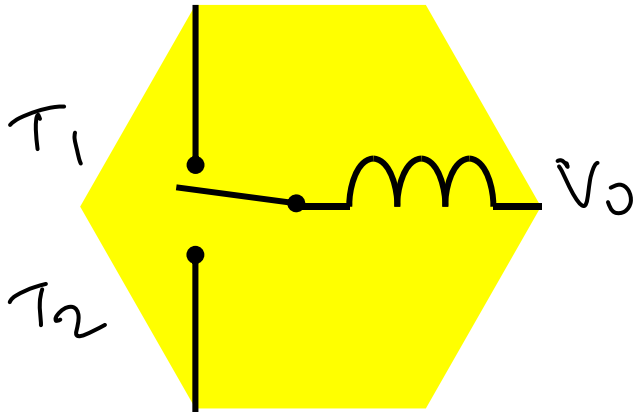
Switched Mode Power Conversion

Buck-Boost Converter



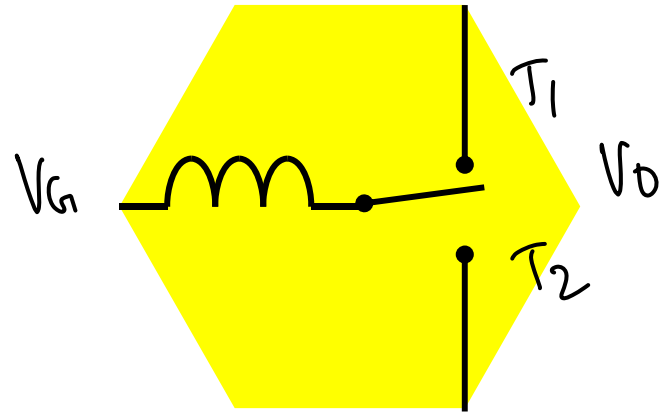
Switched Mode Power Conversion

Converter Cells



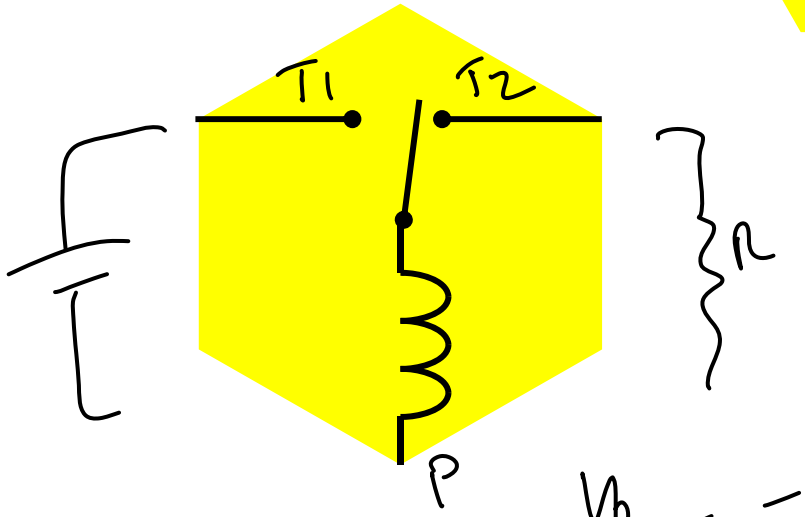
Buck

$$\frac{V_o}{V_G} = D$$



Boost

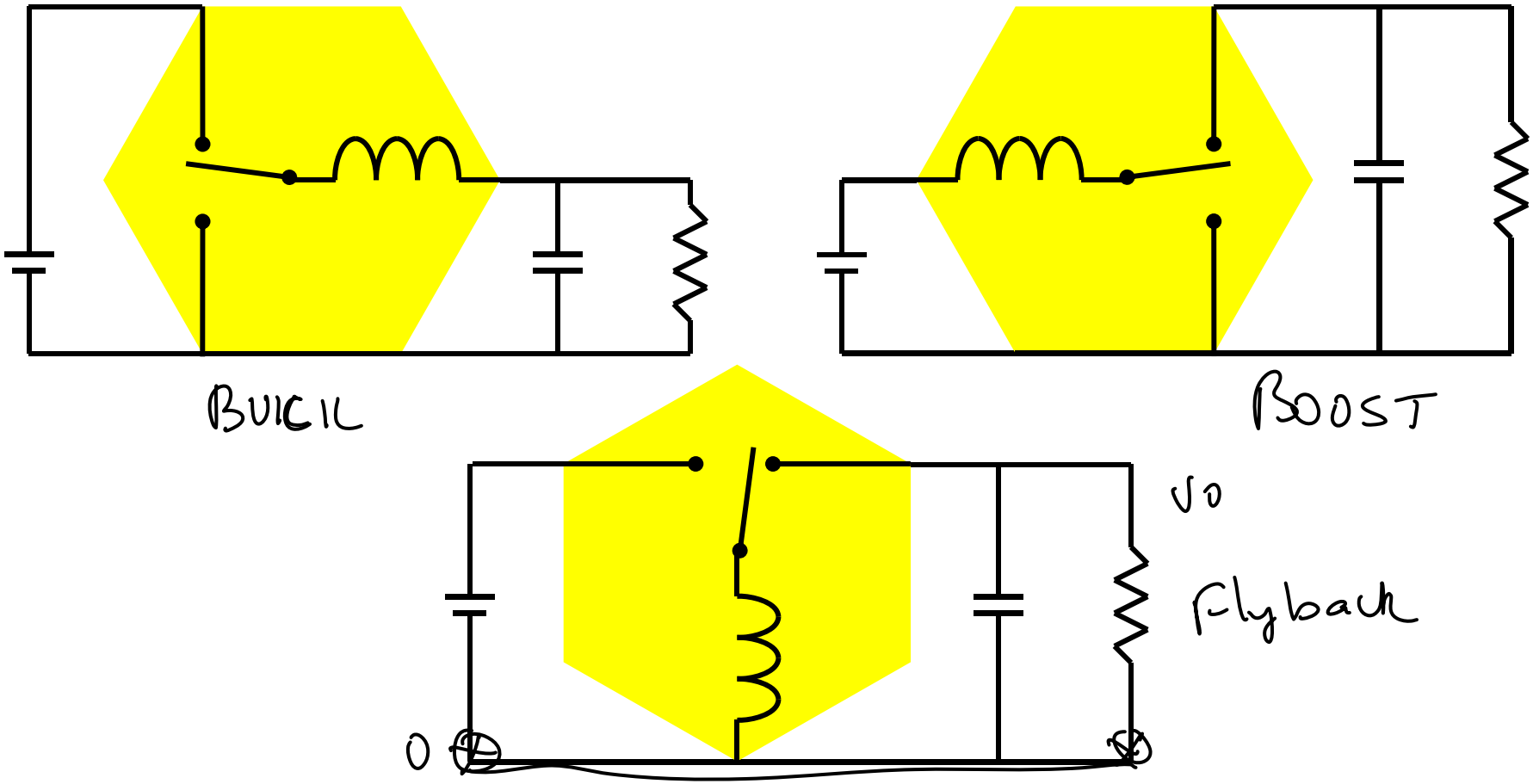
$$\frac{V_o}{V_G} = \frac{1}{1-D}$$



$$\frac{V_o}{V_G} = -\frac{D}{1-D}$$

Switched Mode Power Conversion

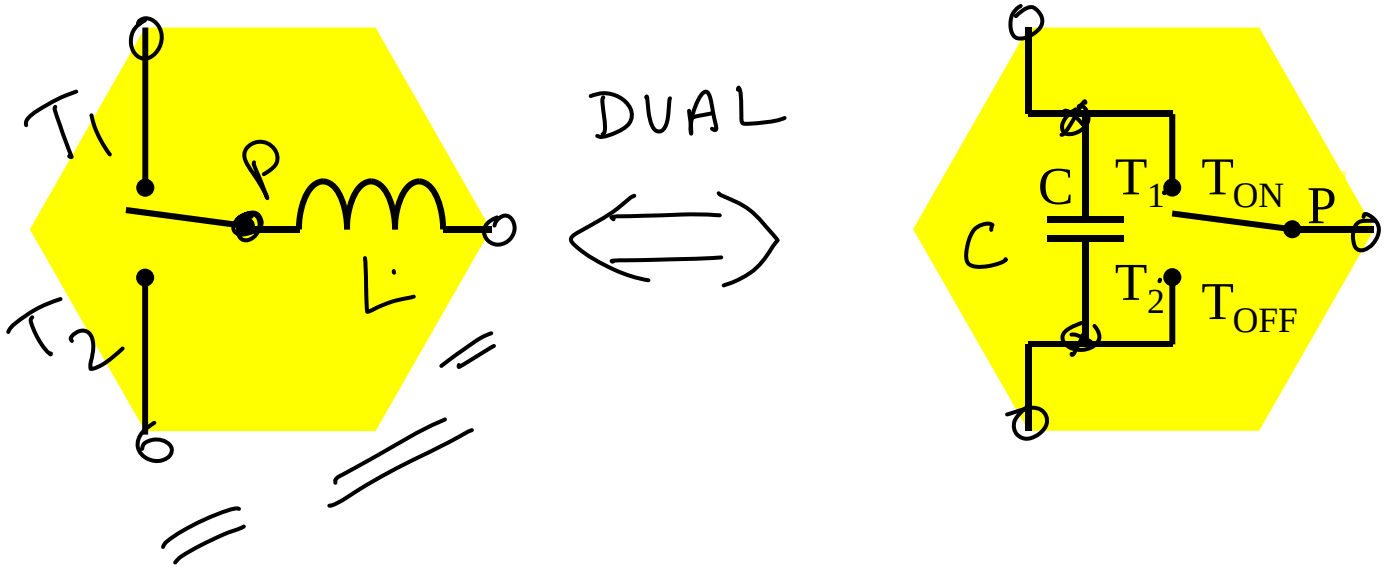
Basic Power Converters



Buck, Boost & Flyback Variants

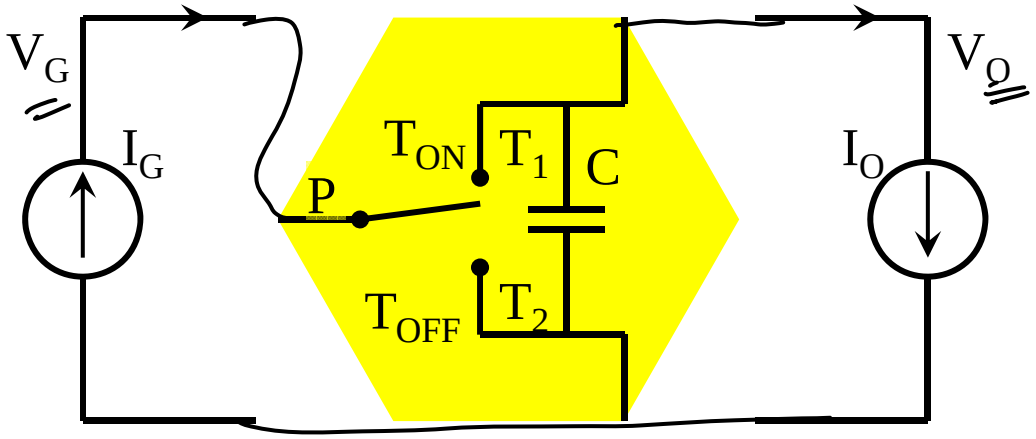
Switched Mode Power Conversion

Dual Converter Cell



Switched Mode Power Conversion

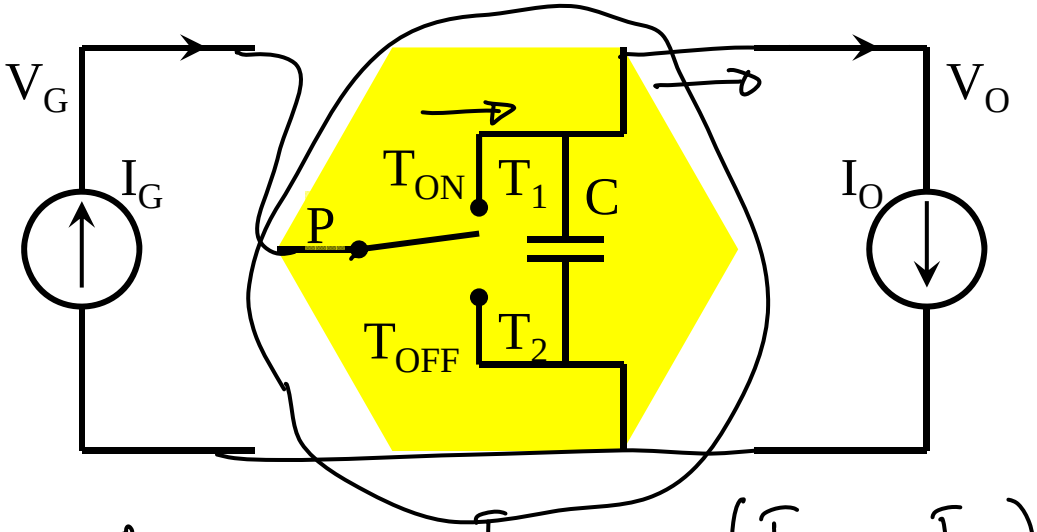
Dual Converter Cell



Buck Current Converter

Switched Mode Power Conversion

Dual Converter Cell



T_{ON} : $I_C = (I_G - I_O)$

T_{OFF} : $I_C = -I_O$

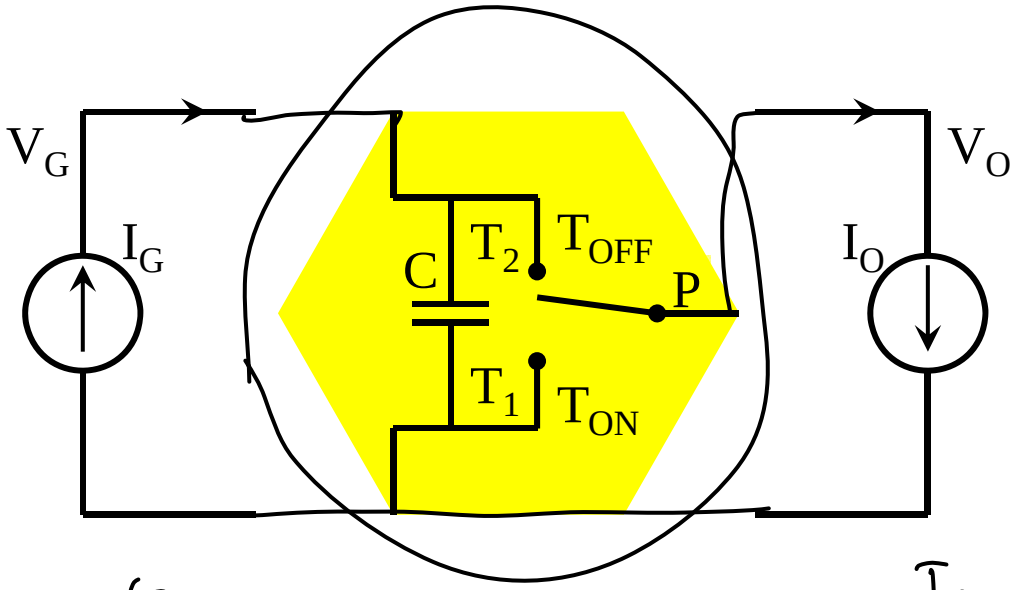
$$(I_G - I_O)\,T_{ON} - I_O\,T_{OFF} = 0$$

$$I_G T_{ON} = I_O T_S \Rightarrow \frac{I_O}{I_G} = \frac{T_{ON}}{T_S} = D$$

Buck Current Converter

Switched Mode Power Conversion

Dual Converter Cell



$$I_G T_{ON} + (I_G - I_O) T_{OFF} = 0$$

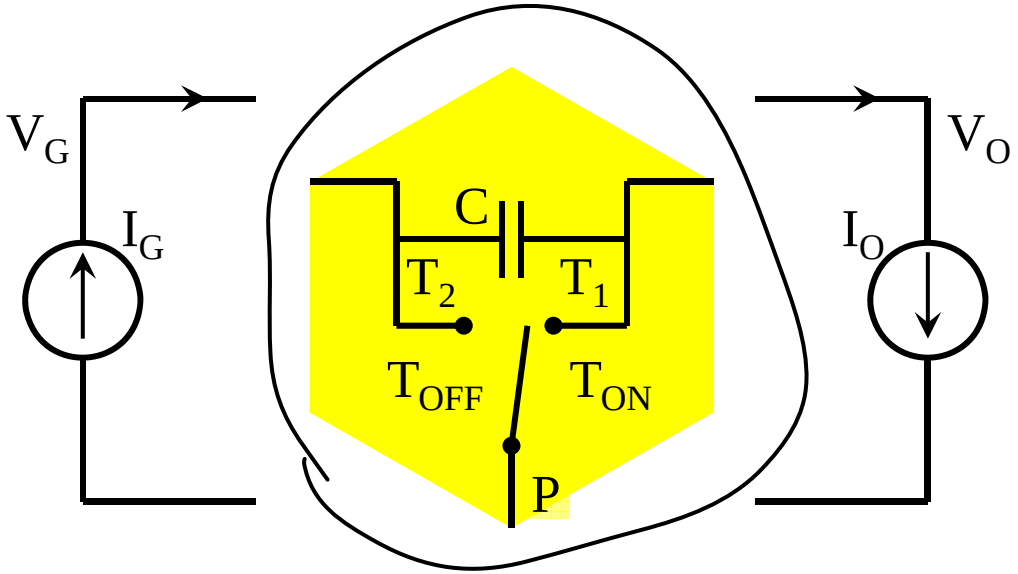
$$I_G T_S = I_O T_{OFF}$$

$$I_O = I_G \frac{T_S}{T_{OFF}} = \frac{I_G}{(1-D)}$$

Boost Current Converter

Switched Mode Power Conversion

Dual Converter Cell



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

Buck-Boost Current Converter

Switched Mode Power Conversion

Steady State Performance

AMP-SEC AVERAGING $\int_0^T i_C \, dt$

Ideal Voltage Gain

Ideal Current Gain

Current Ripple

Voltage Ripple

Real Voltage Gain

Real Current Gain

Efficiency

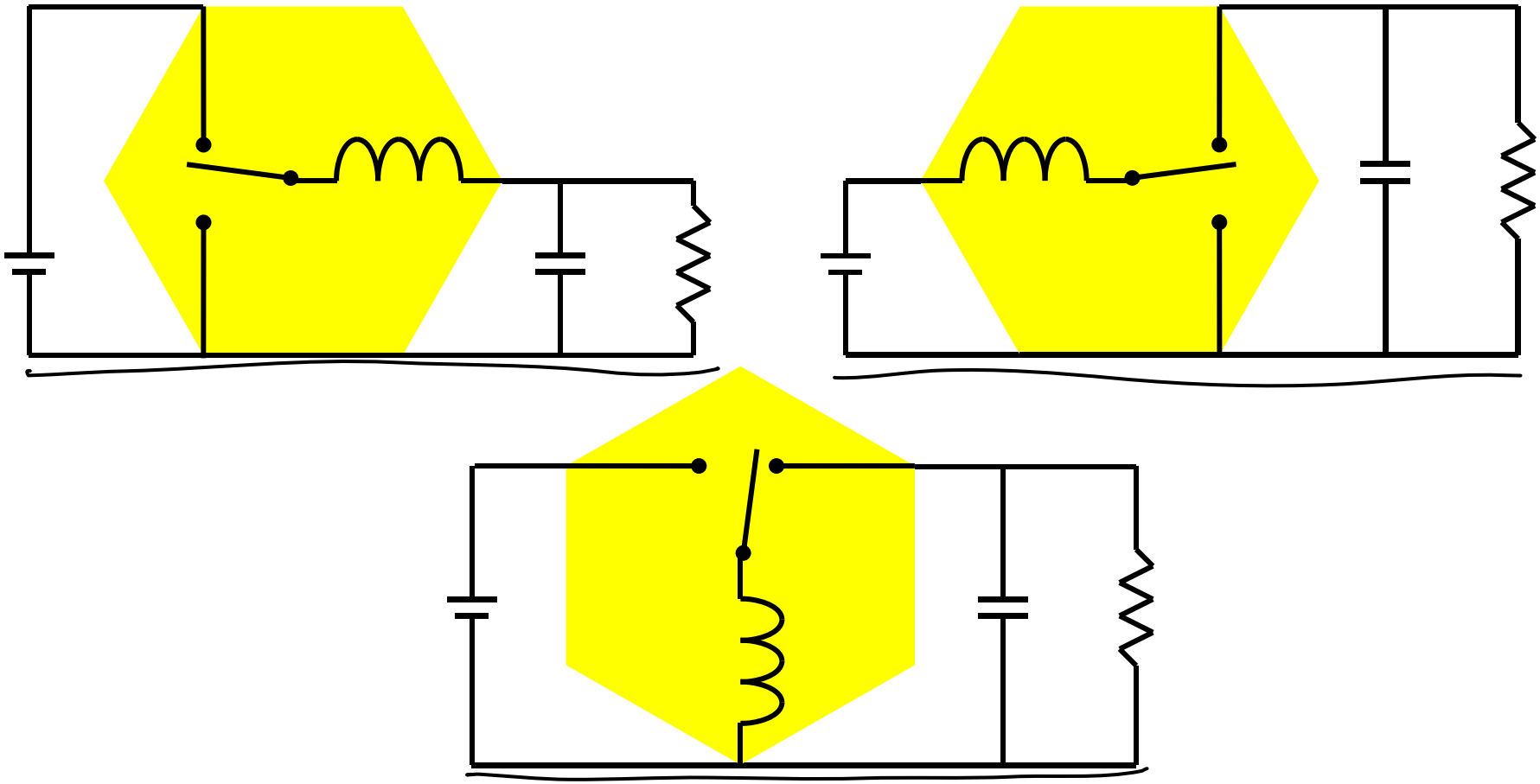
Preferred Operating Range

VOLT. SEC AVERAGING $\int_0^T v_L \, dt$

VOLT. SEC AVERAGING

Switched Mode Power Conversion

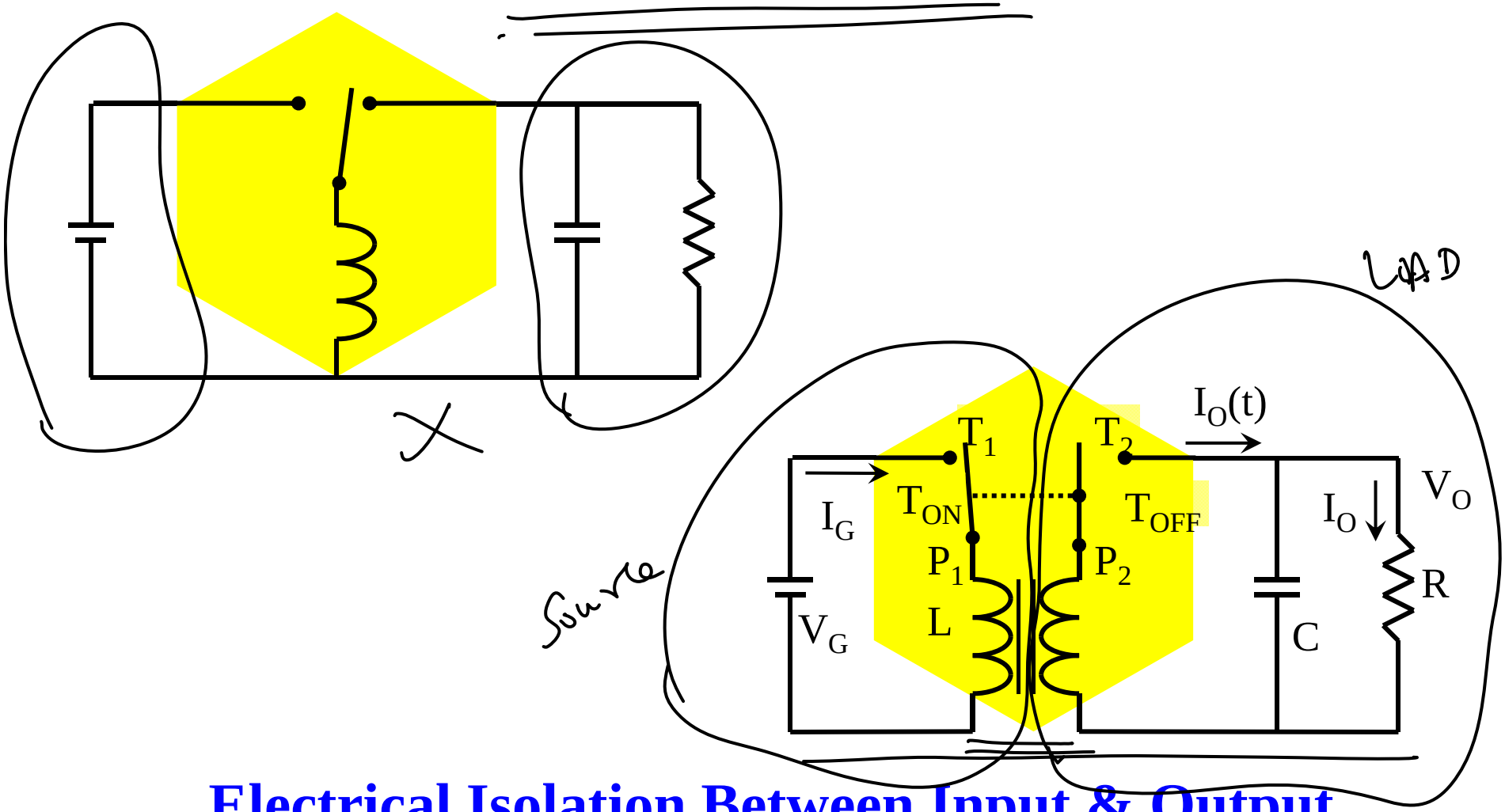
Non-Isolated Converters



Input and Output are Electrically Connected

Switched Mode Power Conversion

Isolated Converters



Electrical Isolation Between Input & Output