Switched Mode Power Conversion

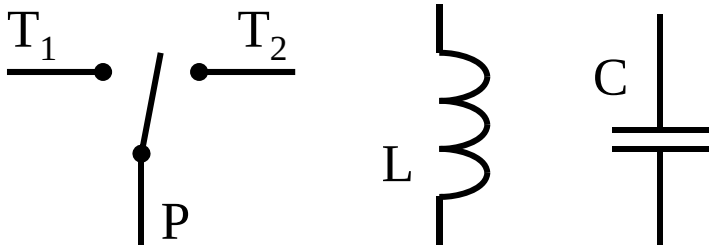
Primitive Converters

Interconnection
of
Switches & Energy Storage Elements

Switched Mode Power Conversion

Primitive Converters

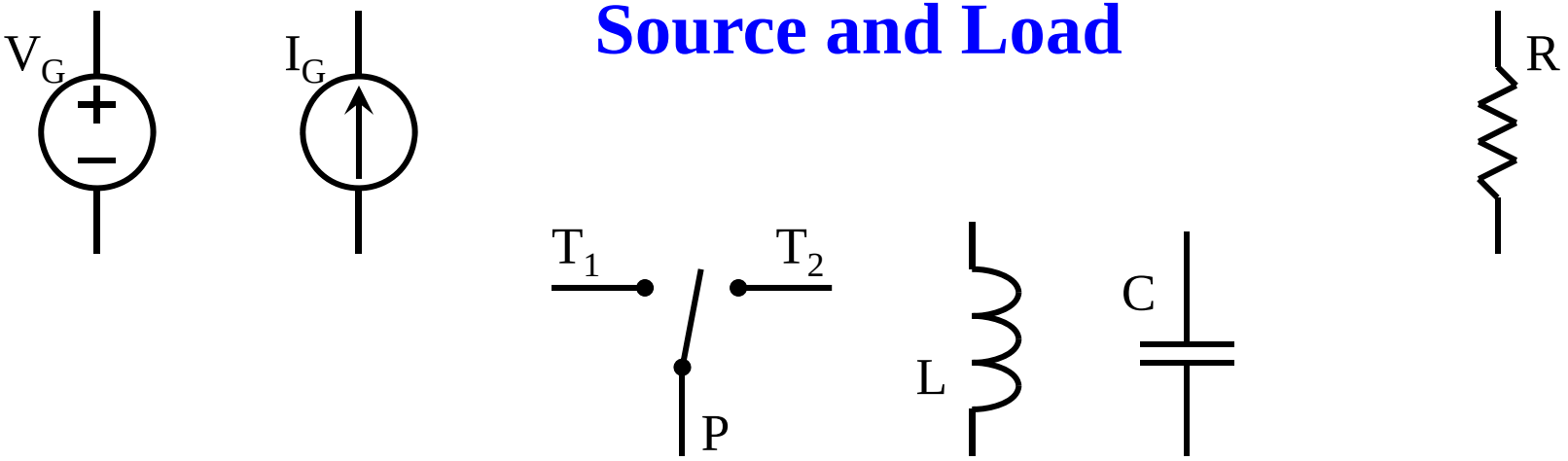
Interconnection
of
Switches & Energy Storage Elements



Switched Mode Power Conversion

Primitive Converters

Interconnection
of
Switches & Energy Storage Elements
to
Source and Load



Switched Mode Power Conversion

Primitive Converters

Interconnection Rules

Sources may not be Overloaded

Voltage Sources are not to be Shorted

Current Sources are not to be Opened

Conservation of Energy

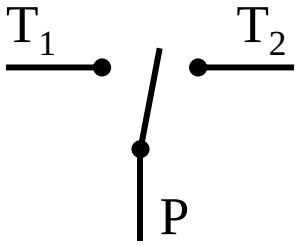
Inductor Currents are not to be Interrupted

Capacitor Voltages are not to be Shorted

Switched Mode Power Conversion

Primitive Converters

Interconnection Rules



Voltage sources may not be connected across PT_1 or PT_2

No Short Circuit of Voltage Sources

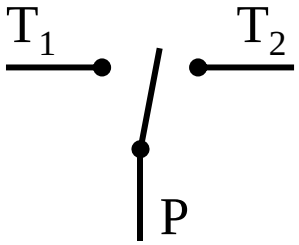
Capacitors may not be connected across PT_1 or PT_2

No Disruption of Energy on the Capacitor

Switched Mode Power Conversion

Primitive Converters

Interconnection Rules



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

No Open Circuit of Current Sources

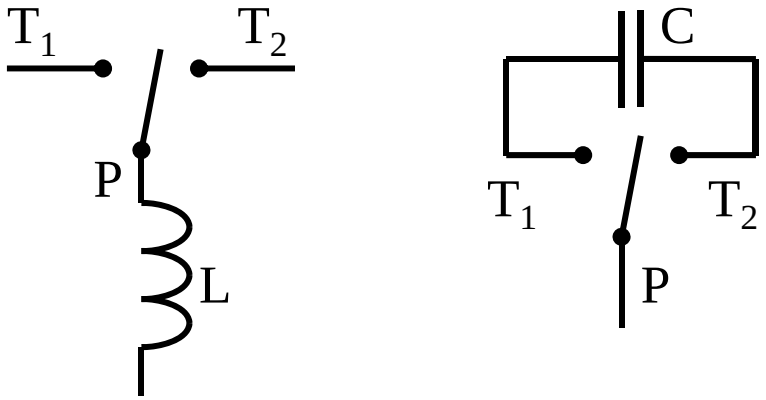
Inductor may not be connected in series with T_1 or T_2

No Disruption of Energy on the Inductor

Switched Mode Power Conversion

Primitive Converters

Acceptable Switch-Storage Cells



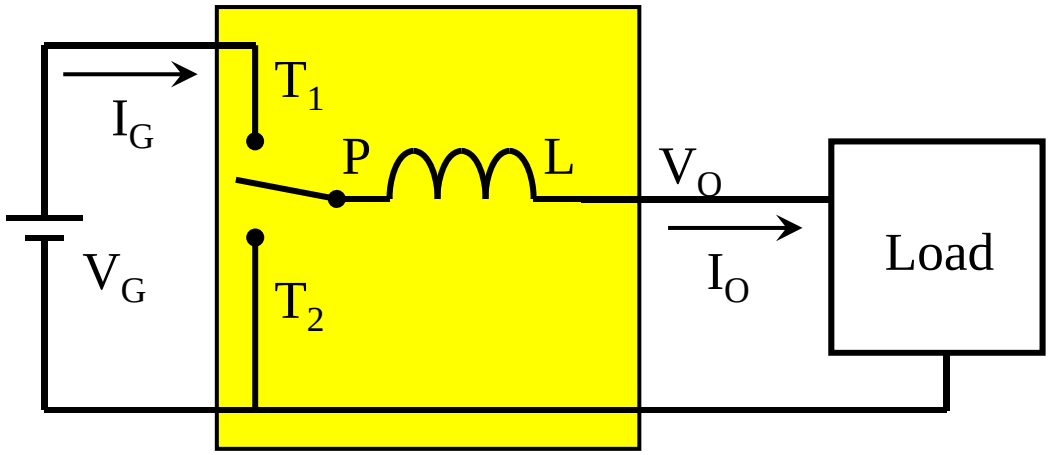
Two possible switch+storage cells

These are dual of each other

Switched Mode Power Conversion

Primitive Converters

Primitive Voltage to Current Converter



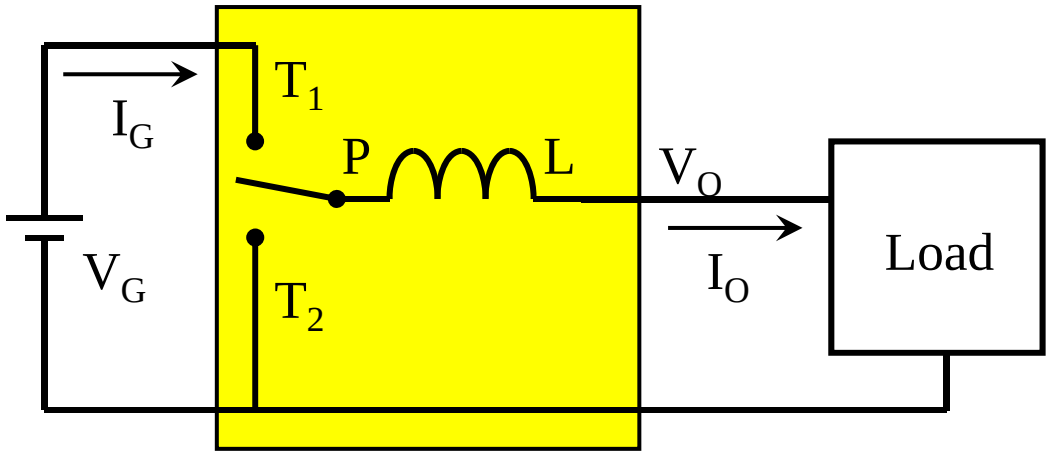
Input average quanities: V_G and I_G

Output average quantities: I_O and V_O

Switched Mode Power Conversion

Primitive Converters

Strategy of Operation & Control



Constant Switching Period

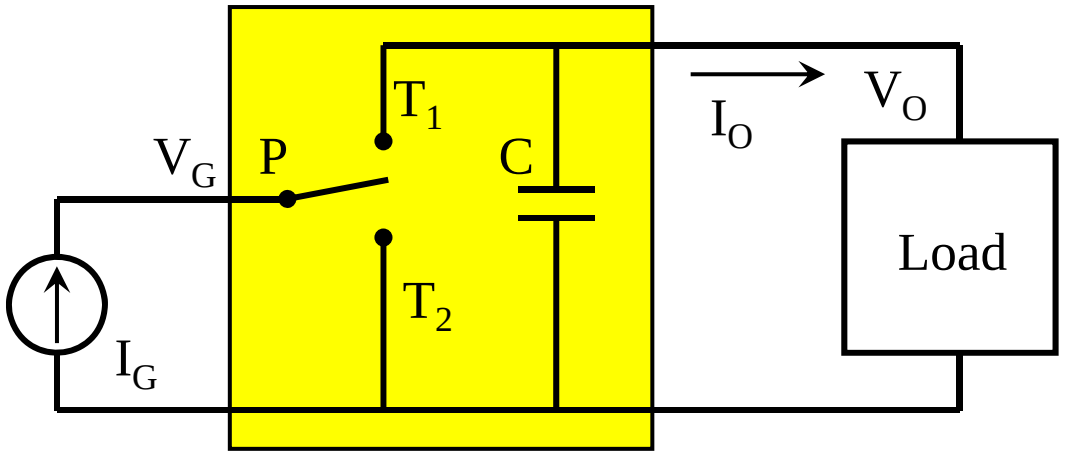
T_1P ON Time T_{ON} ; T_2P OFF Time T_{OFF}

$$T_{ON} + T_{OFF} = T_S$$

Switched Mode Power Conversion

Primitive Converters

Primitive Current to Voltage Converter



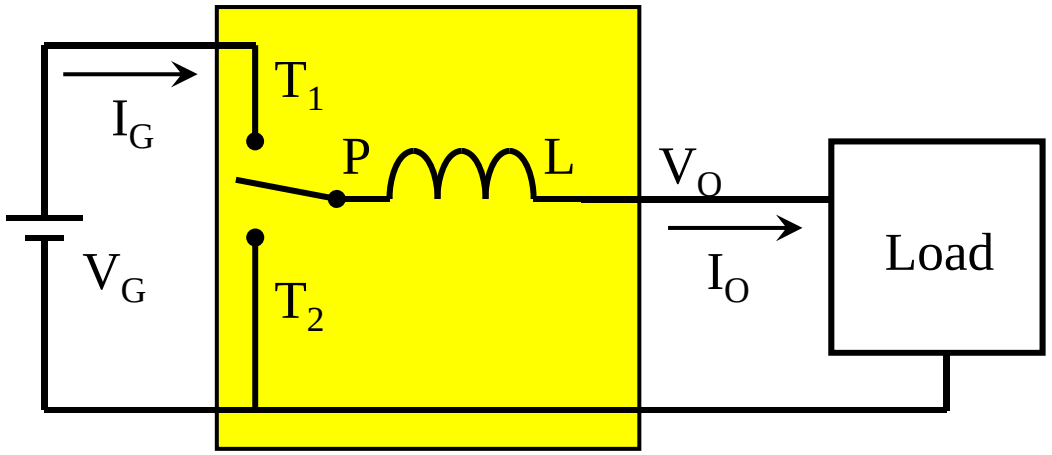
Input average quanities: I_G and V_G

Output average quantities: V_O and I_O

Switched Mode Power Conversion

Primitive Converters

Primitive Voltage to Current Converter

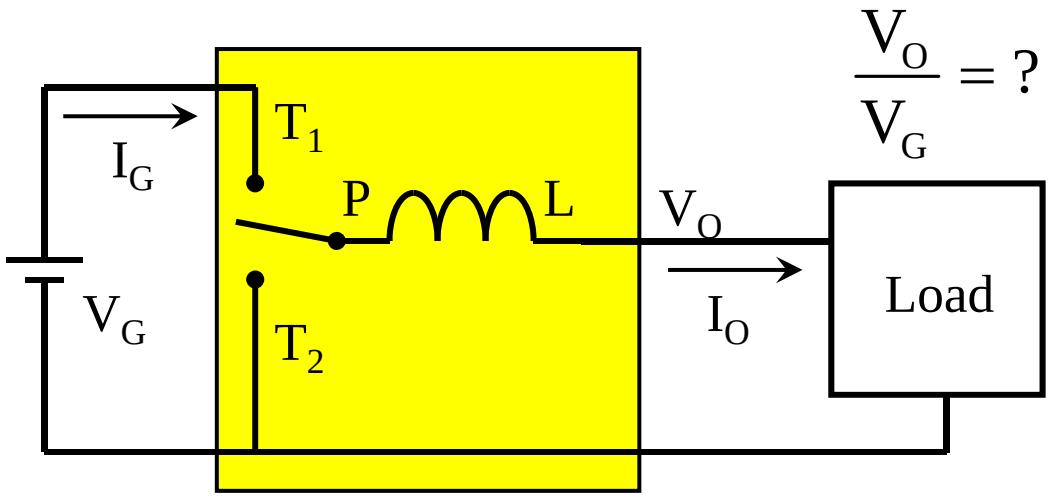


Ideal Performance Measures

Switched Mode Power Conversion

Primitive Converters

Primitive Voltage to Current Converter



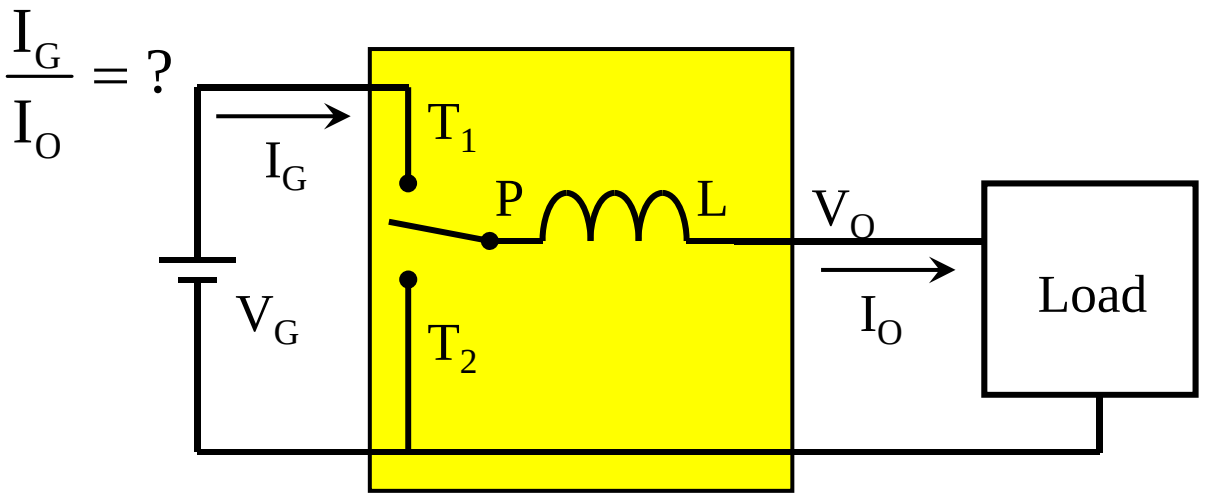
First Performance Measure

Forward Voltage Conversion Ratio

Switched Mode Power Conversion

Primitive Converters

Primitive Voltage to Current Converter



Performance Measures

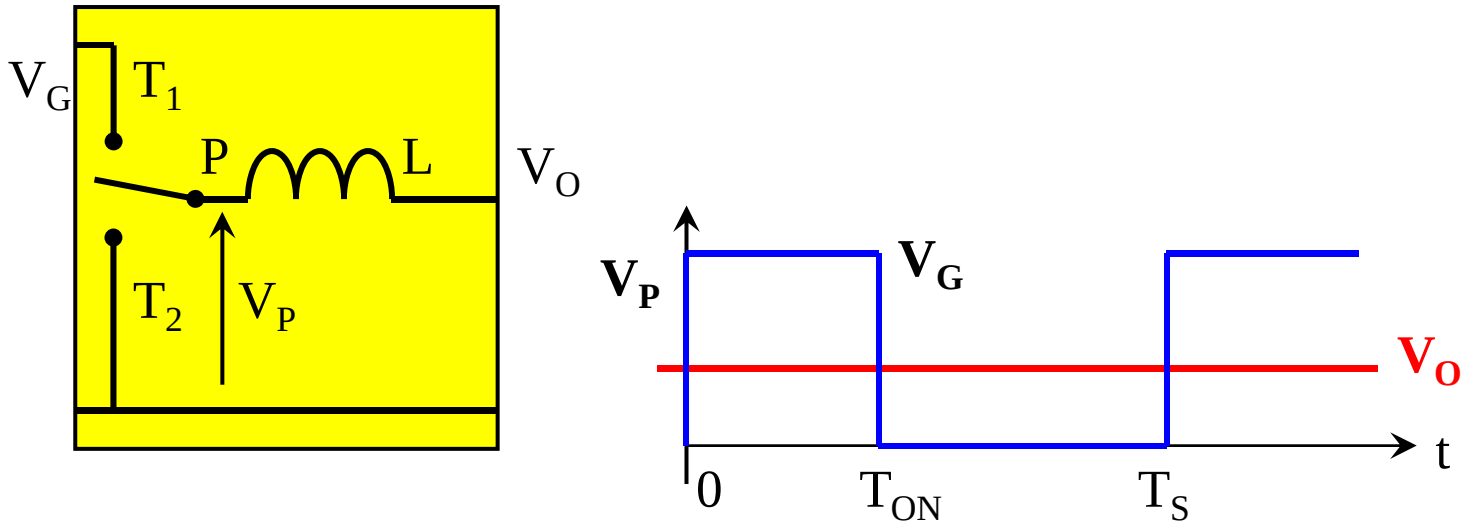
Forward Voltage Conversion Ratio

Reverse Current Conversion Ratio

Switched Mode Power Conversion

Primitive Converters

Forward Voltage Conversion Ratio

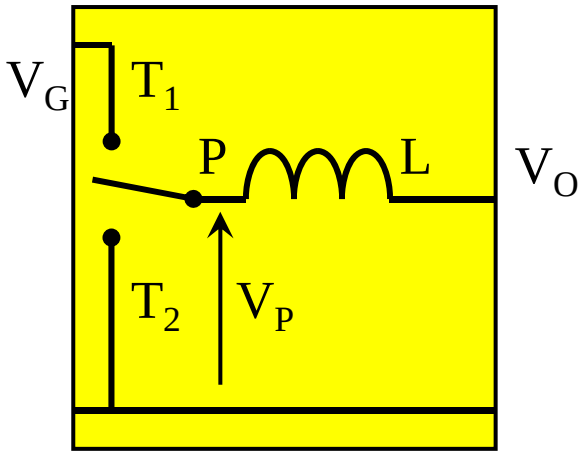


Average voltage across inductor in one cycle is zero

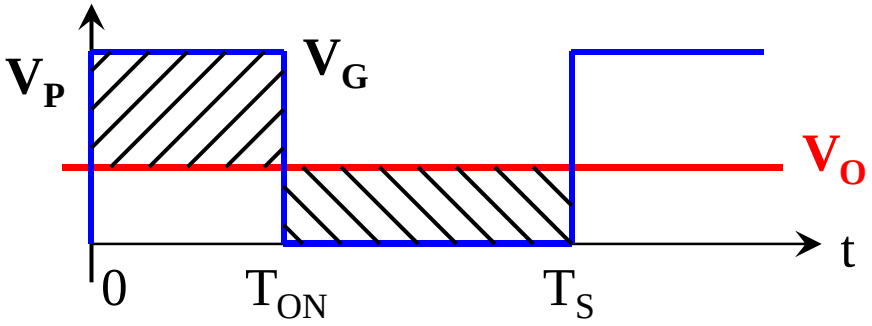
Switched Mode Power Conversion

Primitive Converters

Forward Voltage Conversion Ratio



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

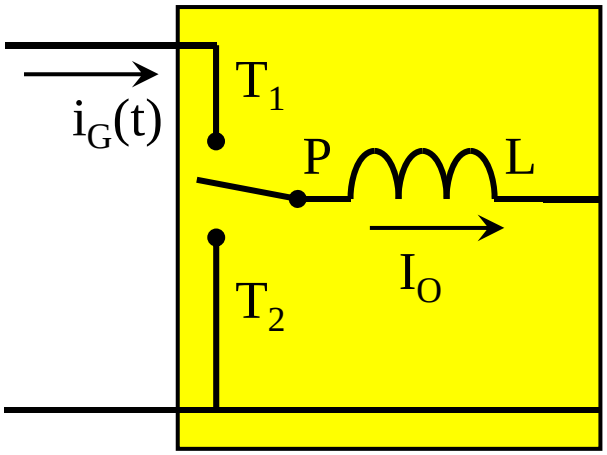


$$\frac{V_O}{V_G} = \frac{T_{ON}}{T_S} = D$$

Switched Mode Power Conversion

Primitive Converters

Reverse Current Transfer Ratio



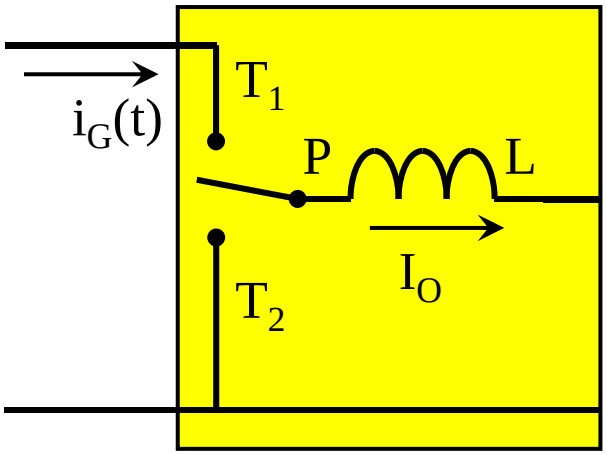
$$\frac{I_G}{I_O} = ?$$

Reverse Current Conversion Ratio

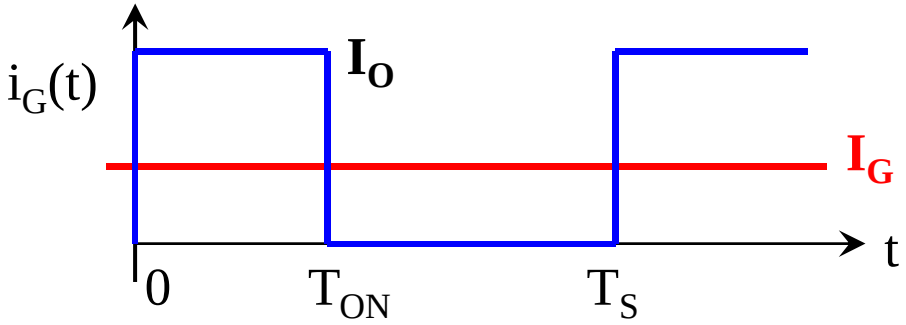
Switched Mode Power Conversion

Primitive Converters

Reverse Current Transfer Ratio



$$I_O T_{ON} - I_G T_S = 0$$

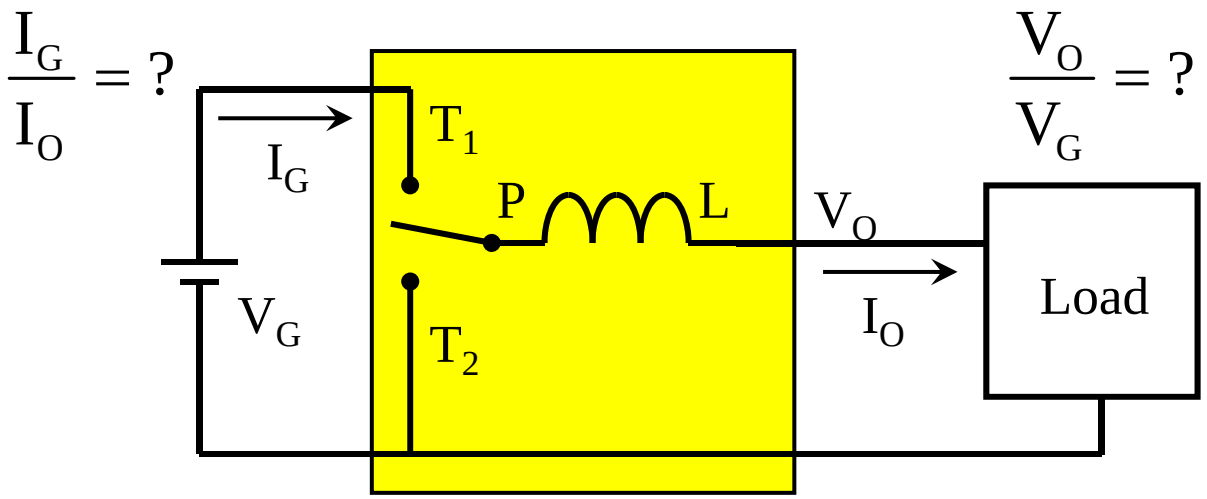


$$\frac{I_G}{I_O} = \frac{T_{ON}}{T_S} = D$$

Switched Mode Power Conversion

Primitive Converters

Efficiency of Ideal Converter is Unity

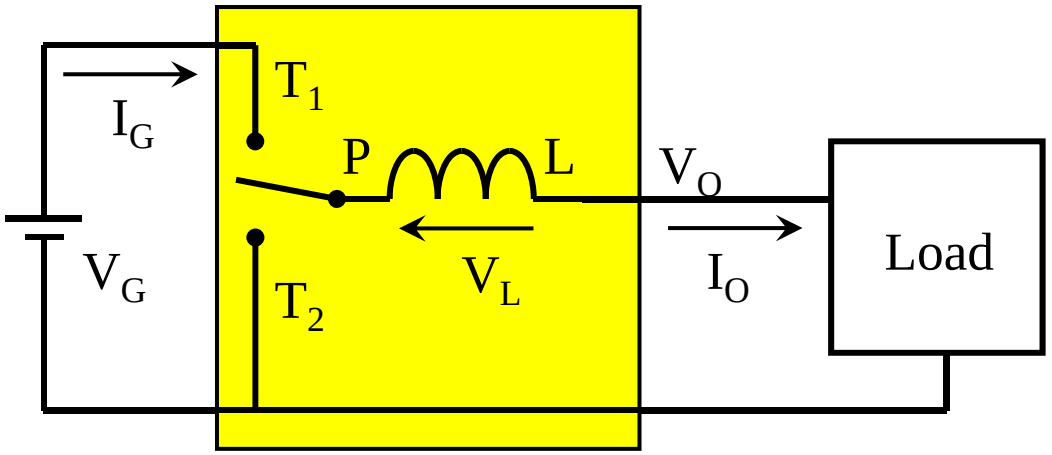


$$\frac{V_O}{V_G} = \frac{I_G}{I_O} = \frac{T_{ON}}{T_S} = D$$

Switched Mode Power Conversion

Primitive Converters

Primitive Voltage to Current Converter

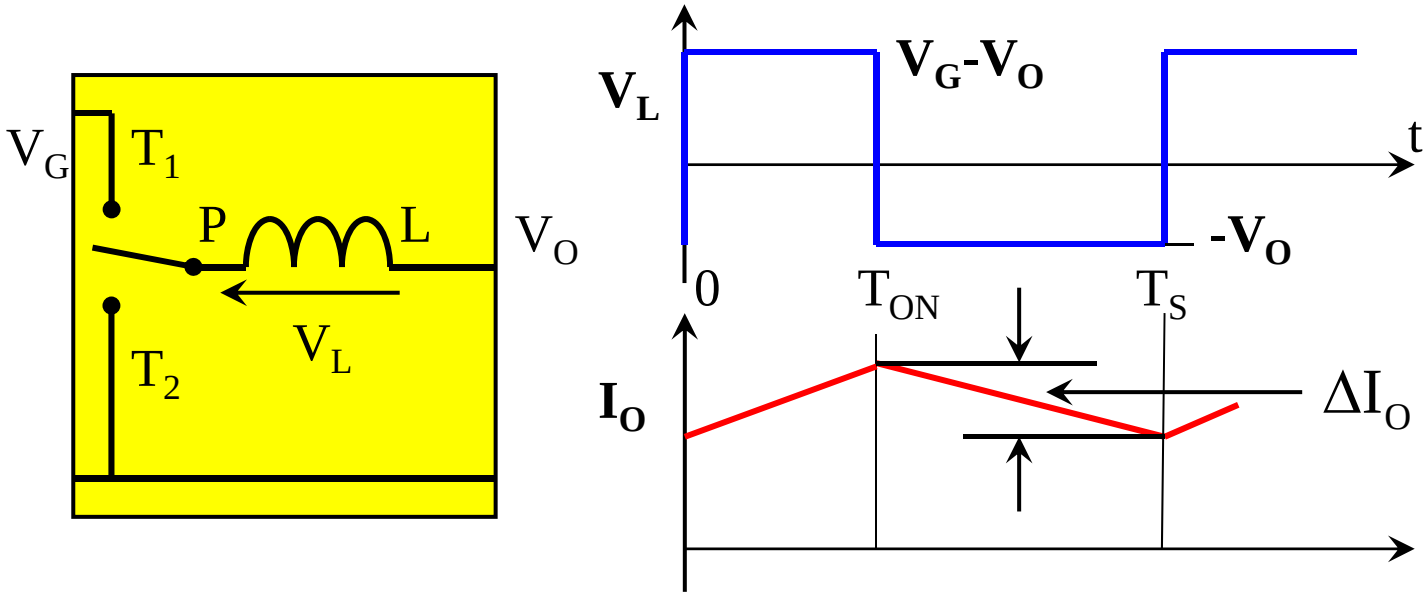


Non-Ideality in the Converter Current I_O

Switched Mode Power Conversion

Primitive Converters

Ripple Current in the Inductor

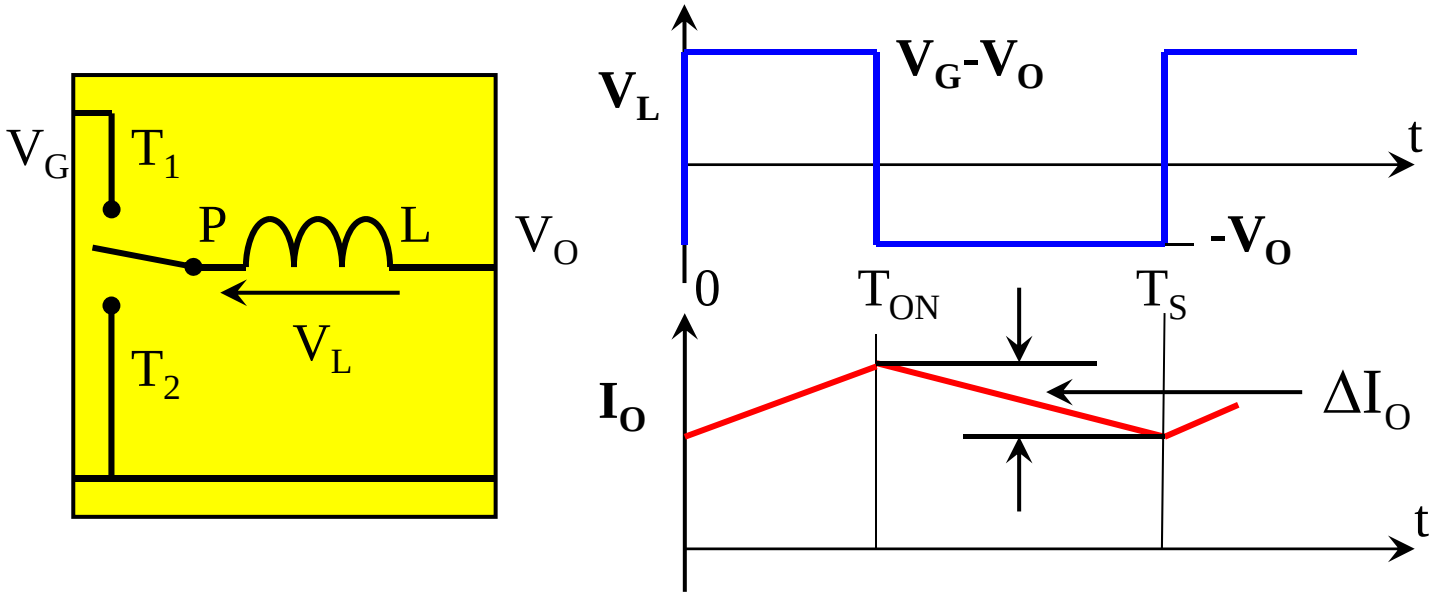


$$\Delta I_O = \frac{V_O}{L}\left(T_S - T_{ON}\right) = \frac{V_O}{L}\left(1 - D\right)T_S$$

Switched Mode Power Conversion

Primitive Converters

Normalised Ripple Curent

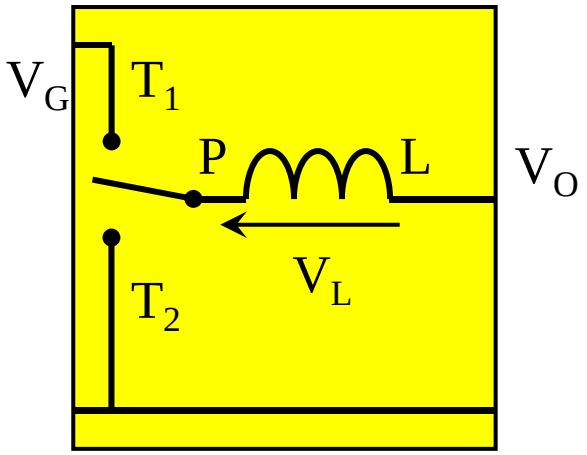


$$\frac{\Delta I_O}{I_O} = \frac{V_O}{I_O L}(1-D)T_S = \frac{(1-D)T_S}{(L/R)}$$

Switched Mode Power Conversion

Primitive Converters

Condition for Ripple Curent to be Low



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

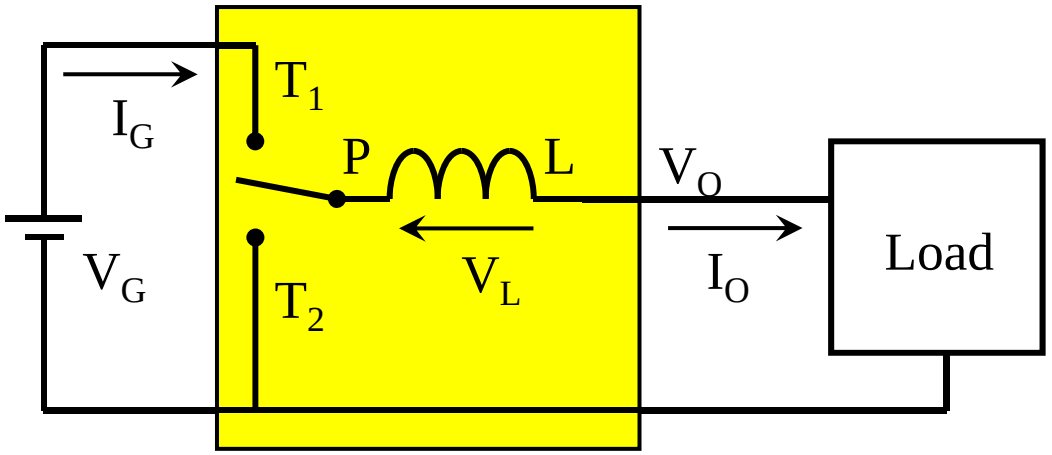
$$T_S \ll \frac{L}{R}$$

Switching Period << Circuit Time Constant

Switched Mode Power Conversion

Primitive Converters

Primitive Voltage to Current Converter

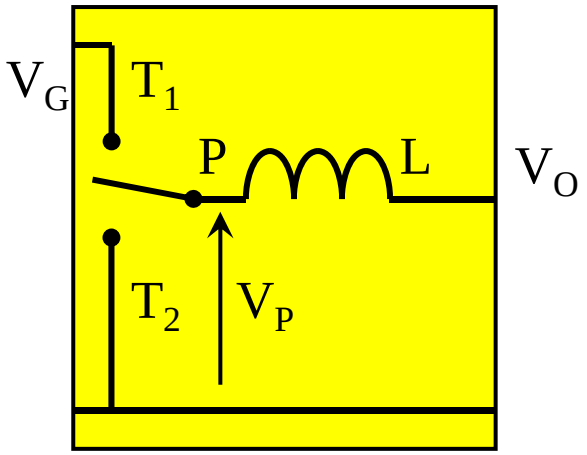


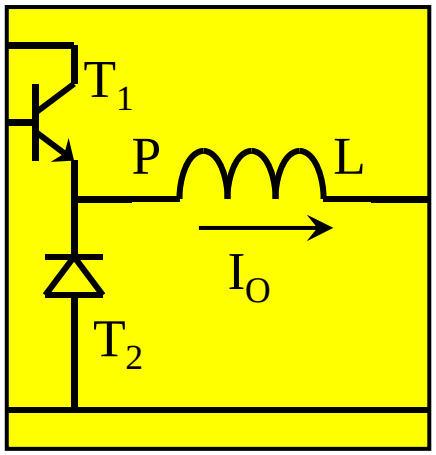
Non-Ideality in the Switches – Conduction Drop

Switched Mode Power Conversion

Primitive Converters

Switches are Realised by Real Devices



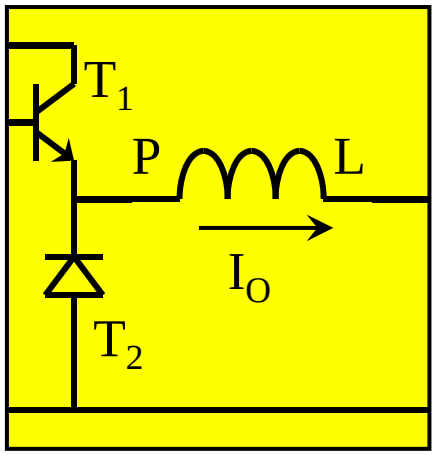


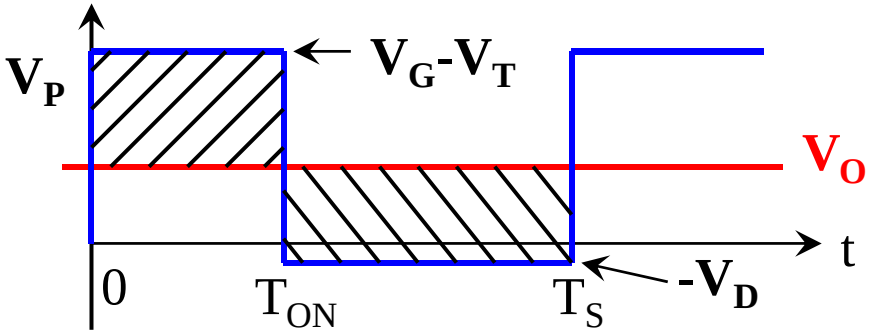
T_{1P} Drop is V_T; T_{2P} Drop is V_D

Switched Mode Power Conversion

Primitive Converters

T_{1P} Drop is V_T; T_{2P} Drop is V_D





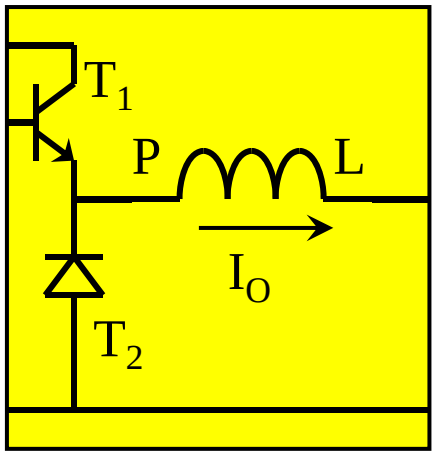
Inductor ON State Voltage is V_G-V_T-V_O

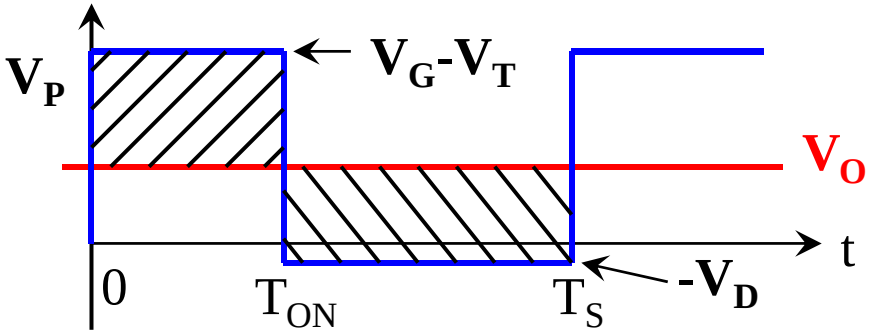
Inductor OFF State Voltage is -V_D-V_O

Switched Mode Power Conversion

Primitive Converters

Volt-Sec Balance on the Inductor



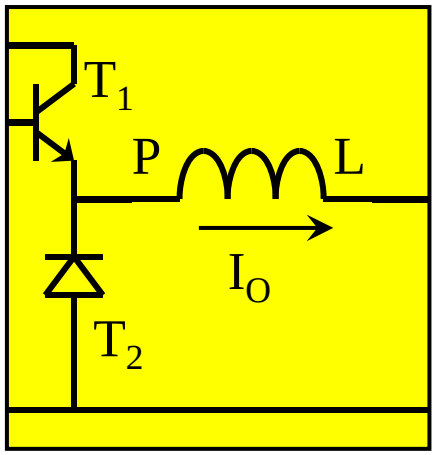


$$\left(V_G - V_T - V_O\right)T_{ON} - \left(V_D + V_O\right)\left(T_S - T_{ON}\right) = 0$$

Switched Mode Power Conversion

Primitive Converters

Forward Voltage Transfer Ratio



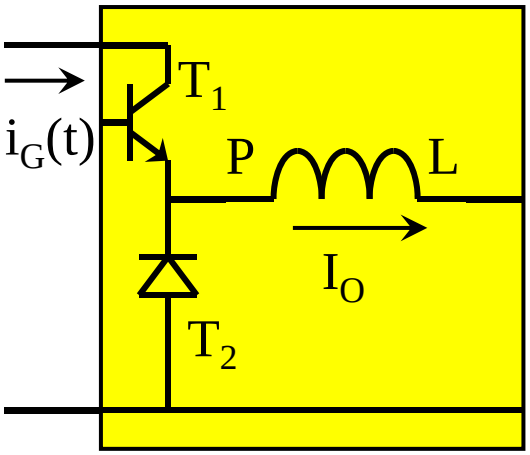
$$(V_G - V_T)T_{ON} - V_D T_{OFF} = V_O T_S$$

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

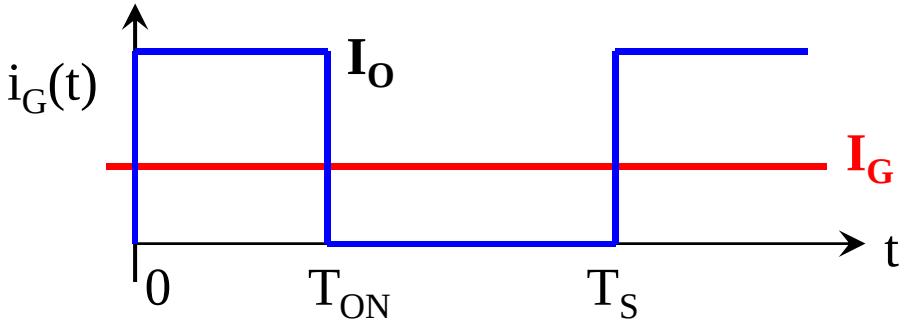
Switched Mode Power Conversion

Primitive Converters

Reverse Current Transfer Ratio



$$I_O T_{ON} - I_G T_S = 0$$

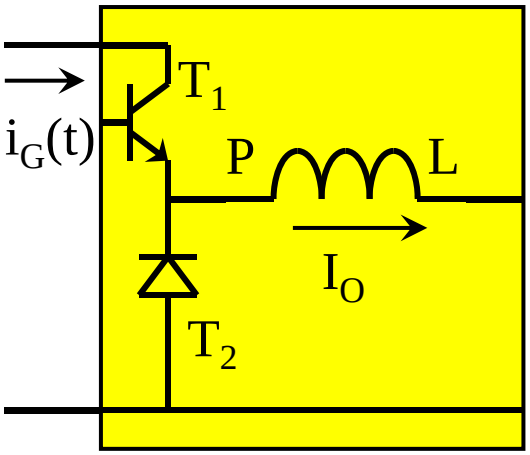


$$\frac{I_G}{I_O} = \frac{T_{ON}}{T_S} = D$$

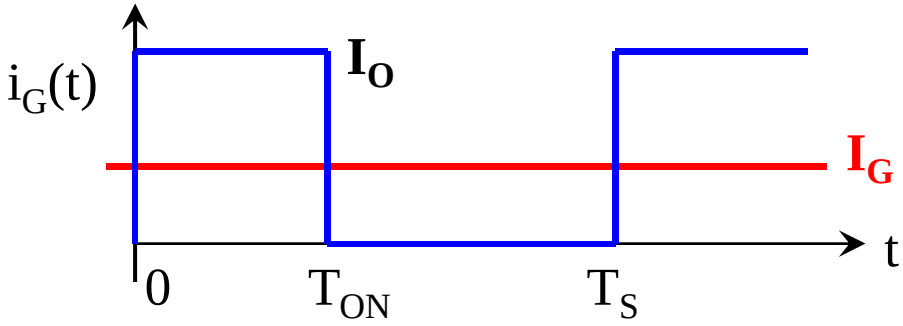
Switched Mode Power Conversion

Primitive Converters

Switch Non-ideality is Series Non-ideality



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

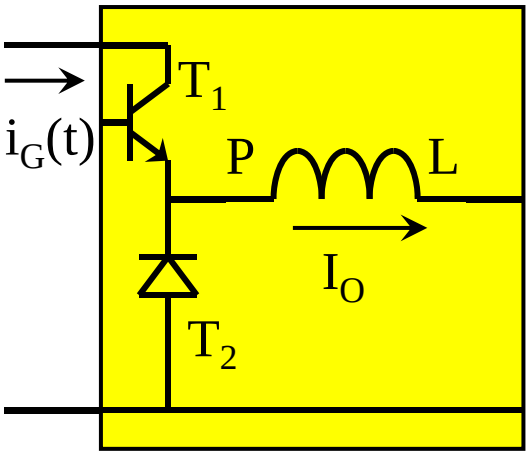


Switch Non-idealities have no Effect on Current Ratio

Switched Mode Power Conversion

Primitive Converters

Efficiency



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

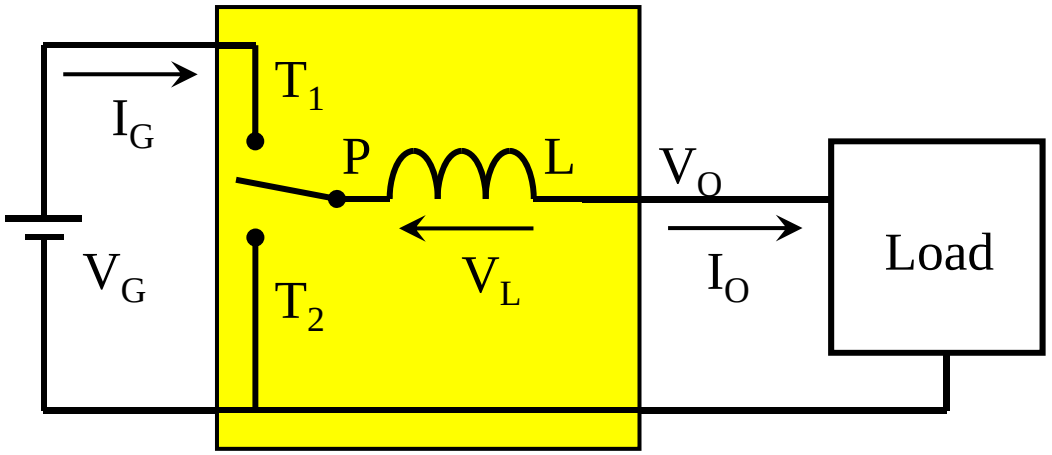
$$\frac{V_O}{V_G} = D\left(1 - \frac{V_T}{V_G} - \frac{(1-D)V_D}{DV_G}\right)$$

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

Switched Mode Power Conversion

Primitive Converters

Primitive Voltage to Current Converter

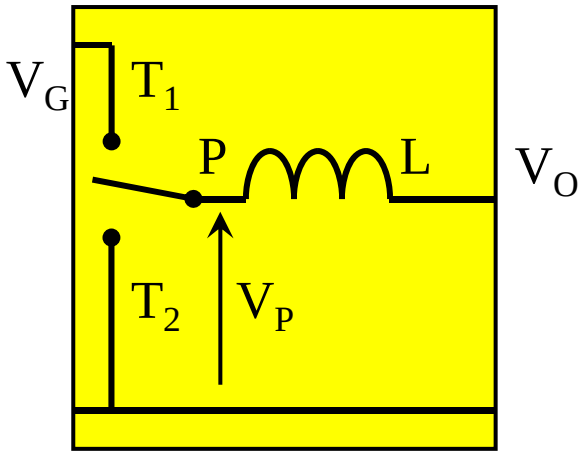


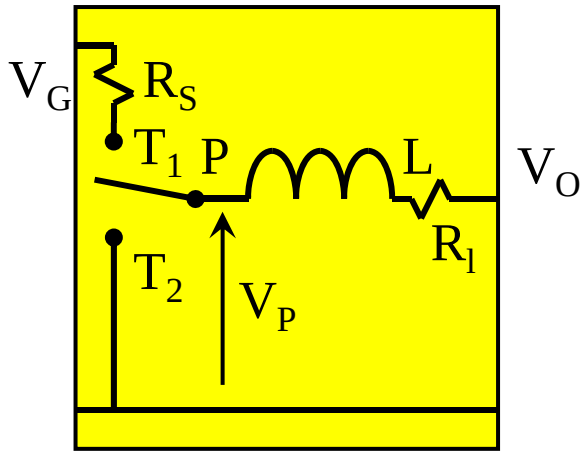
Non-Ideality in the Source & Inductor

Switched Mode Power Conversion

Primitive Converters

Source & Inductor Have Internal Resistances





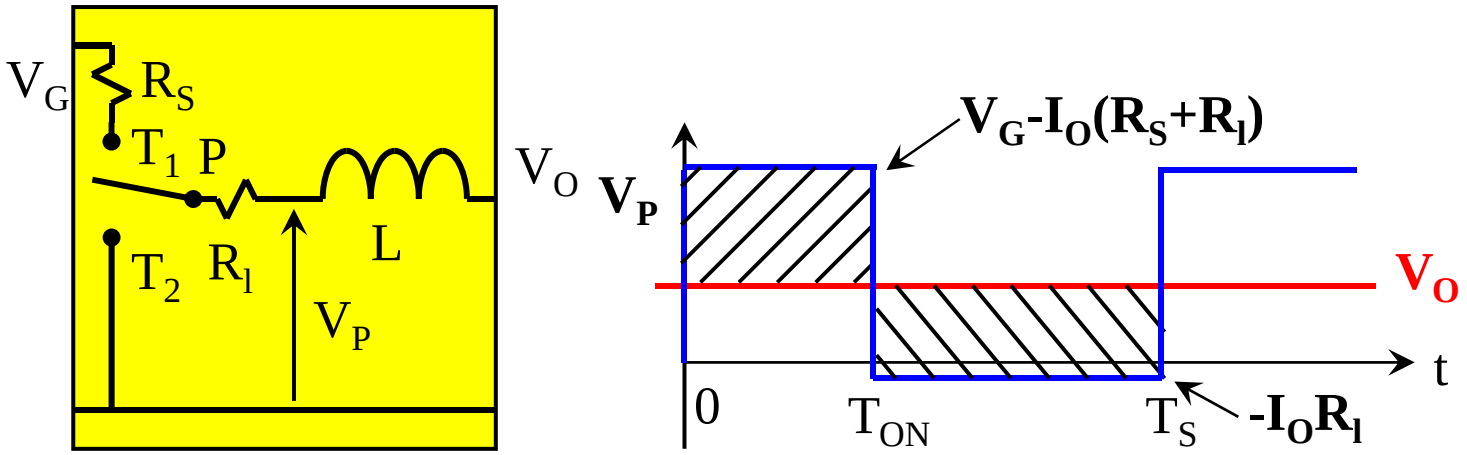
Source Resistance is R_S

Inductor Resistance is R_l

Switched Mode Power Conversion

Primitive Converters

Volt-Sec Balance on the Inductor

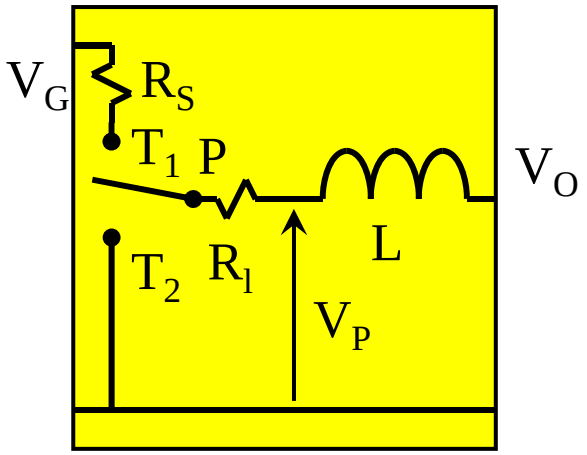


$$\left(V_G - I_O\left(R_S + R_l\right) - V_O\right)T_{ON} - \left(I_O R_l + V_O\right)\left(T_S - T_{ON}\right) = 0$$

Switched Mode Power Conversion

Primitive Converters

Forward Voltage Transfer Ratio



$$\frac{V_O}{V_G} = D\left(\frac{R}{R + DR_S + R_l}\right)$$

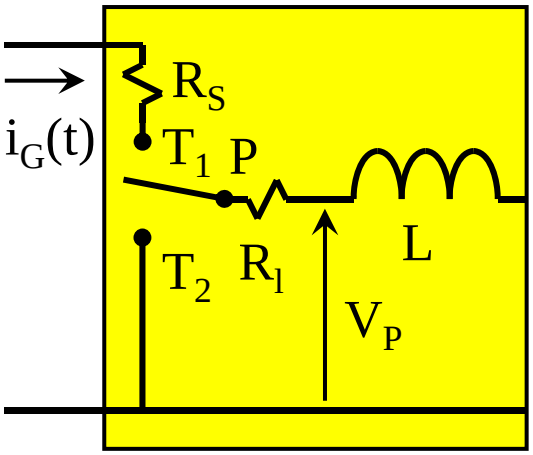
$$\frac{V_O}{V_G} = D\left(\frac{1}{1 + \frac{DR_S}{R} + \frac{R_l}{R}}\right)$$

$$\left(V_G - I_O\left(R_S + R_l\right) - V_O\right)T_{ON} - \left(I_O R_l + V_O\right)\left(T_S - T_{ON}\right) = 0$$

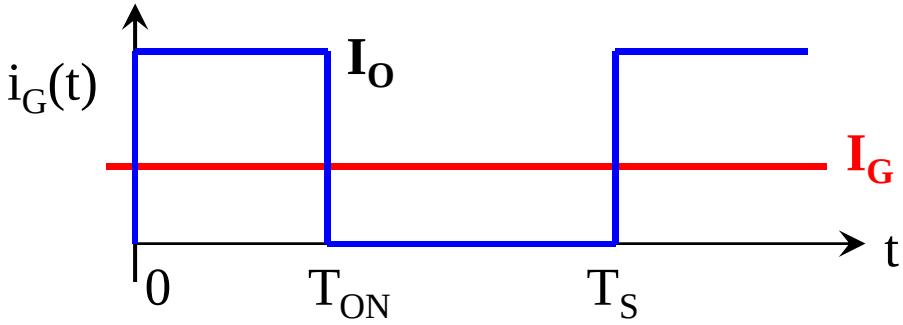
Switched Mode Power Conversion

Primitive Converters

Reverse Current Transfer Ratio



$$I_O T_{ON} - I_G T_S = 0$$

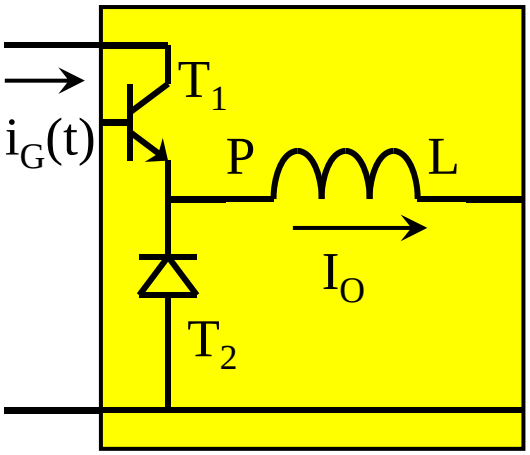


$$\frac{I_G}{I_O} = \frac{T_{ON}}{T_S} = D$$

Switched Mode Power Conversion

Primitive Converters

Efficiency



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

$$\frac{V_O}{V_G} = D\left(\frac{R}{R + DR_S + R_l}\right)$$

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

Switched Mode Power Conversion

Primitive Converters

Efficiency with Switch/Source/Inductor Drops

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

Switched Mode Power Conversion

Primitive Converters

Guidelines for Good Efficiency

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

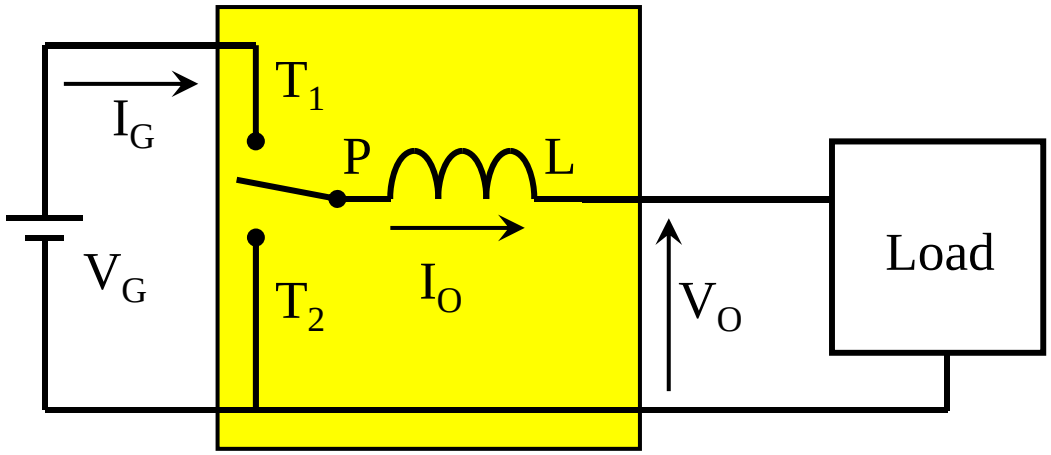
$$V_T \ll V_G \; ; \; V_D \ll V_O$$

$$R_S \ll R \; ; \; R_l \ll R$$

Switched Mode Power Conversion

Primitive Converters

Non-ideality Related to Output Voltage

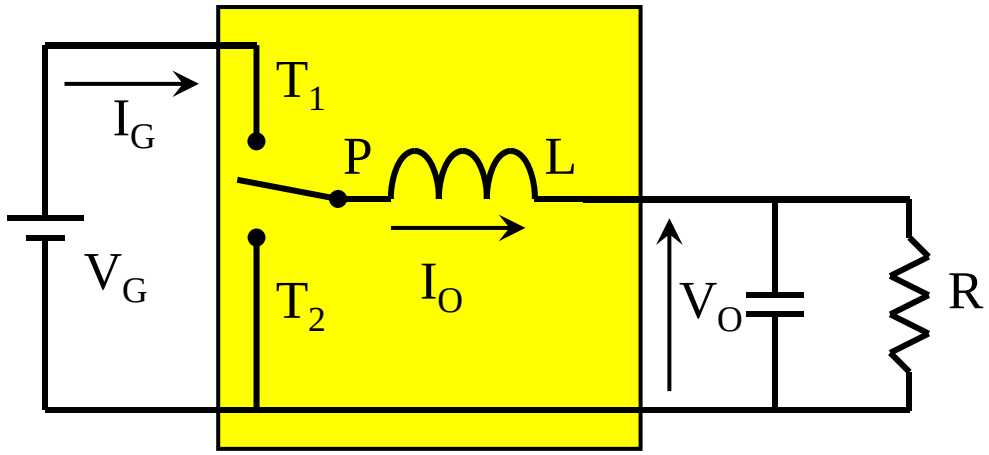


Output Voltage Ripple is a Function of the Load

Switched Mode Power Conversion

Primitive Converters

Evaluation of the Output Voltage Ripple

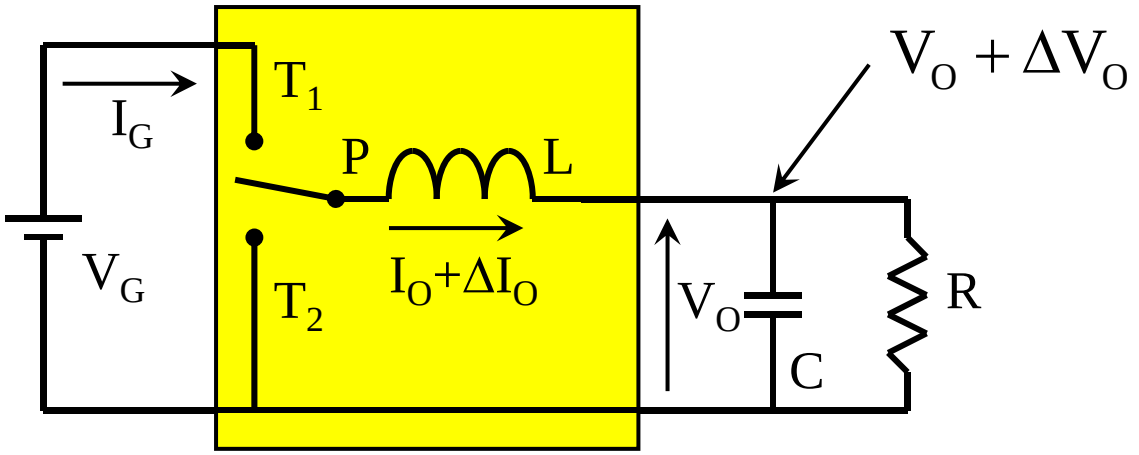


Capacitor Supported Load is Common

Switched Mode Power Conversion

Primitive Converters

Inductor Current & Output Voltage Ripple

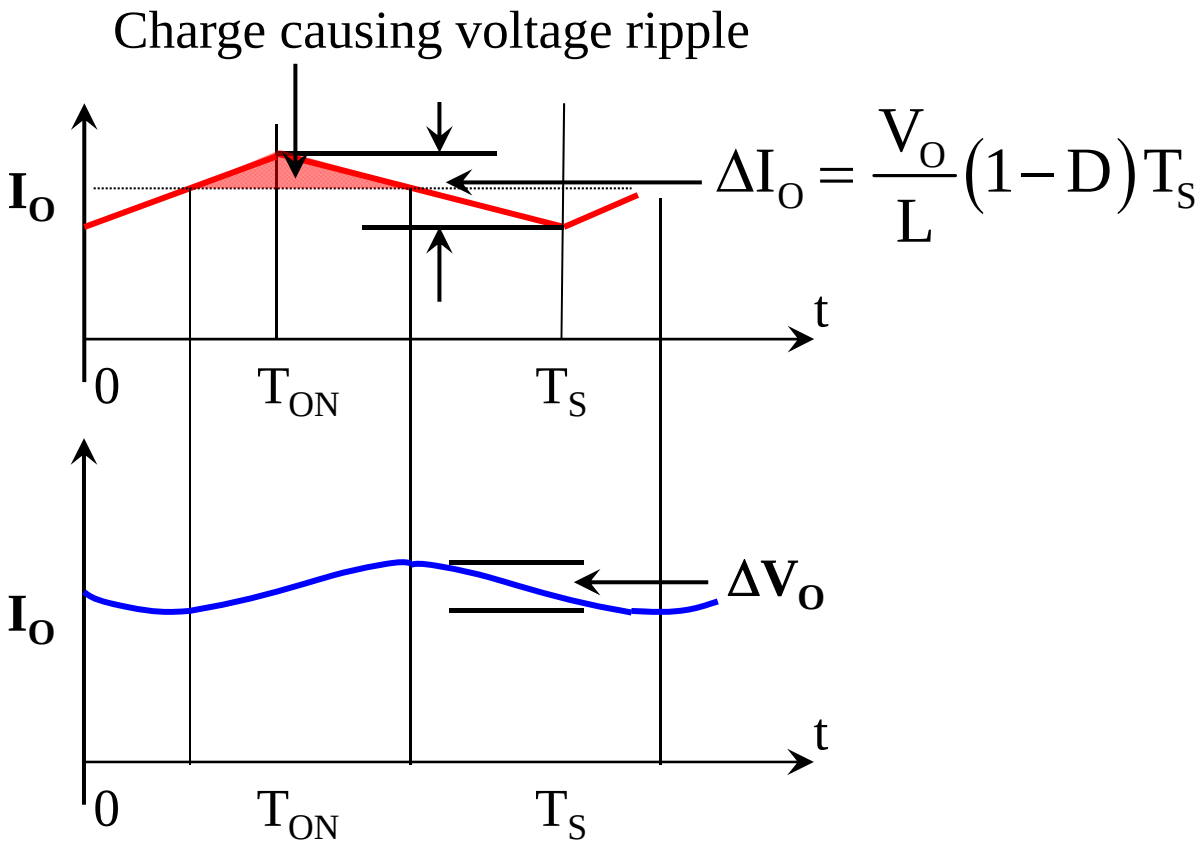


Output Voltage Ripple is ΔV_O

Switched Mode Power Conversion

Primitive Converters

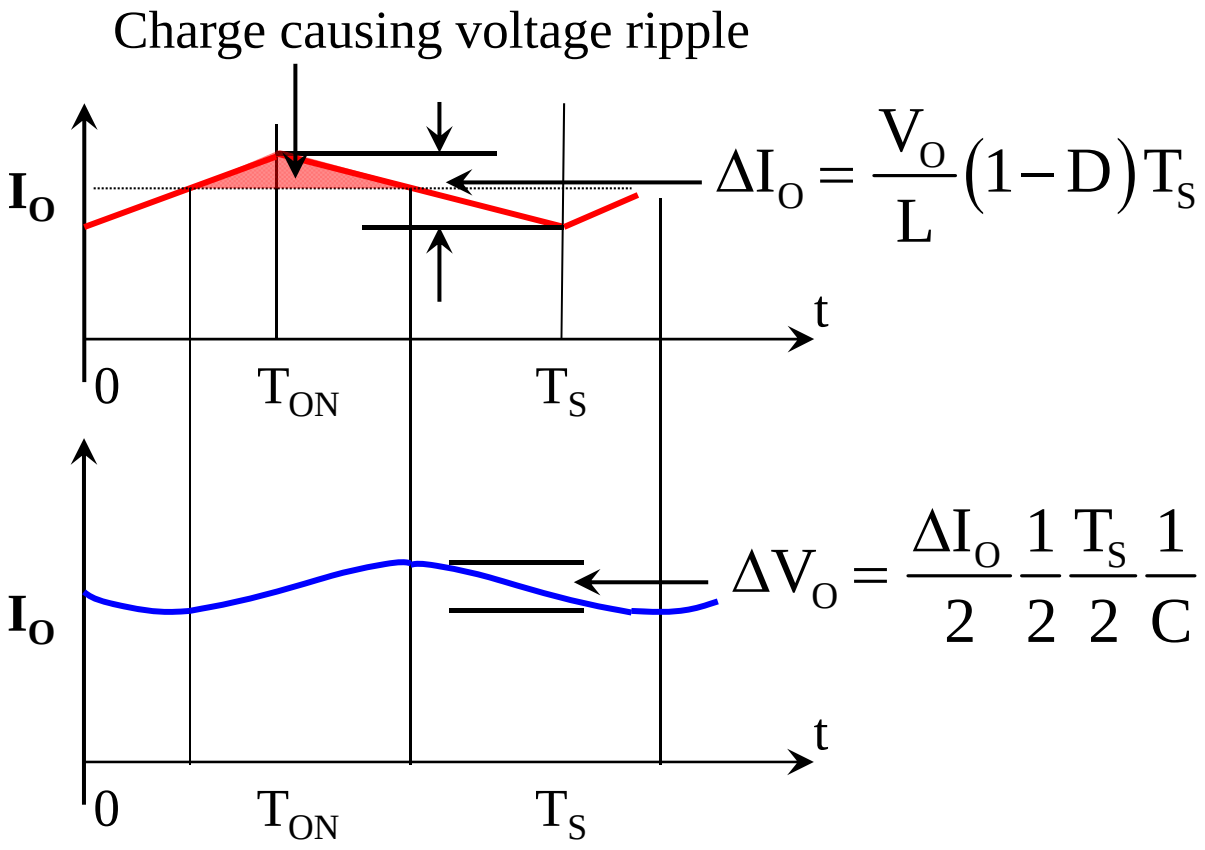
Inductor Current & Output Voltage Ripple



Switched Mode Power Conversion

Primitive Converters

Inductor Current & Output Voltage Ripple



Switched Mode Power Conversion

Primitive Converters

Inductor Current & Output Voltage Ripple

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

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

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

Switched Mode Power Conversion

Primitive Converters

Guidelines for Low Output Ripple

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

Switching Period << Natural Frequency

$$T_S \square \frac{1}{\sqrt{LC}}$$

Switched Mode Power Conversion

Primitive Converters

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

Switched Mode Power Conversion

Primitive Converters

Summary of Steady State Performance

Inductor Volt-sec Balance: V_O/V_G

Current Averaging: I_O/I_G

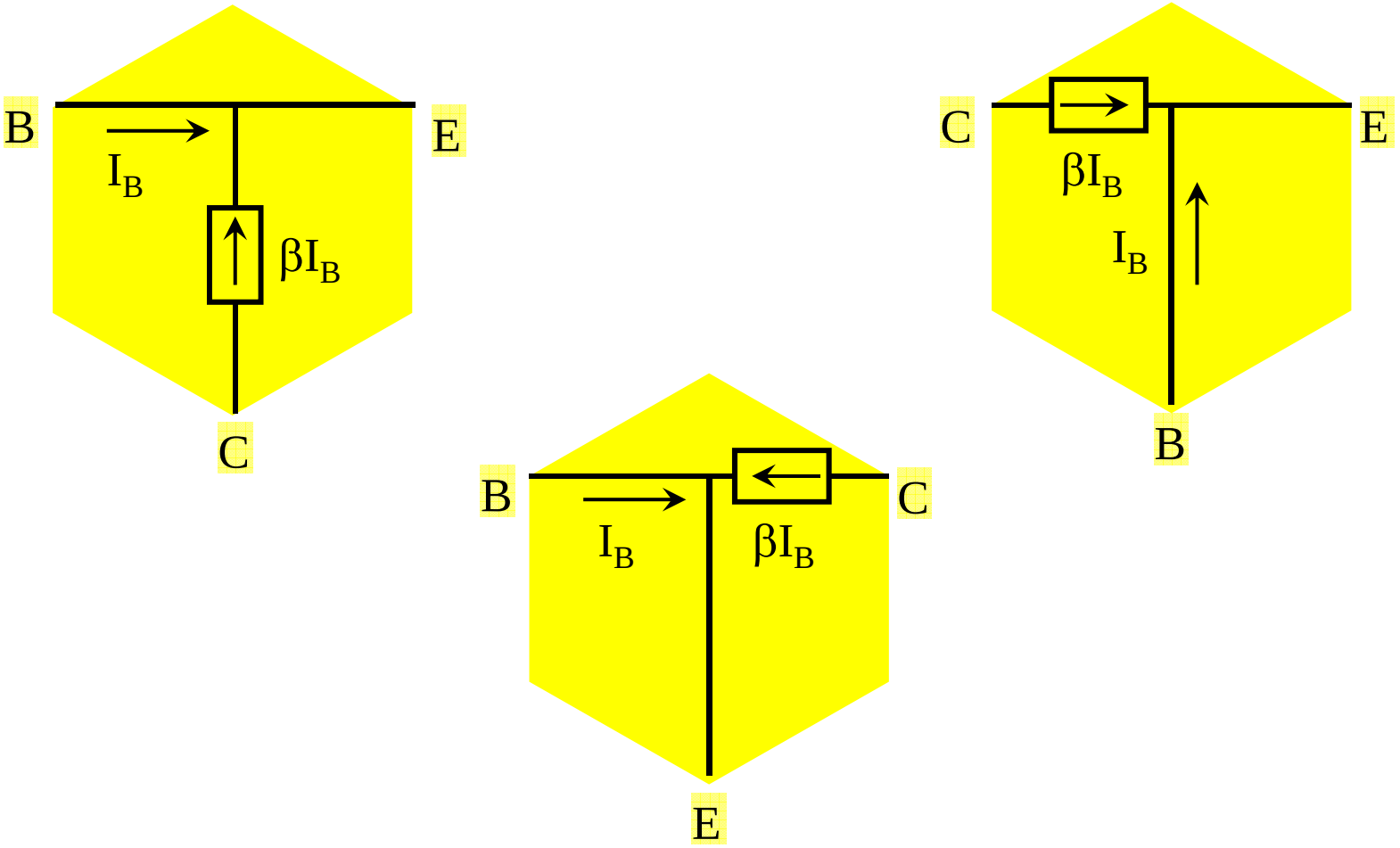
Inductor Volt-sec in Sub-period: $\Delta I_O/I_O$

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

Inductor Volt-sec Balance with Non-ideality: η

Switched Mode Power Conversion

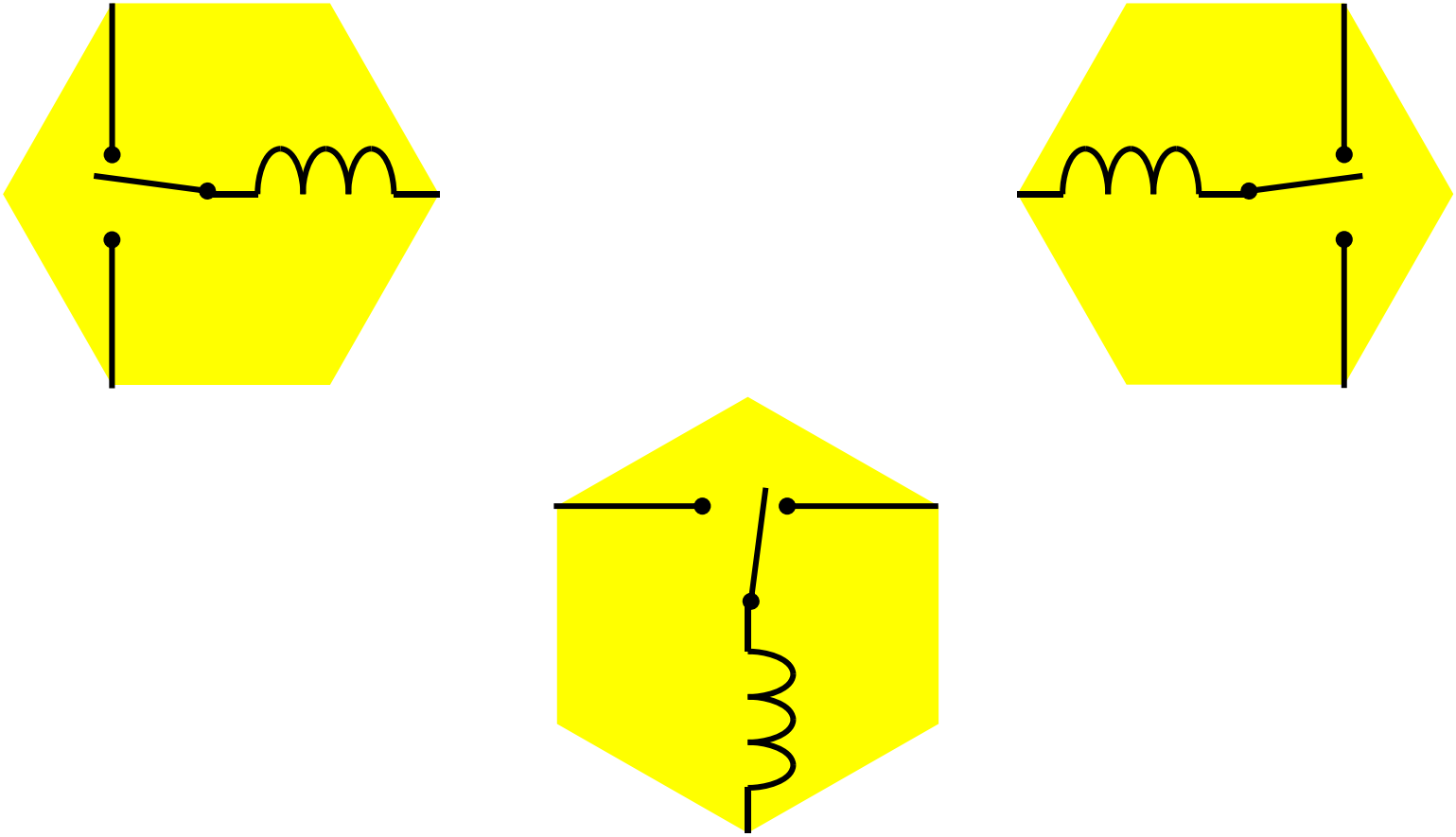
Transistor Amplifiers



Transistor Amplifier Variants

Switched Mode Power Conversion

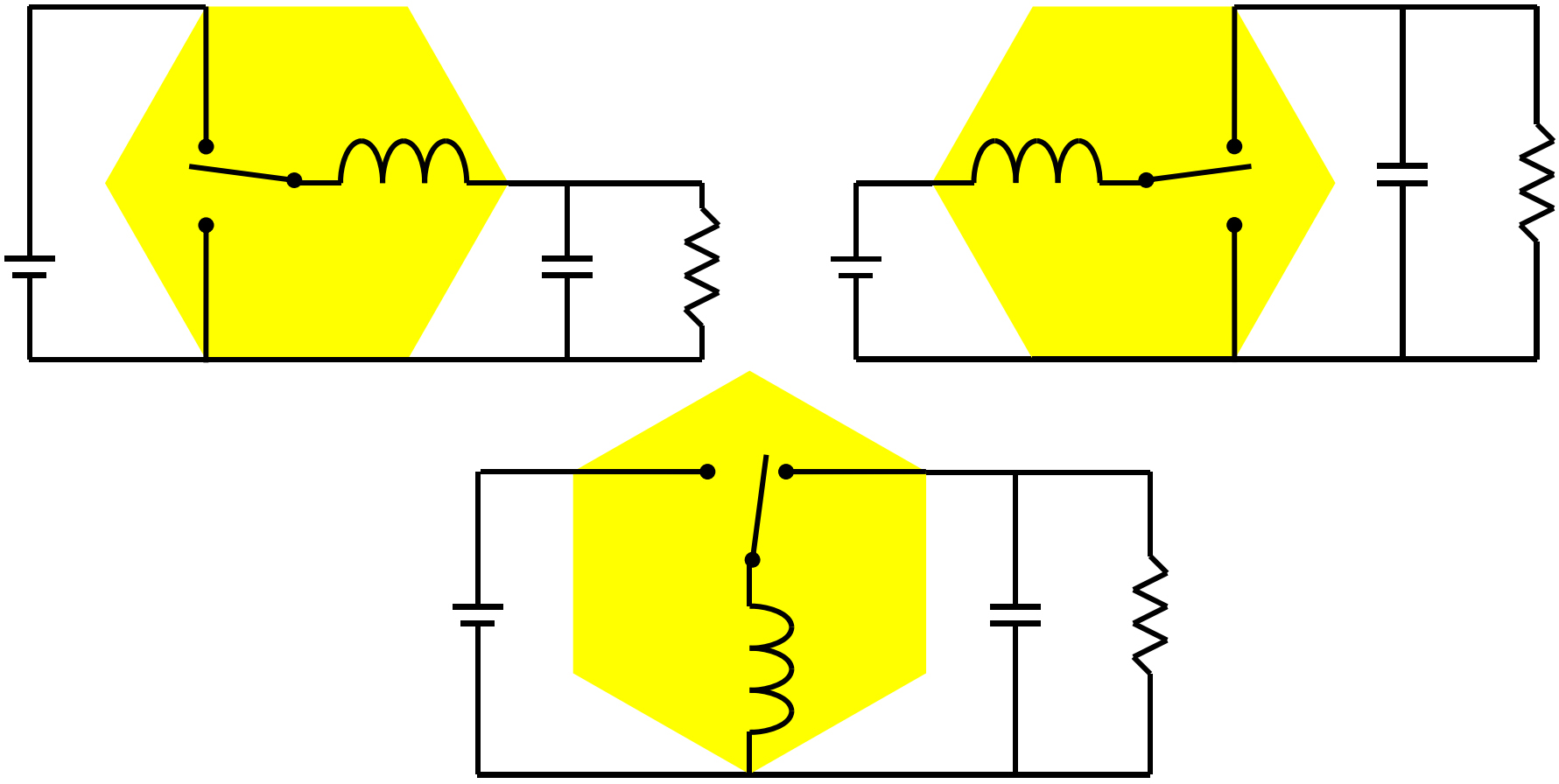
Primitive Converters



Buck, Boost & Buck-Boost Variants

Switched Mode Power Conversion

Primitive Converters



Buck, Boost & Buck-Boost Variants