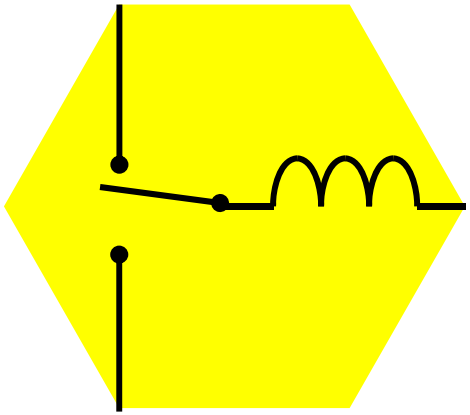
Switched Mode Power Conversion

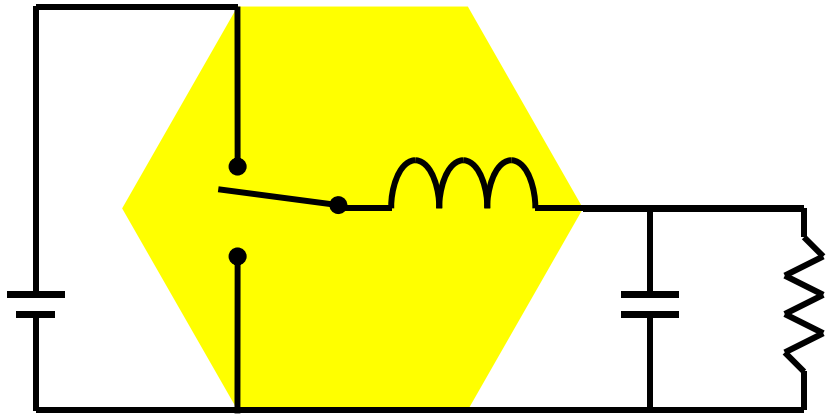
Non-Isolated Converters



Basic Converter Cell

Switched Mode Power Conversion

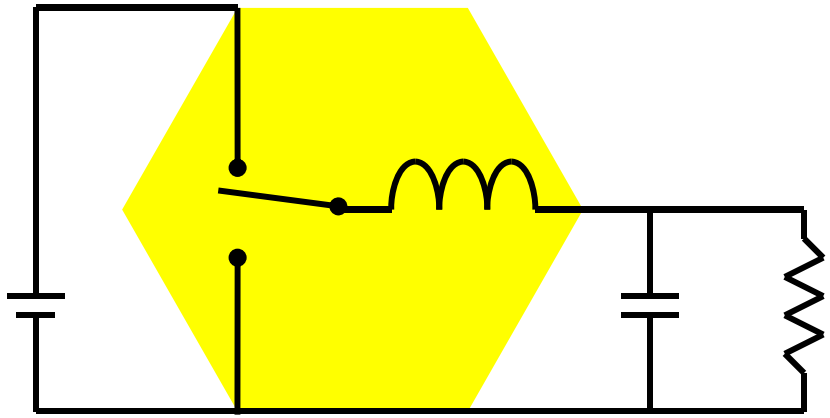
Non-Isolated Converters



Buck Converter

Switched Mode Power Conversion

Non-Isolated Converters



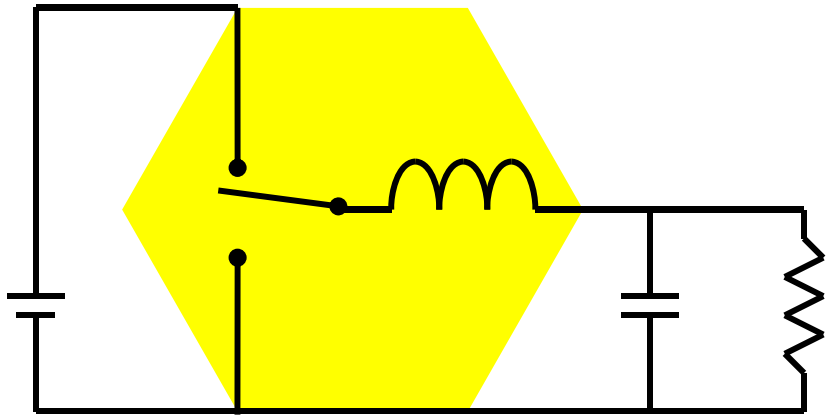
$$\frac{V_O}{V_G} = D$$

Buck Converter

Switched Mode Power Conversion

Non-Isolated Converters

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



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

Buck Converter

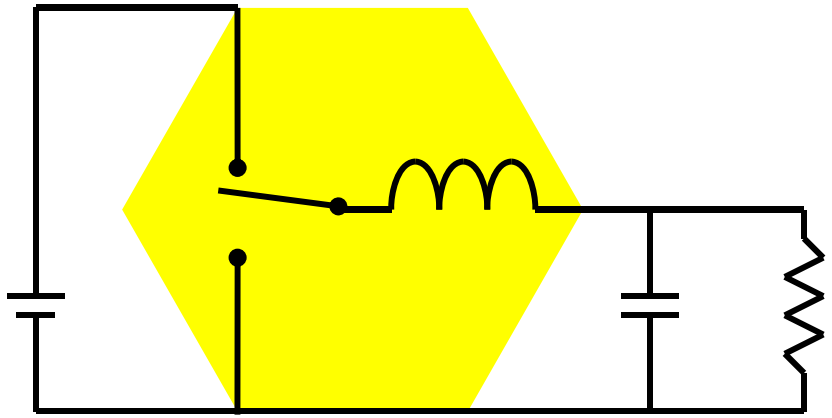
Switched Mode Power Conversion

Non-Isolated Converters

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

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

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



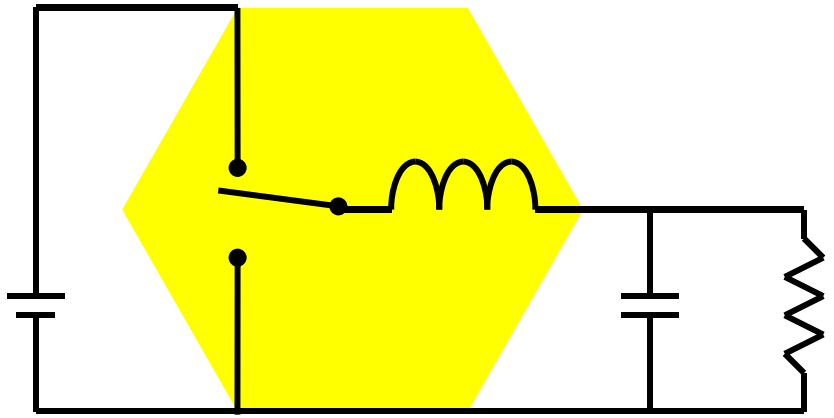
Buck Converter

Switched Mode Power Conversion

Non-Isolated Converters

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

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



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

$$\frac{\Delta V_O}{V_O} = \frac{(1-D)T_S^2}{8LC}$$

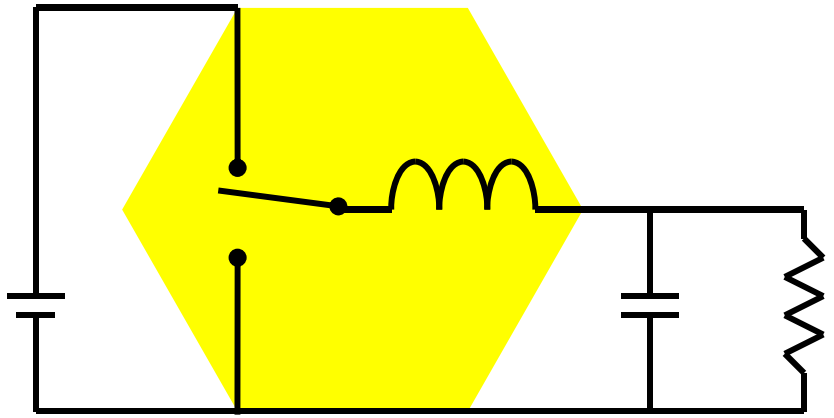
Buck Converter

Switched Mode Power Conversion

Non-Isolated Converters

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

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



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

$$\frac{\Delta V_O}{V_O}=\frac{(1-D)T_S^2}{8LC}$$

$$\frac{V_O}{V_G}=D\left(\frac{1-\frac{V_T}{V_G}-\frac{(1-D)V_D}{DV_G}}{1+\frac{DR_S}{R}+\frac{R_l}{R}}\right)$$

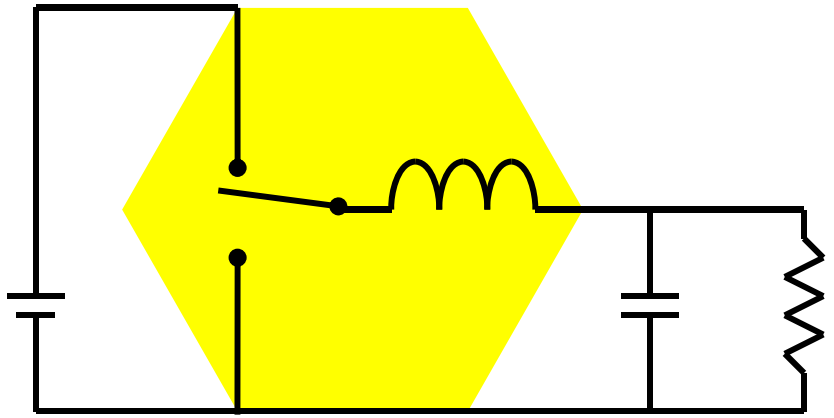
Buck Converter

Switched Mode Power Conversion

Non-Isolated Converters

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

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



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

$$\frac{\Delta V_O}{V_O}=\frac{(1-D)T_S^2}{8LC}$$

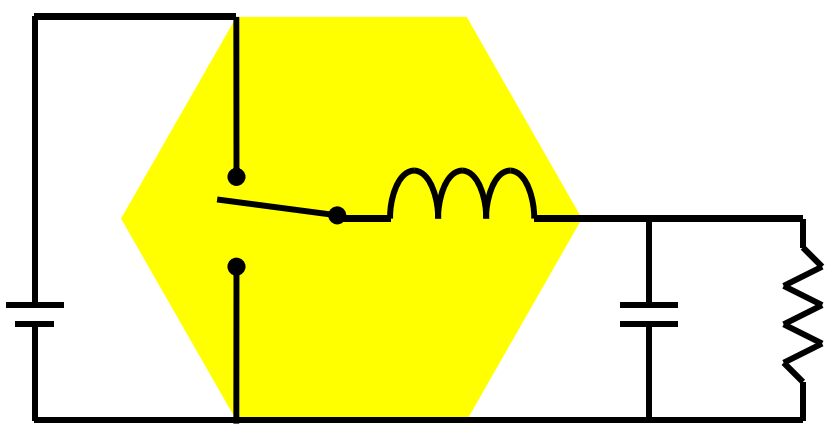
$$\frac{V_O}{V_G}=D\left(\frac{1-\frac{V_T}{V_G}-\frac{(1-D)V_D}{DV_G}}{1+\frac{DR_S}{R}+\frac{R_l}{R}}\right)$$

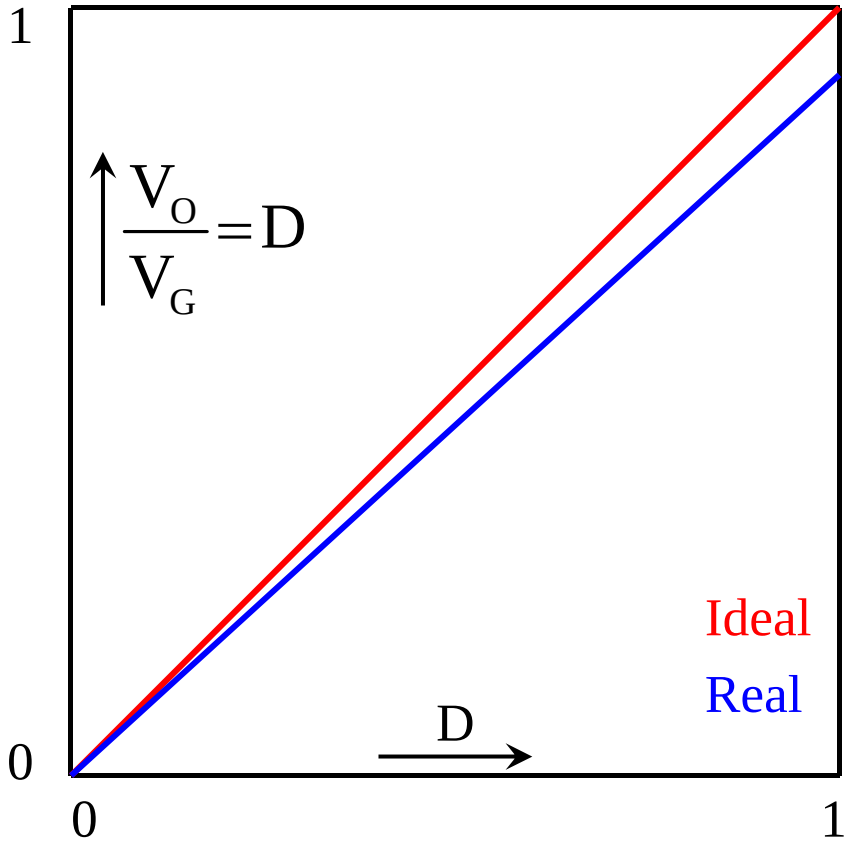
$$\eta=\frac{V_O I_O}{V_G I_G}=\left(\frac{1-\frac{V_T}{V_G}-\frac{(1-D)V_D}{DV_G}}{1+\frac{DR_S}{R}+\frac{R_l}{R}}\right)$$

Buck Converter

Switched Mode Power Conversion

Non-Isolated Converters

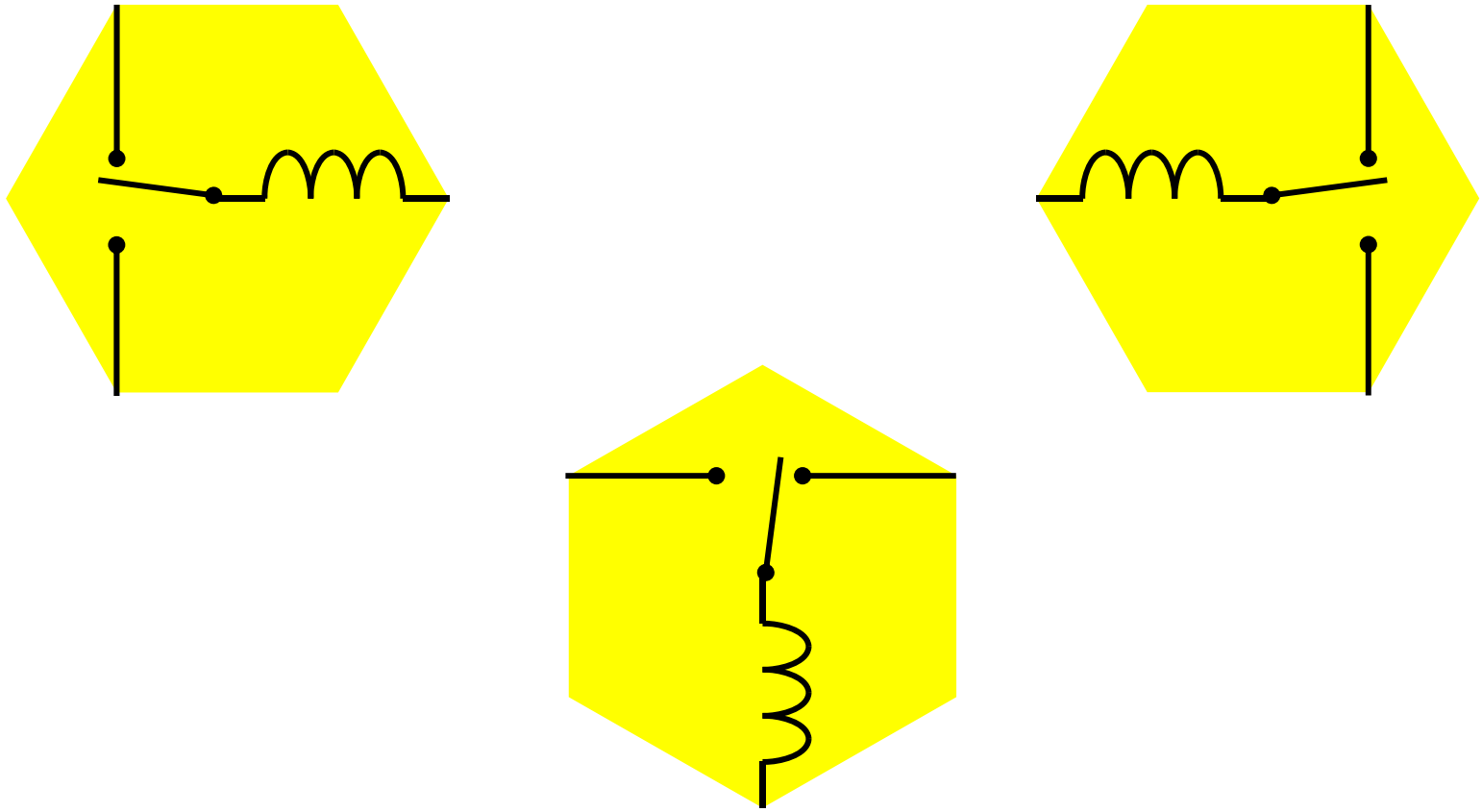




Step-Down Converter

Switched Mode Power Conversion

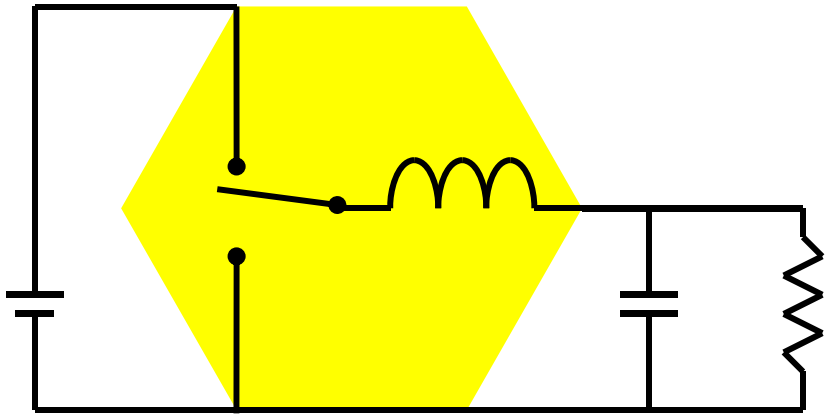
Basic Converter Cell



Three Variants of the Switch-Inductor Cell

Switched Mode Power Conversion

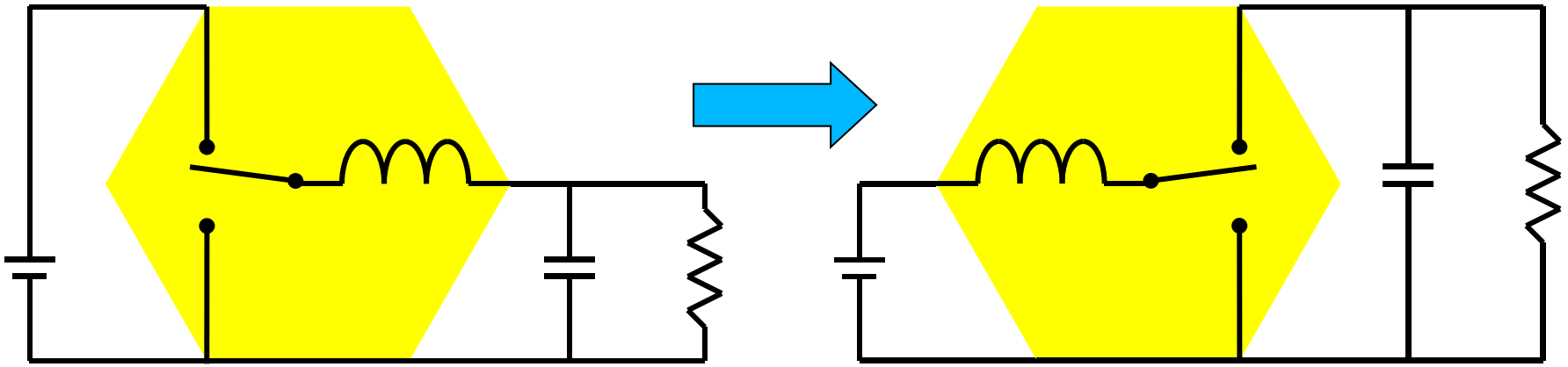
Buck Converter



Voltage Input Current Output Converter

Switched Mode Power Conversion

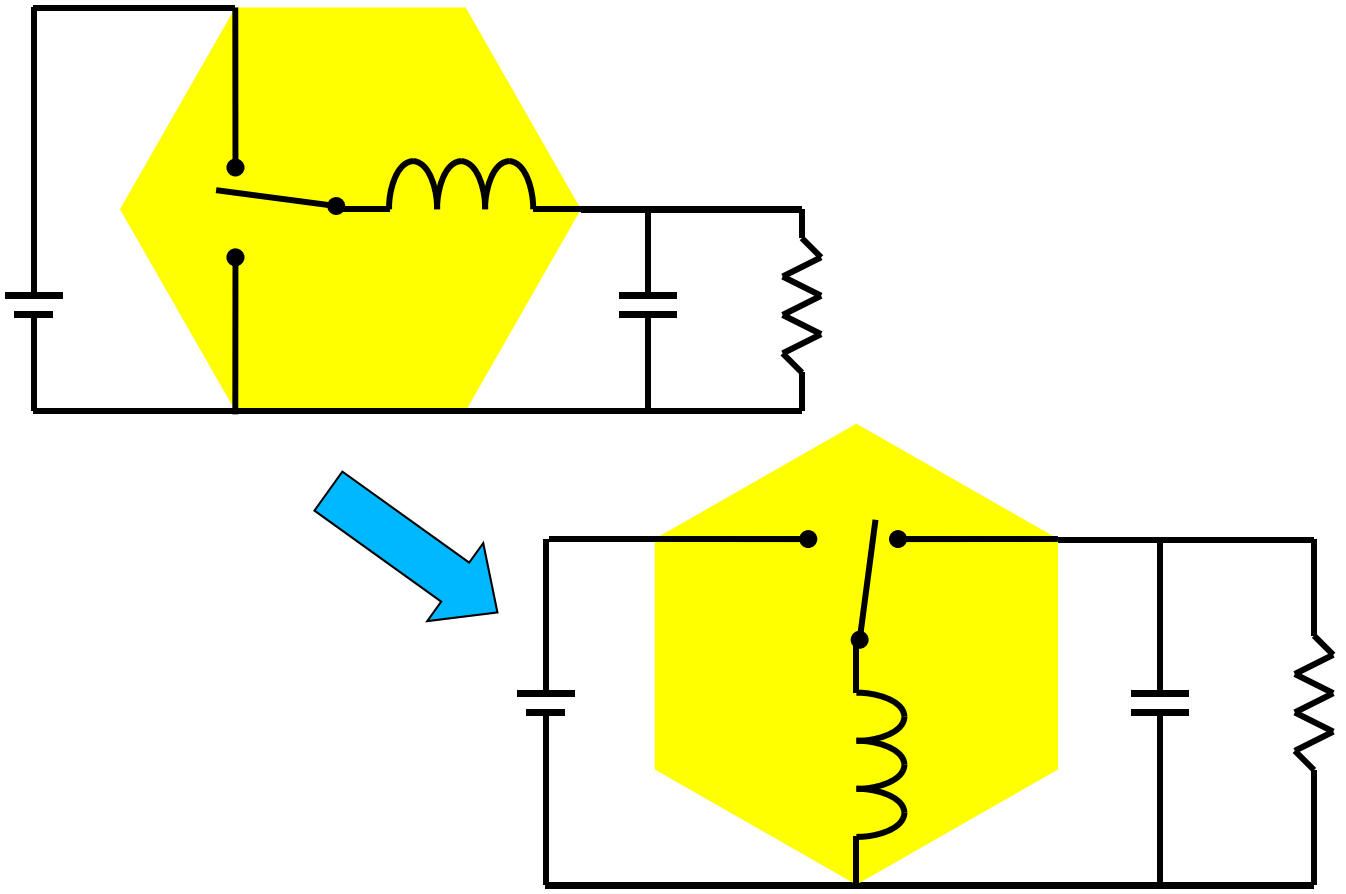
Basic Power Converters



Current Input Voltage Output Variant

Switched Mode Power Conversion

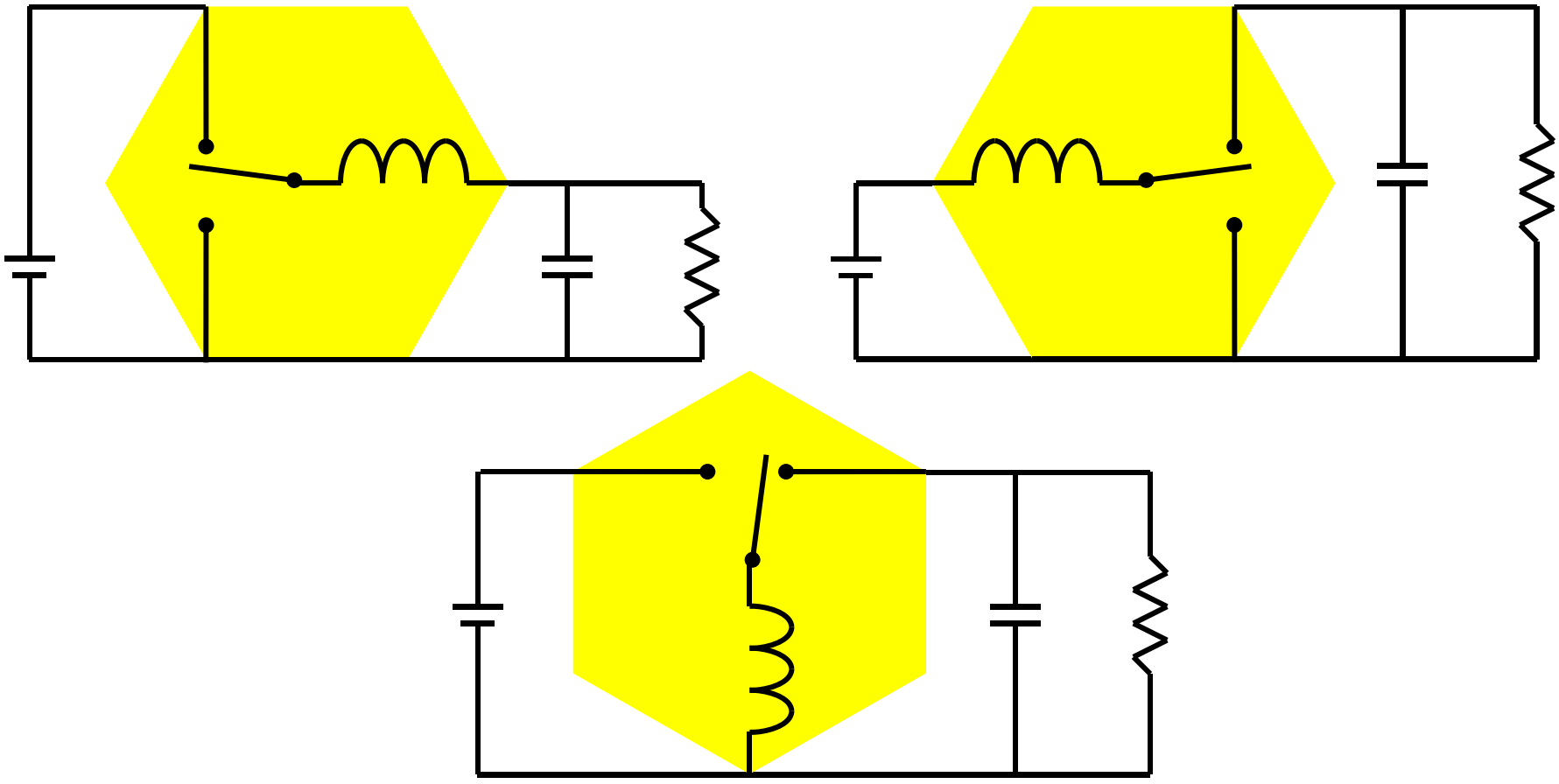
Basic Power Converters



Current Input Current Output Variant

Switched Mode Power Conversion

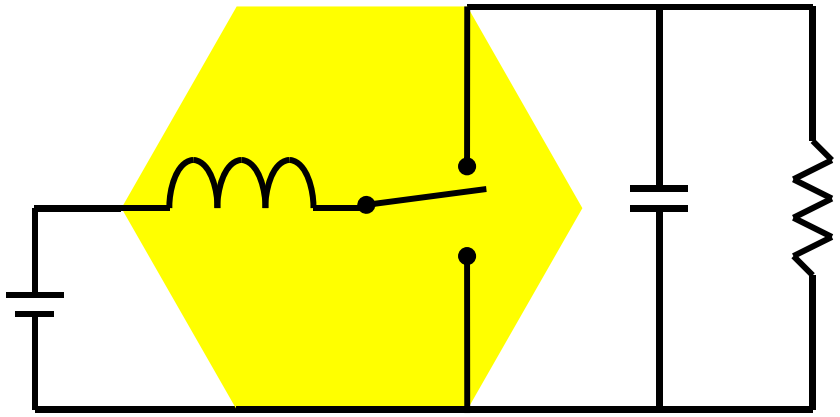
Basic Power Converters



Buck, Boost & Buck-Boost Variants

Switched Mode Power Conversion

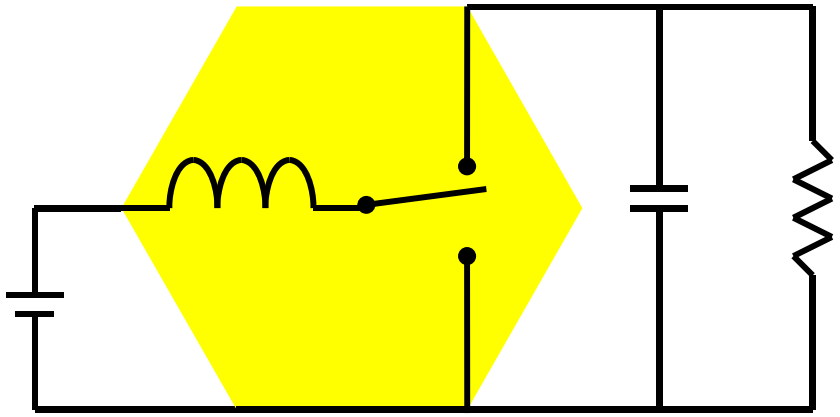
Analysis of Boost Converters



Boost Converter

Switched Mode Power Conversion

Analysis of Boost Converters



Voltage Gain V_O/V_G

Current Gain I_O/I_G

Current Ripple $\Delta I_O/I_O$

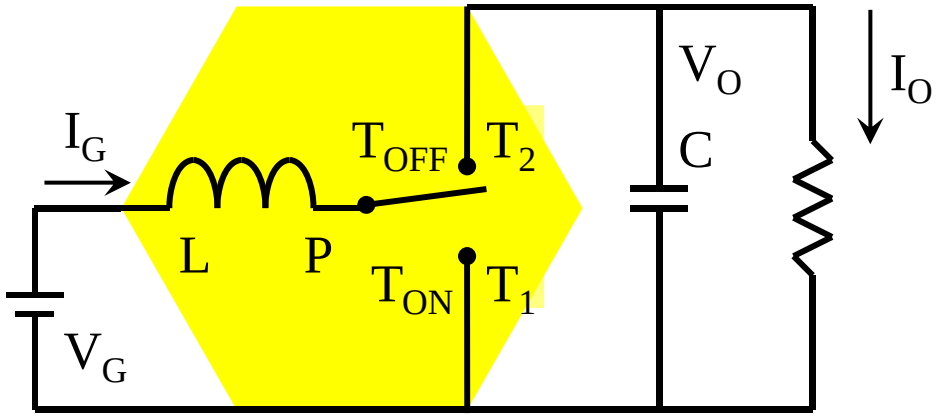
Voltage Ripple $\Delta V_O/V_O$

Switch, Source, Storage Non-ideality

Efficiency

Switched Mode Power Conversion

Boost Converter

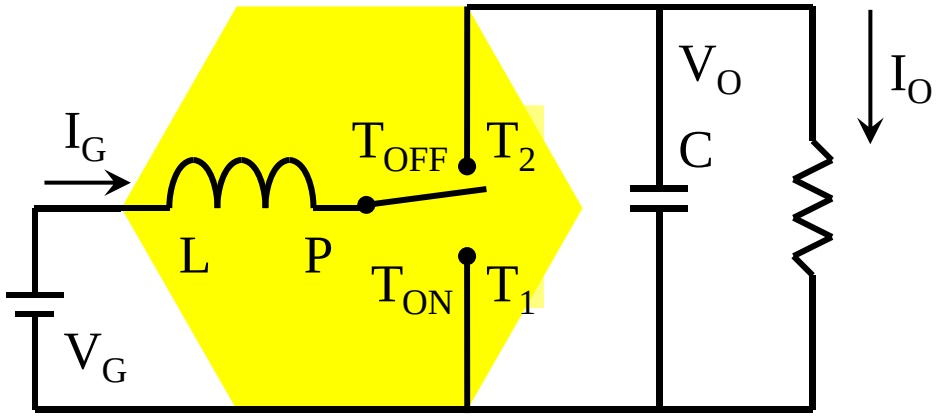


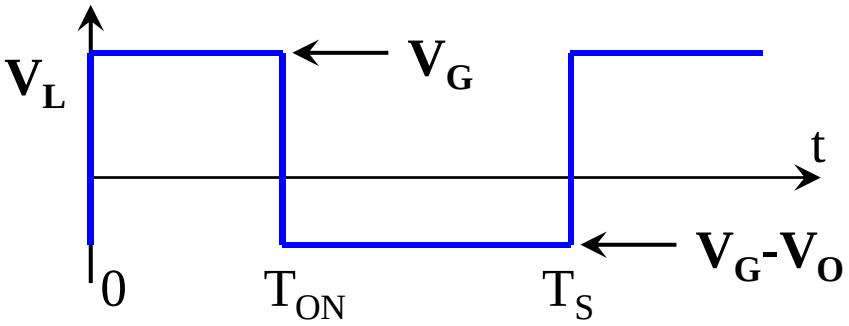
$$\frac{V_O}{V_G} = ?$$

Voltage Conversion Ratio

Switched Mode Power Conversion

Boost Converter

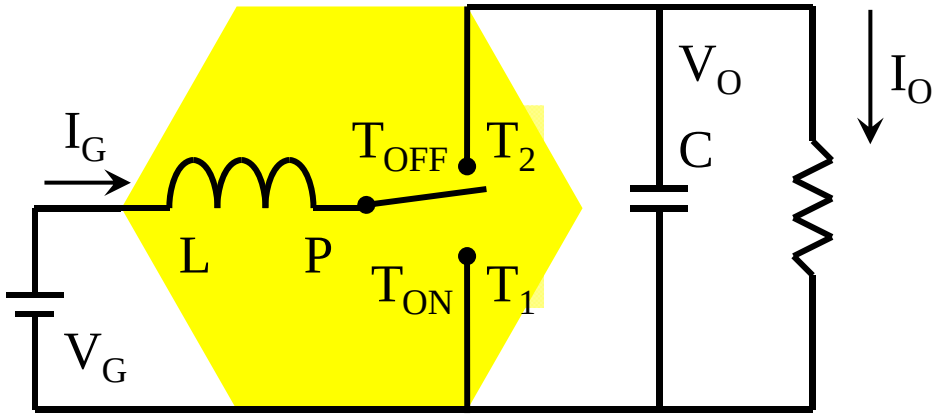


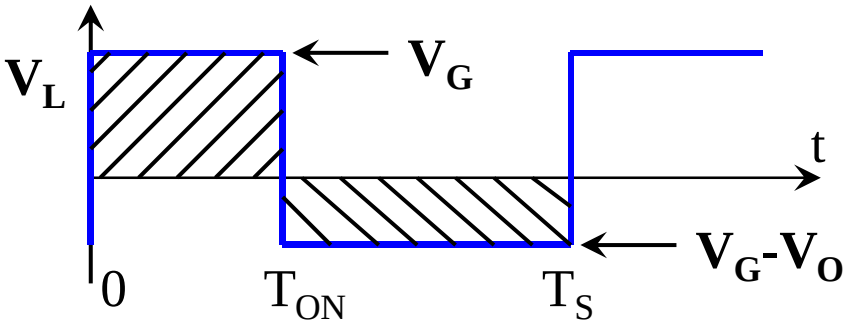


Inductor Volt-Sec Balance

Switched Mode Power Conversion

Boost Converter

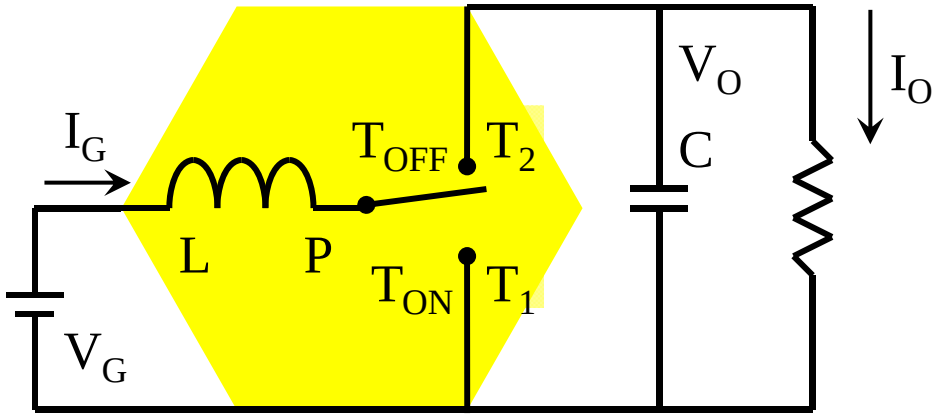




Inductor Volt-Sec Balance

Switched Mode Power Conversion

Boost Converter

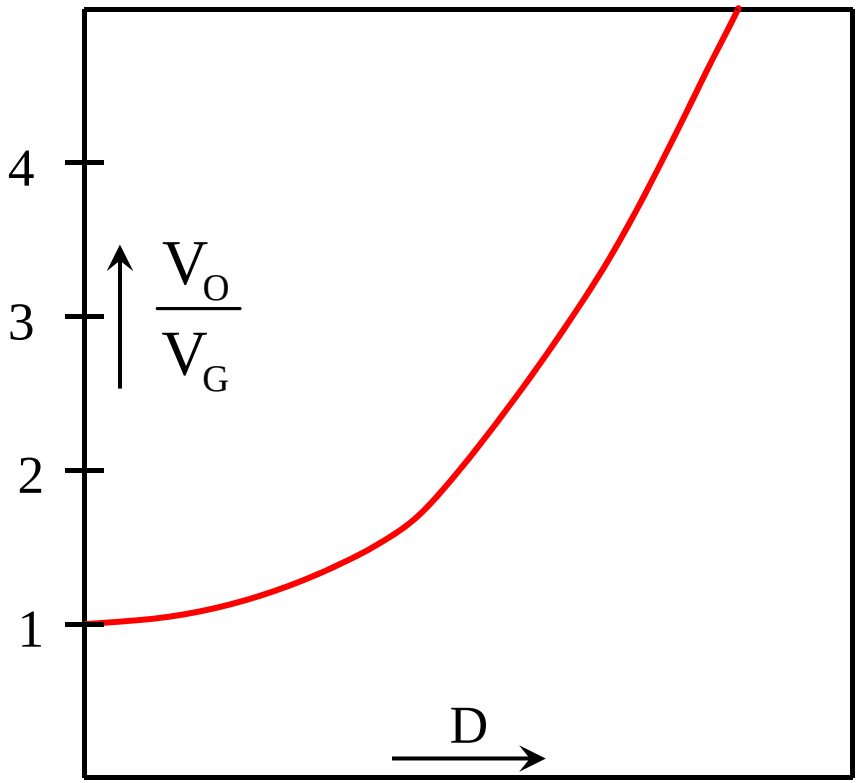


$$\left(V_G\right)T_{ON}+\left(V_G-V_O\right)T_{OFF}=0$$

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

Switched Mode Power Conversion

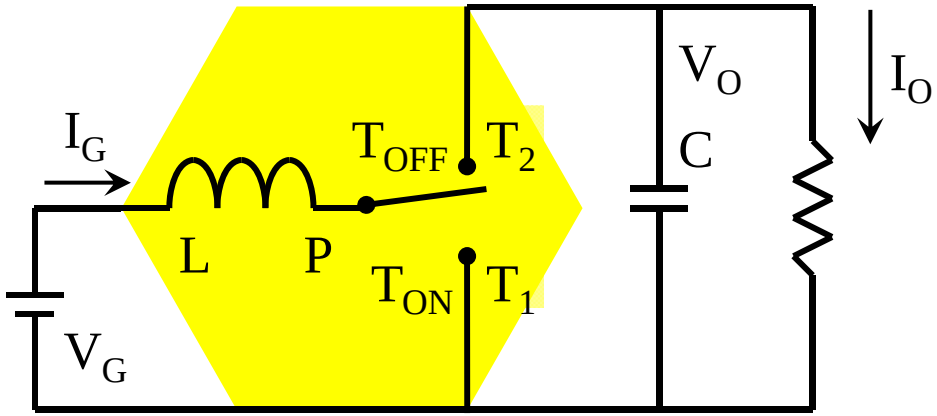
Boost Converter



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

Switched Mode Power Conversion

Boost Converter

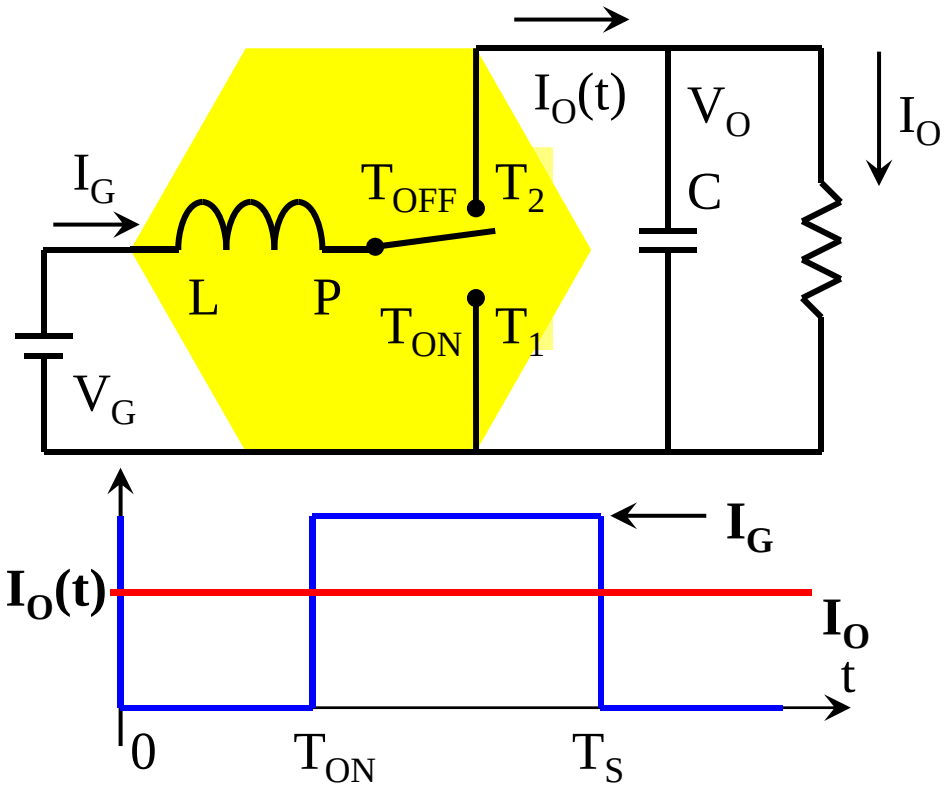


$$\frac{I_G}{I_O} = ?$$

Current Conversion Ratio

Switched Mode Power Conversion

Boost Converter

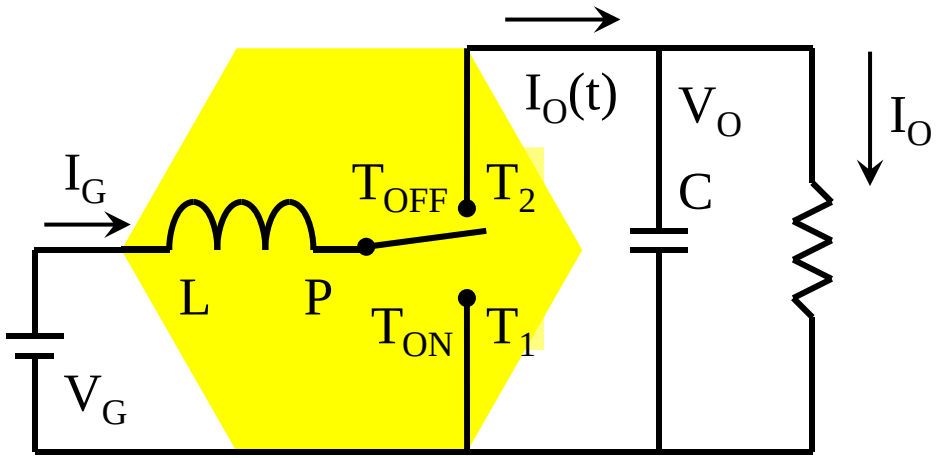


$$I_G \, T_{OFF} = I_O \, T_S$$

Average Output Current

Switched Mode Power Conversion

Boost Converter



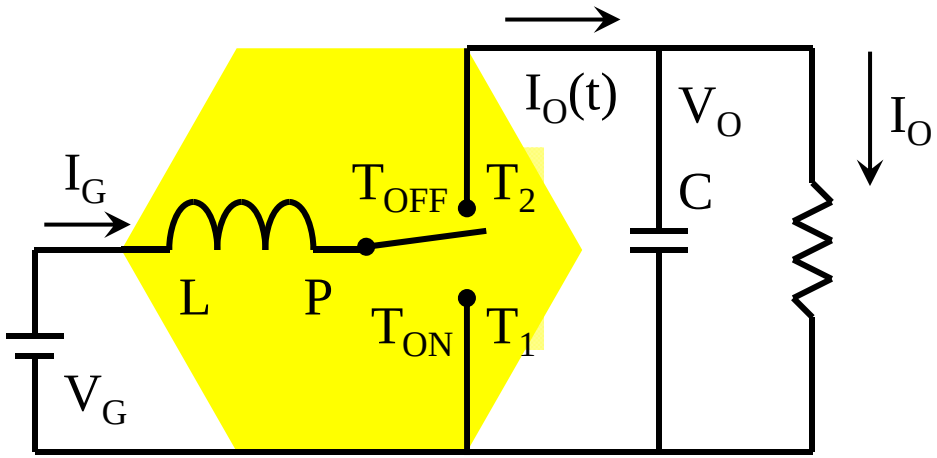
$$I_G \, T_{OFF} = I_O T_S$$

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

Current Conversion Ratio

Switched Mode Power Conversion

Boost Converter

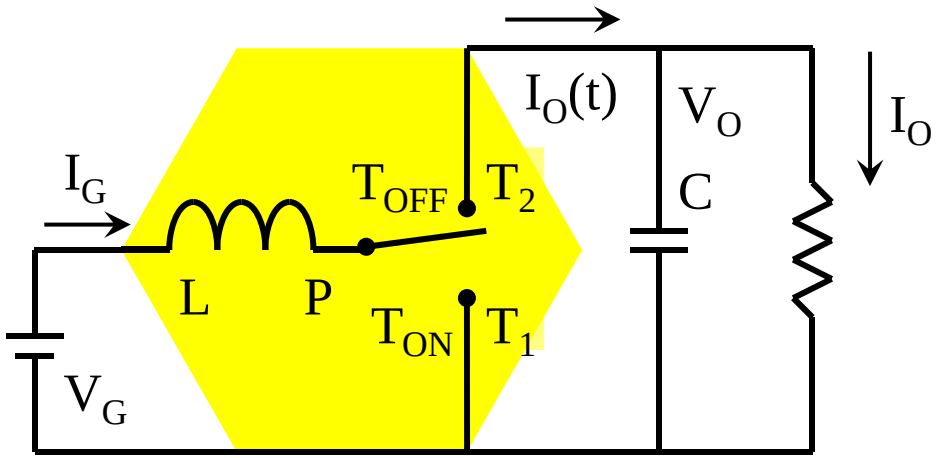


$$\frac{V_O}{V_G}\frac{I_O}{I_G} = \frac{1}{1-D}\frac{1-D}{1} = 1$$

Ideal Efficiency is Unity

Switched Mode Power Conversion

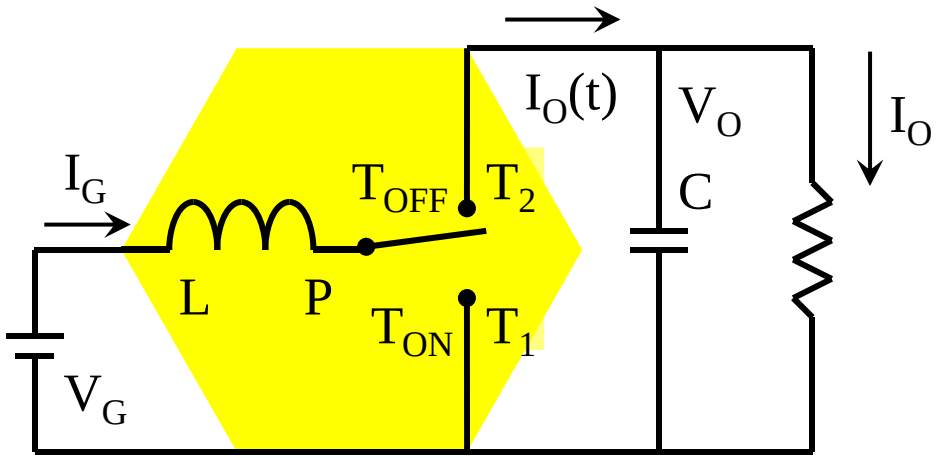
Boost Converter

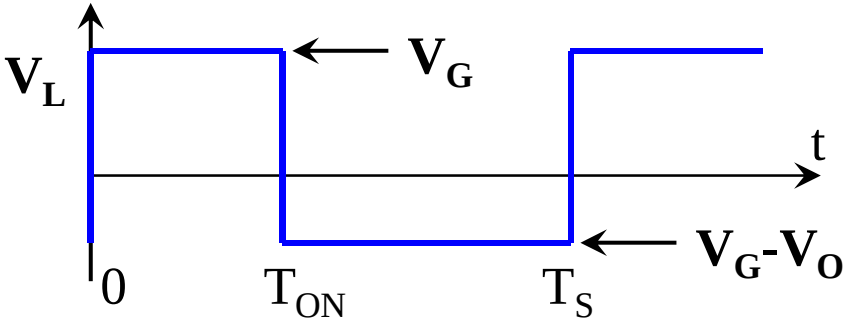


Non-Ideality in the Inductor Current

Switched Mode Power Conversion

Boost Converter

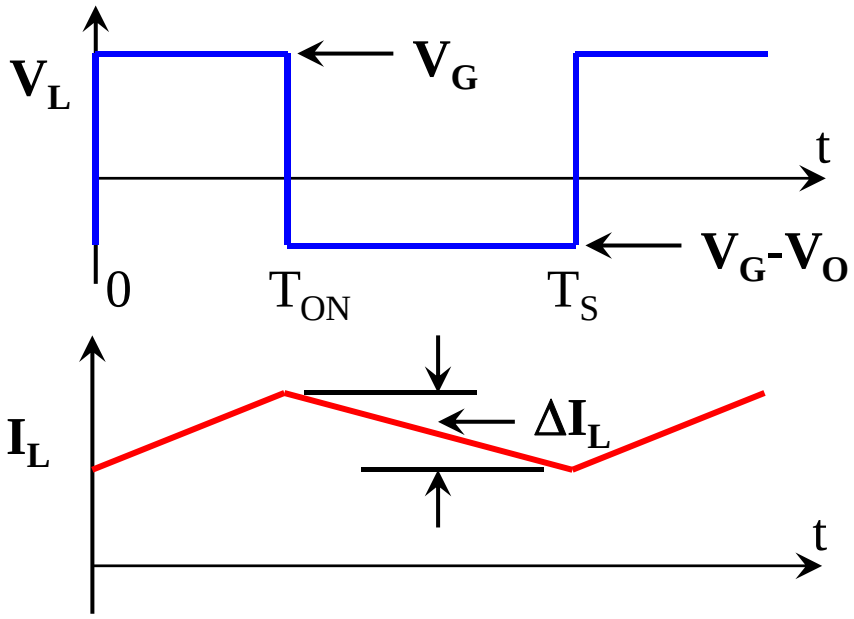




Inductor Current Ripple – Integral of Inductor Voltage

Switched Mode Power Conversion

Boost Converter

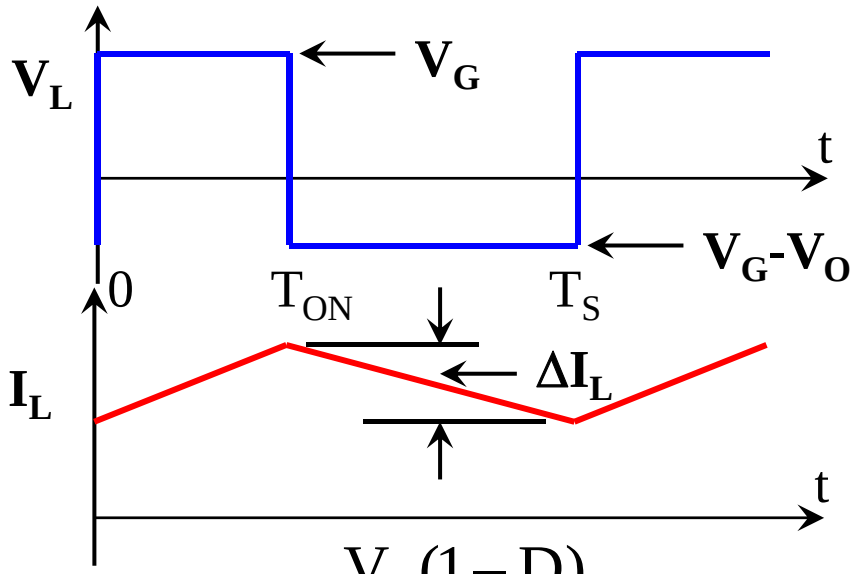


$$\Delta I_L = \frac{V_G}{L} D T_S$$

Inductor Current Ripple – Integral of Inductor Voltage

Switched Mode Power Conversion

Boost Converter



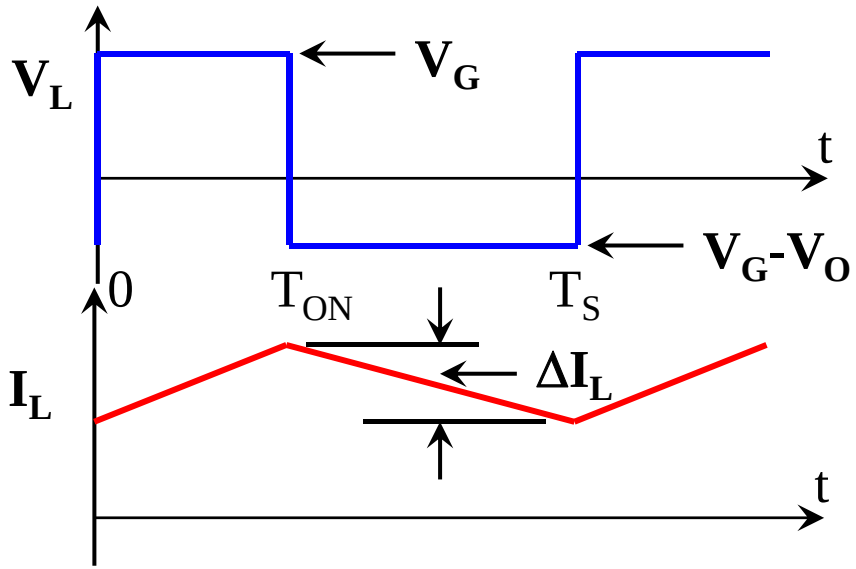
$$\Delta I_L = \frac{V_O(1-D)}{L} DT_S$$

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

Inductor Current Ripple – Integral of Inductor Voltage

Switched Mode Power Conversion

Boost Converter

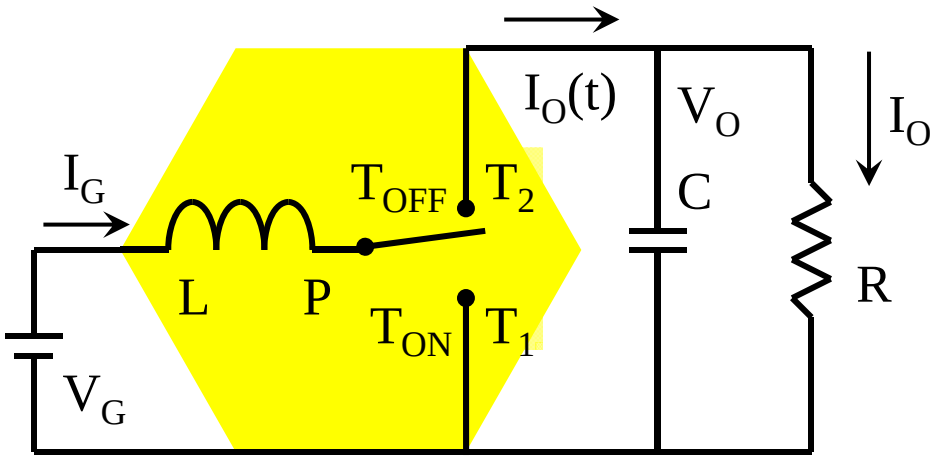


$$\frac{\Delta I_L}{I_L} = \frac{(1-D)^2}{(L/R)} DT_S$$

Inductor Current Ripple – Integral of Inductor Voltage

Switched Mode Power Conversion

Boost Converter



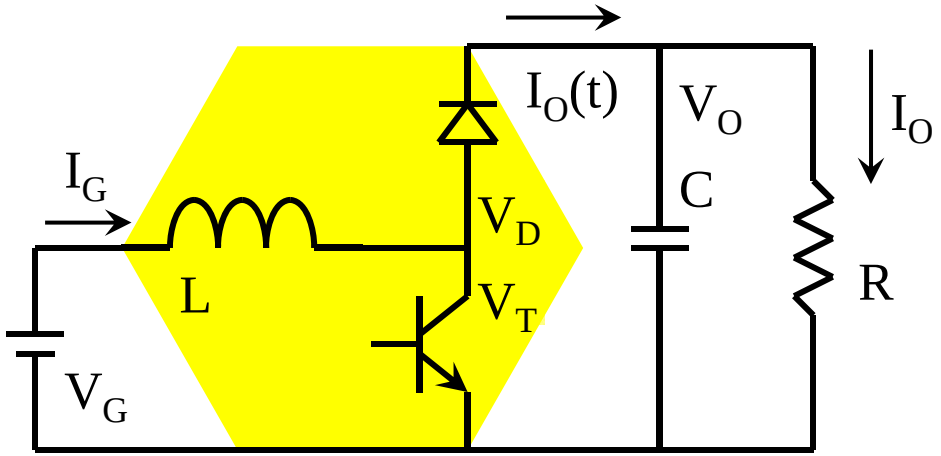
$$\frac{\Delta I_L}{I_L} = \frac{(1-D)^2}{(L/R)} DT_S \qquad T_S \ll \frac{L}{R}$$

Condition for Low Ripple Current

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

Switched Mode Power Conversion

Boost Converter

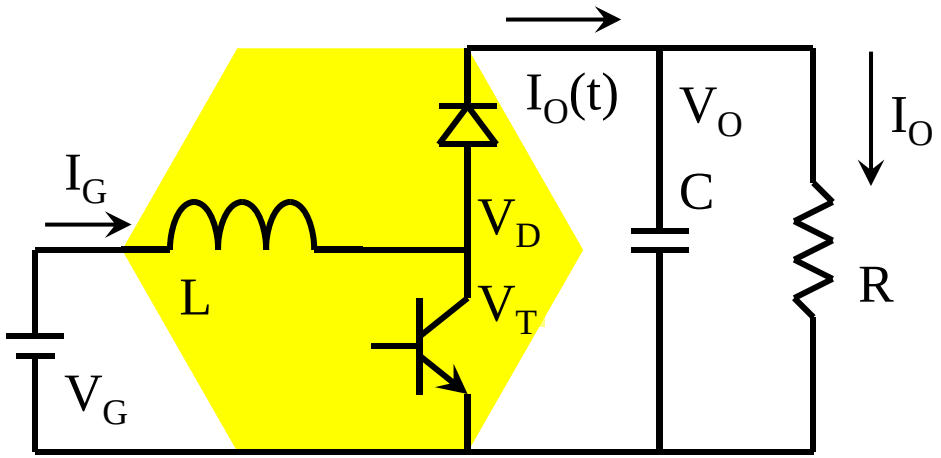


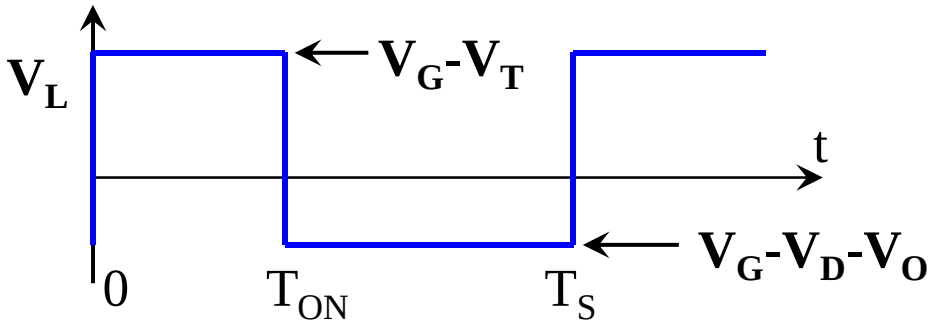
$$\frac{V_O}{V_G} = ?$$

Non-Ideality of the Switches

Switched Mode Power Conversion

Boost Converter

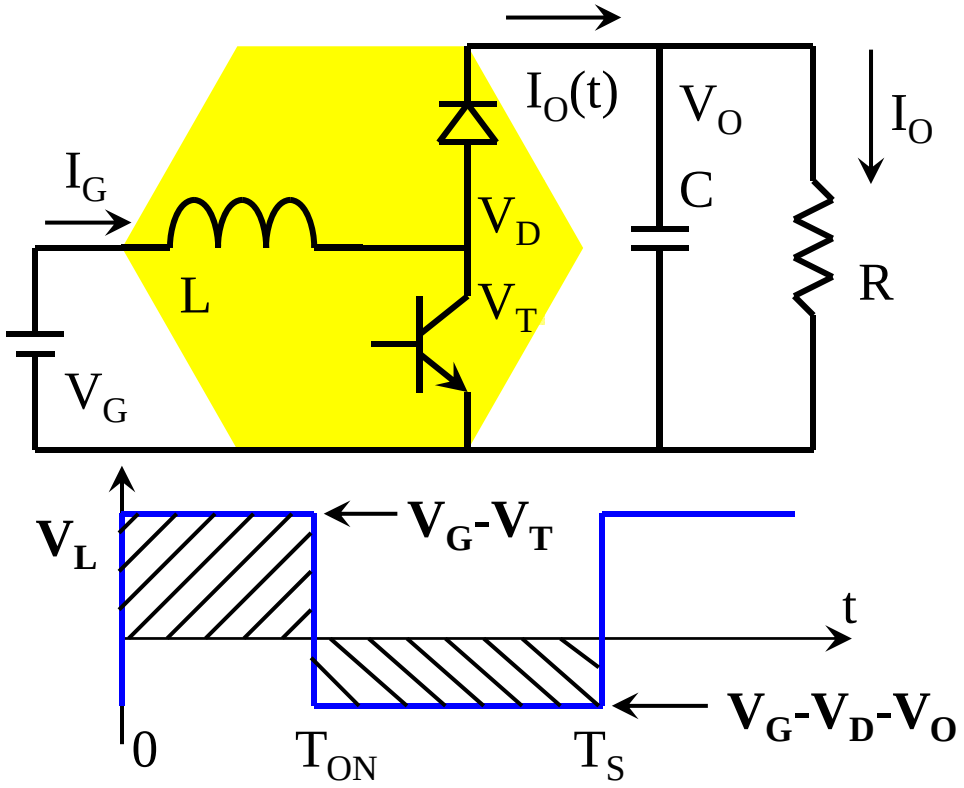




Volt-Sec Balance on Inductor

Switched Mode Power Conversion

Boost Converter

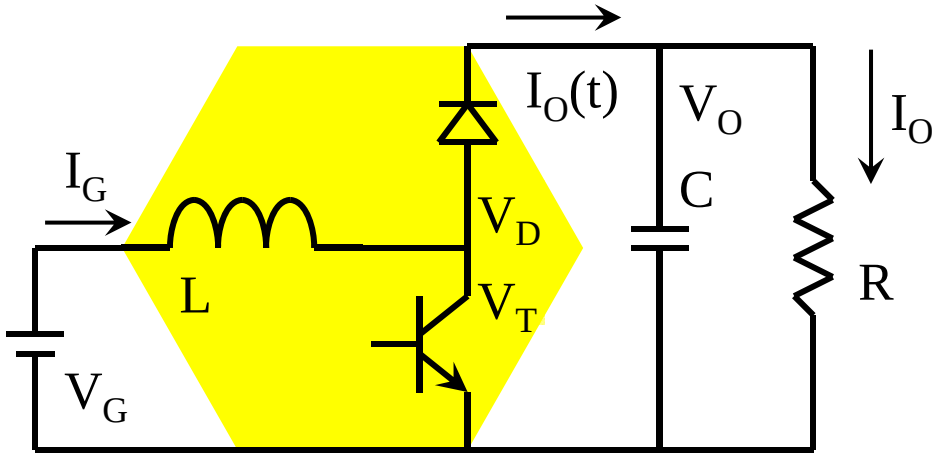


$$\left(V_G - V_T\right)T_{ON} + \left(V_G - V_D - V_O\right)T_{OFF} = 0$$

Volt-Sec Balance on Inductor

Switched Mode Power Conversion

Boost Converter



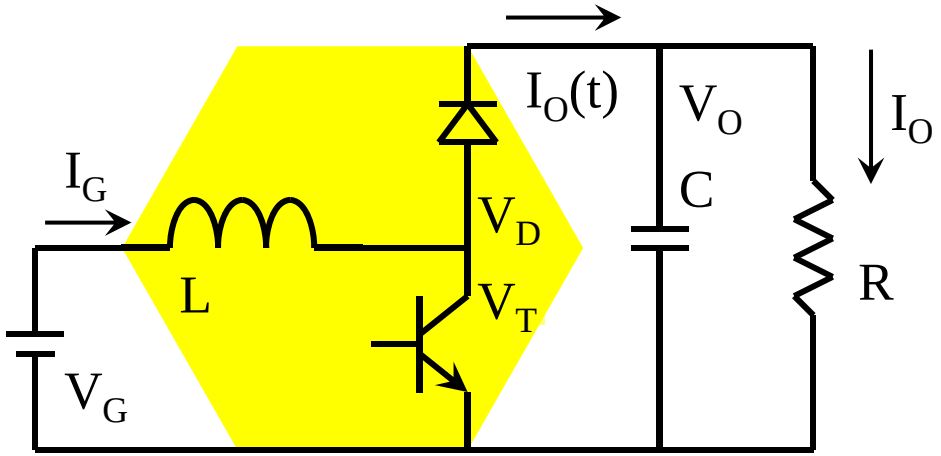
$$\frac{V_O}{V_G} = \frac{1}{1-D}\left(1 - \frac{DV_T}{V_G} - \frac{(1-D)V_D}{V_G}\right)$$

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

Volt-Sec Balance on Inductor

Switched Mode Power Conversion

Boost Converter

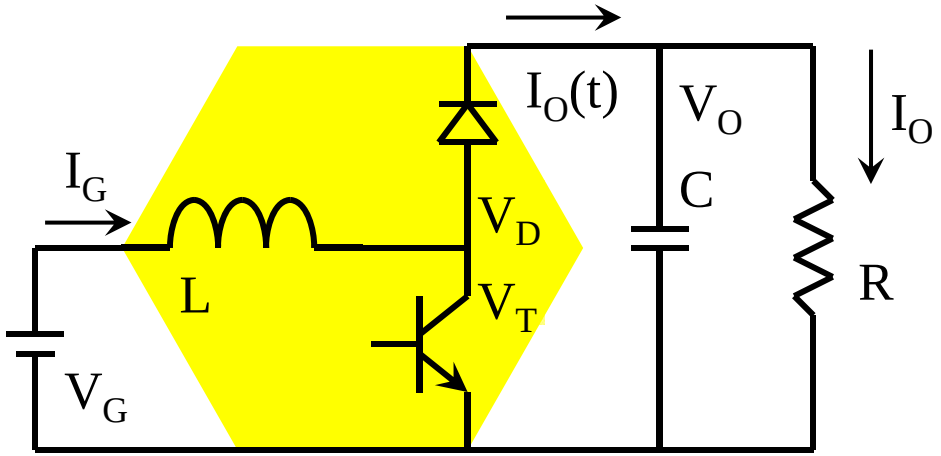


$$\frac{I_G}{I_O} = \frac{1}{1-D}$$

Current Averaging

Switched Mode Power Conversion

Boost Converter



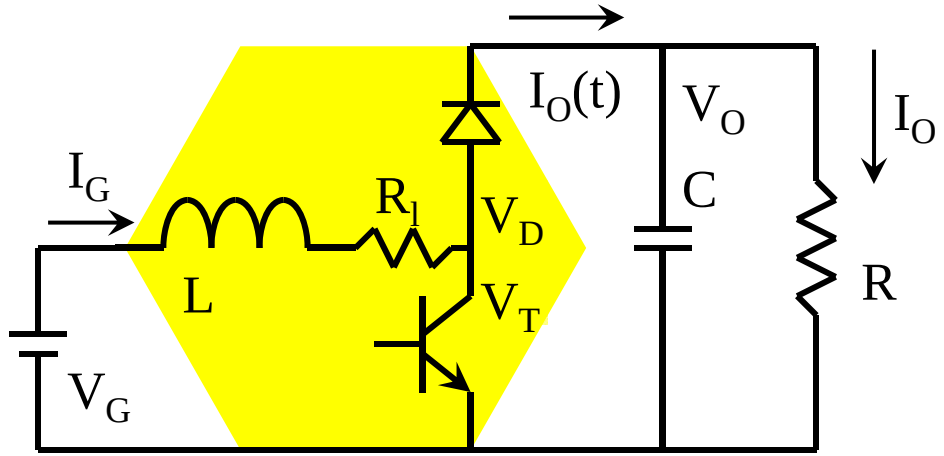
$$\frac{V_O I_O}{V_G I_G} = \frac{1}{1-D}\left(1-\frac{DV_T}{V_G}-\frac{(1-D)V_D}{V_G}\right)\frac{1-D}{1}$$

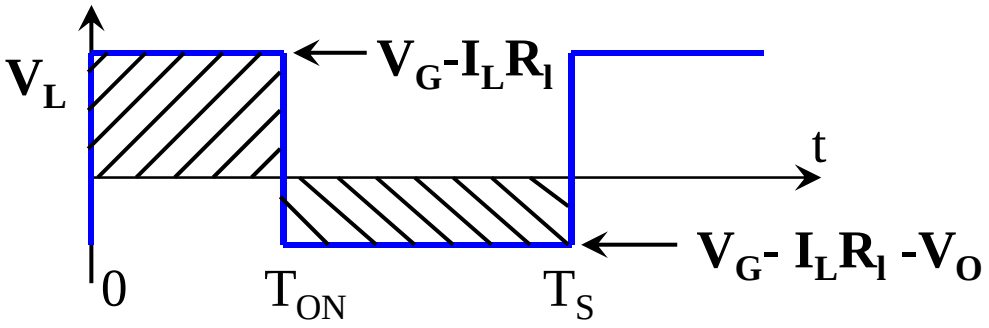
$$\eta = \left(1-\frac{DV_T}{V_G}-\frac{(1-D)V_D}{V_G}\right)$$

Efficiency of Power Conversion

Switched Mode Power Conversion

Boost Converter





Non-Ideality of the Inductor

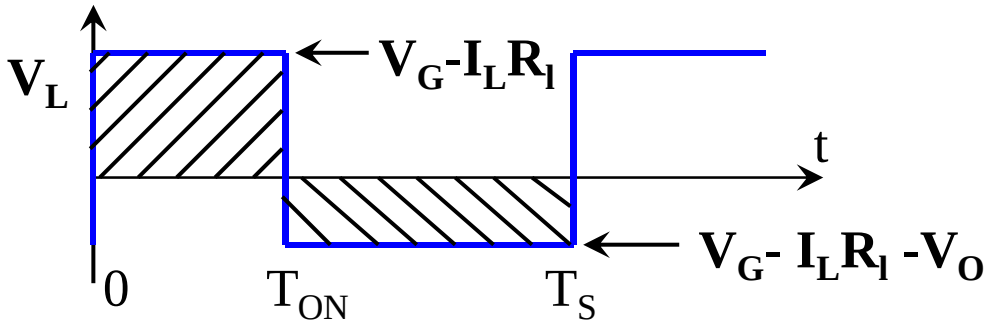
Switched Mode Power Conversion

Boost Converter

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

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

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



Volt-Second Balance

Switched Mode Power Conversion

Boost Converter

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

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

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

Voltage Conversion Ratio

Switched Mode Power Conversion

Boost Converter

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

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

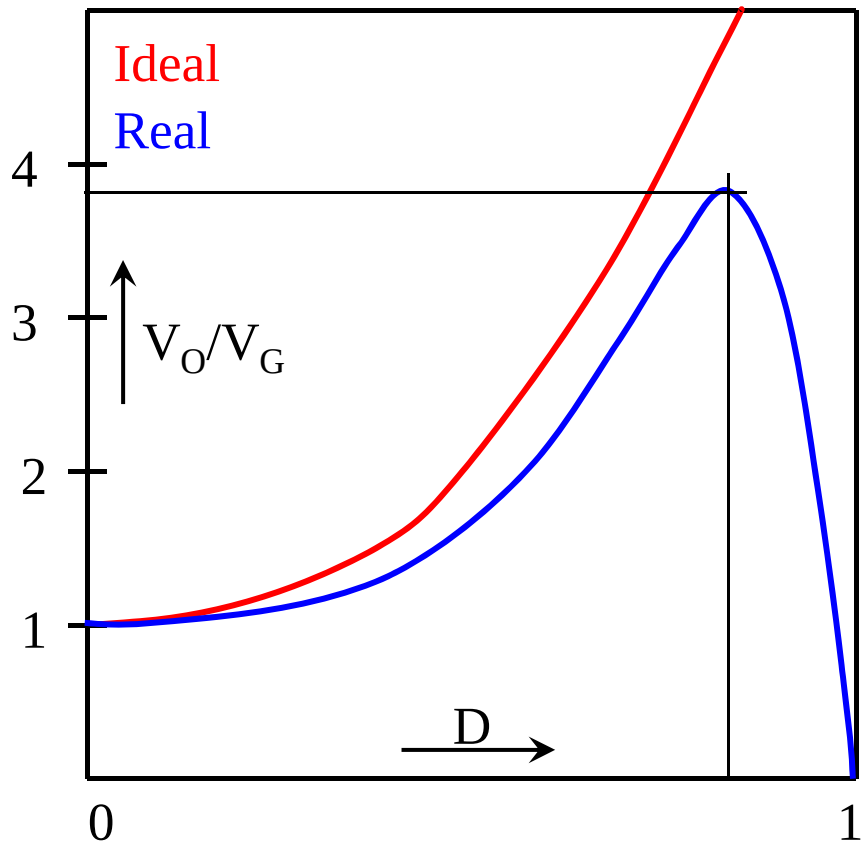
$$\eta = \frac{V_O I_O}{V_G I_G} = \frac{1}{\left(1+\frac{\alpha}{(1-D)^2}\right)}$$

Efficiency of Power Conversion

Switched Mode Power Conversion

Boost Converter

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

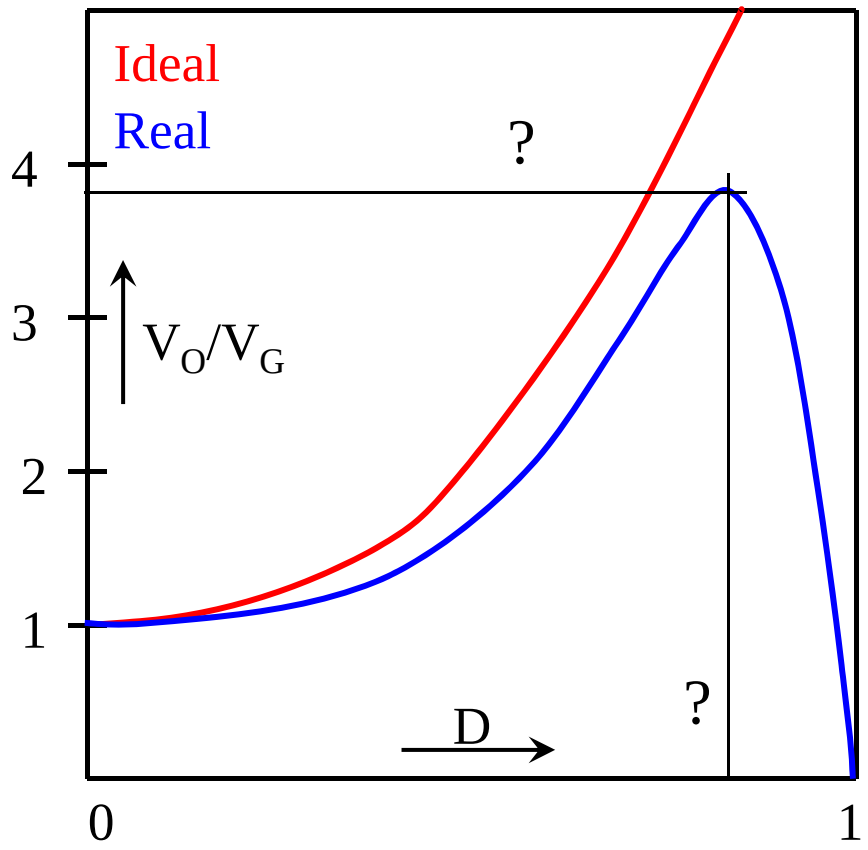


Real Forward Voltage Gain

Switched Mode Power Conversion

Boost Converter

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



Real Forward Voltage Gain

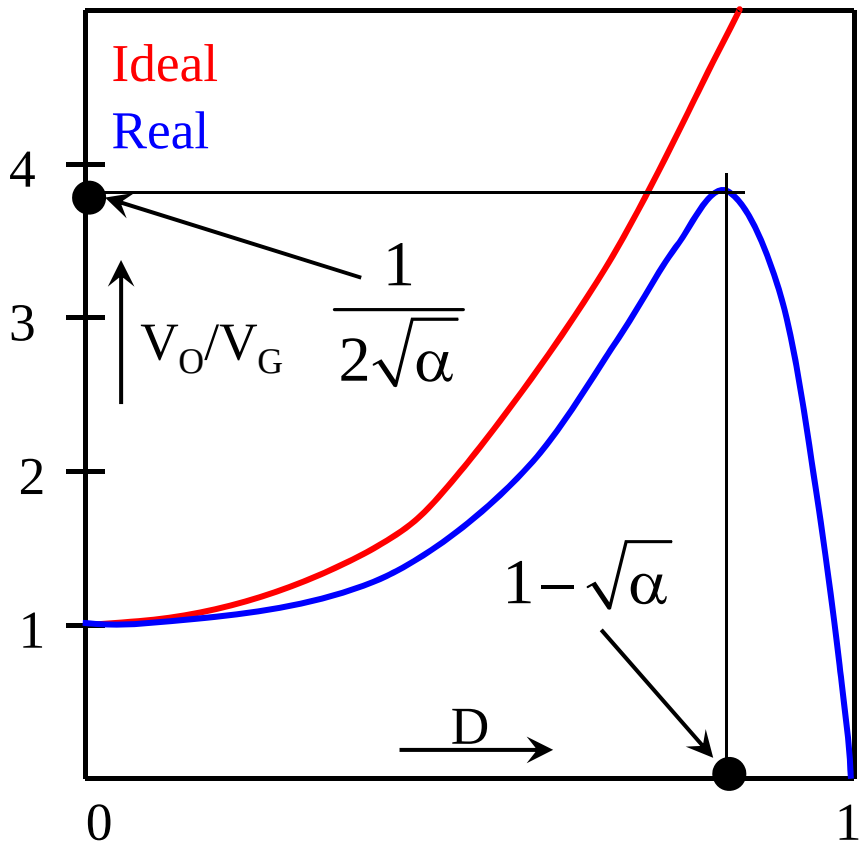
Switched Mode Power Conversion

Boost Converter

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

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

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



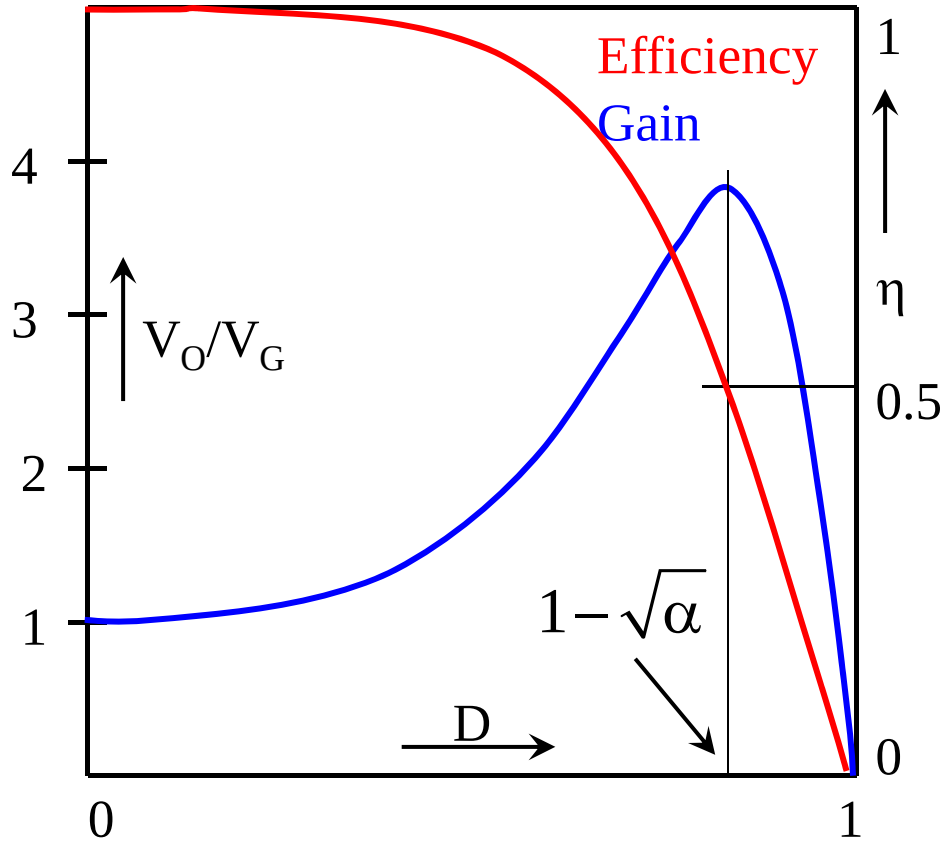
Real Forward Voltage Gain

Switched Mode Power Conversion

Boost Converter

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

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



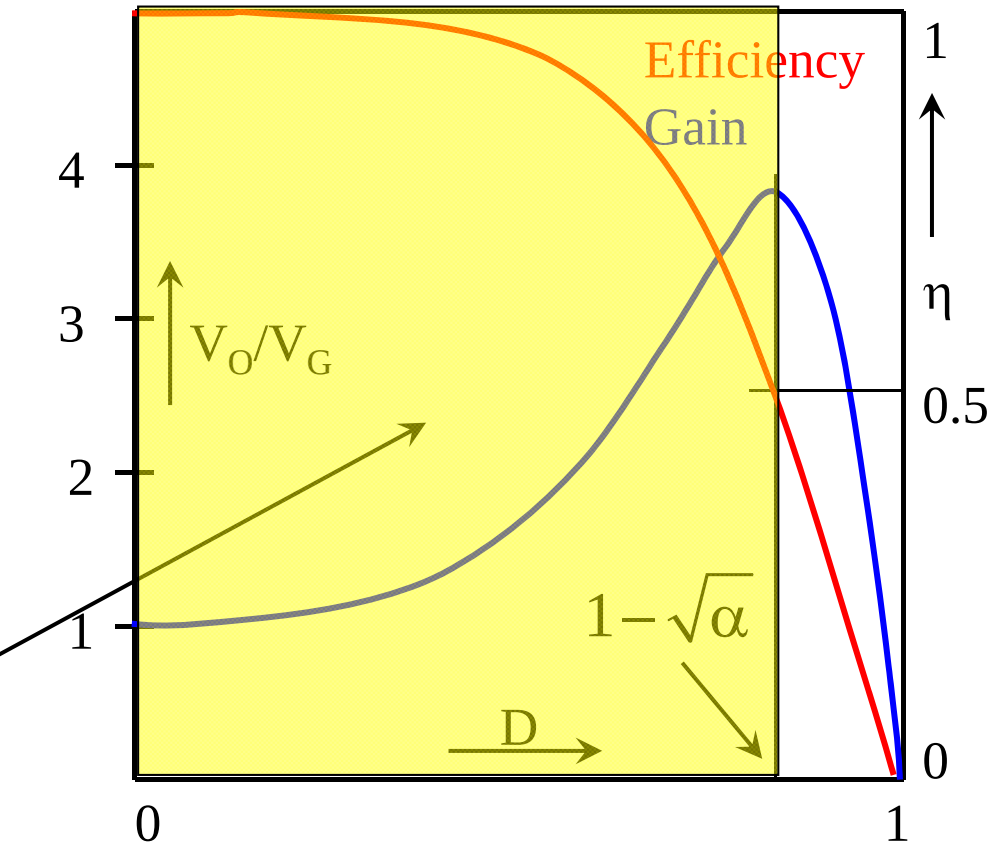
Efficiency of a Real Converter

Switched Mode Power Conversion

Boost Converter

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

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

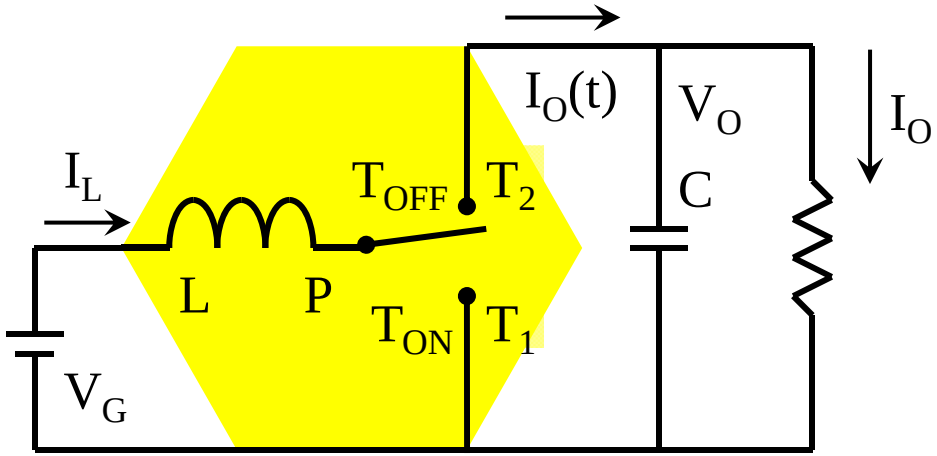


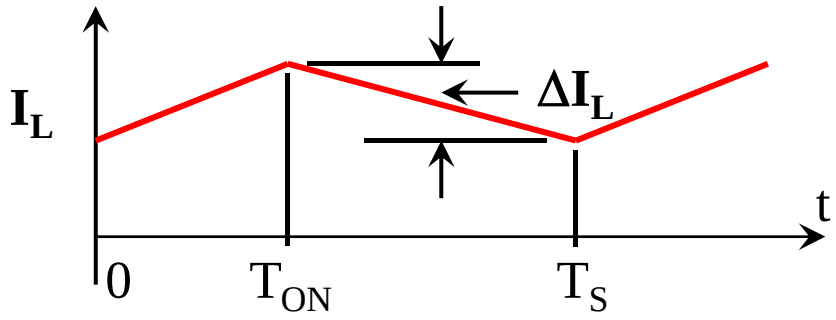
Preferred
Operating Region

Preferred Range of Duty Ratio

Switched Mode Power Conversion

Boost Converter

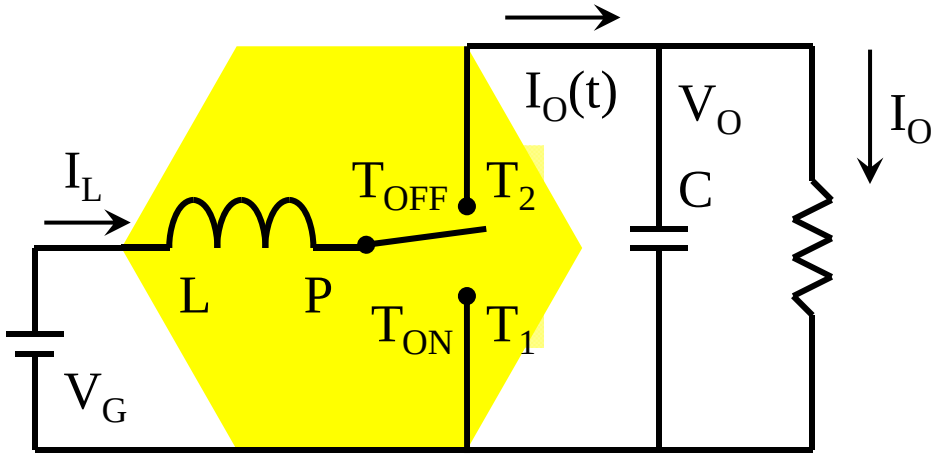


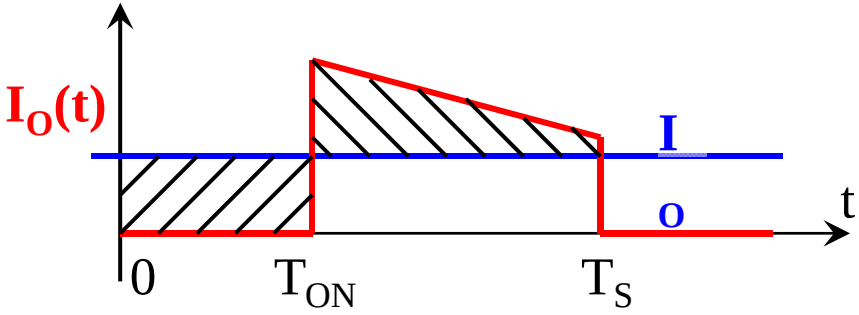


Output Voltage Ripple

Switched Mode Power Conversion

Boost Converter

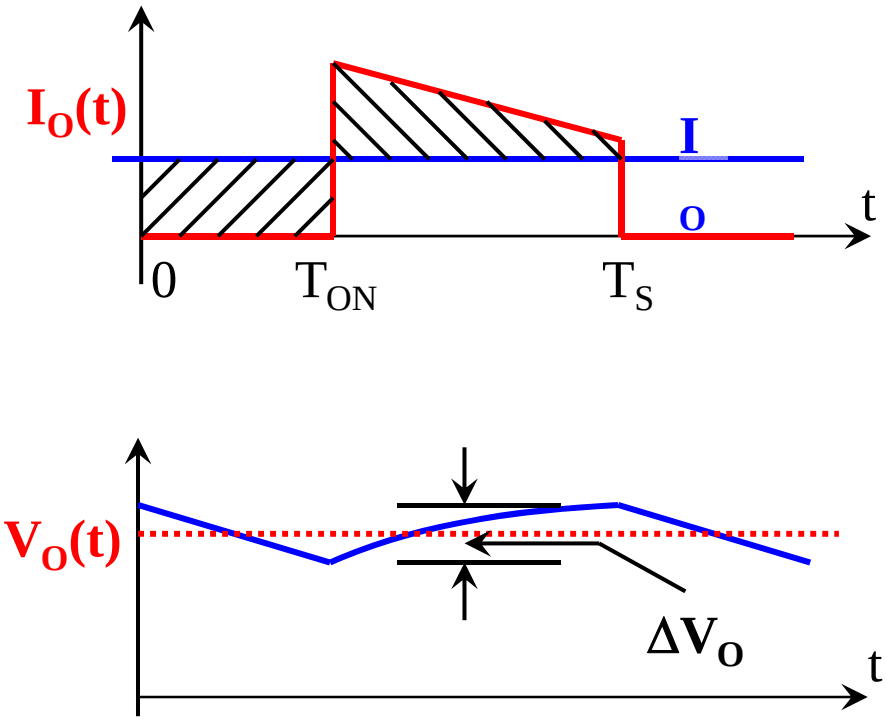




Capacitor Charge Balance

Switched Mode Power Conversion

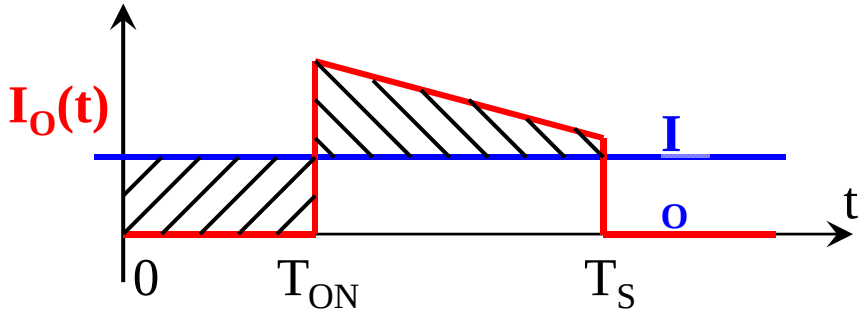
Boost Converter



Capacitor Charge Balance

Switched Mode Power Conversion

Boost Converter

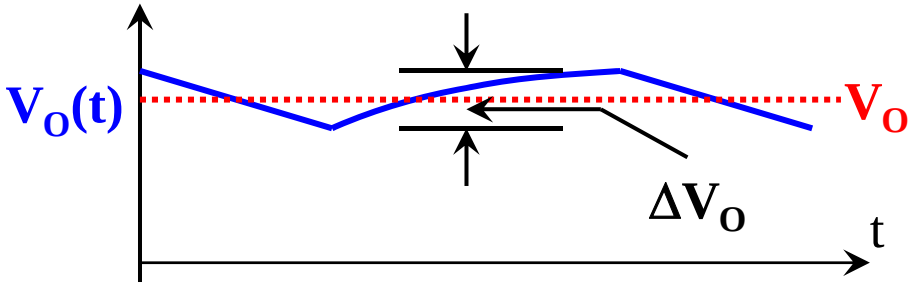


$$\Delta V_O = \frac{I_O D T_S}{C} = \frac{V_O D T_S}{R C}$$

Capacitor Charge Balance

Switched Mode Power Conversion

Boost Converter



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

Design Guideline: $T_S << RC$

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

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

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

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

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

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

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

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

Switched Mode Power Conversion

Buck-Boost Converter