Switched Mode One-Quadrant Power Converters

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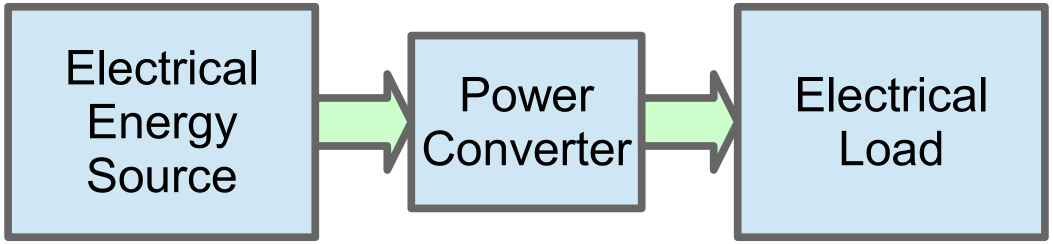
The CERN Accelerator School

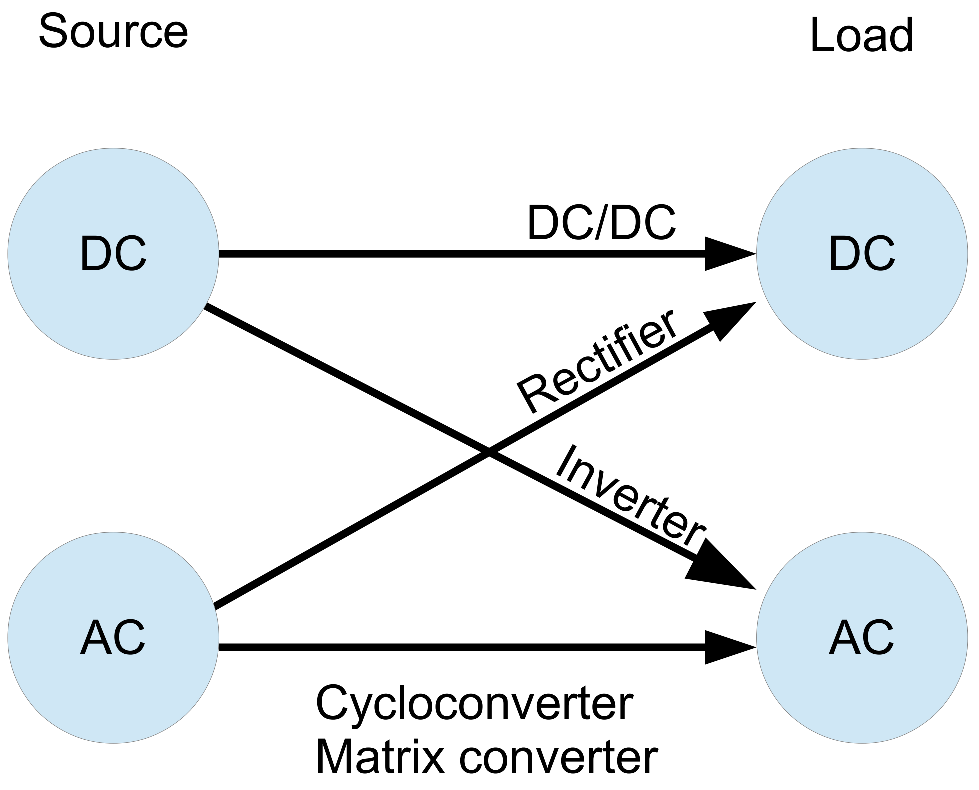
Summary

- Power Electronics. Basics definitions and rules
- Basic DC-DC Power Converters
- Control of DC-DC Power Converters
- Derived Topologies
- Other Issues

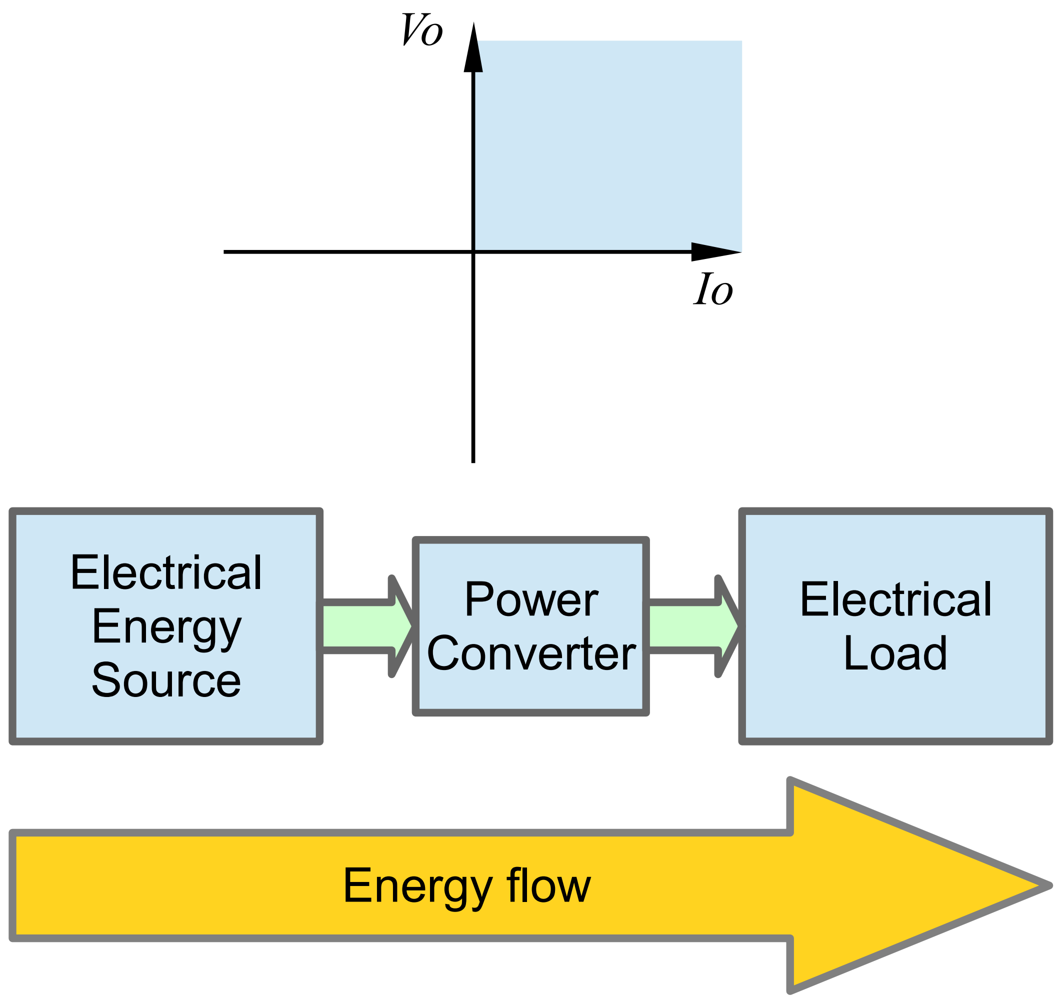
Power converter Definition



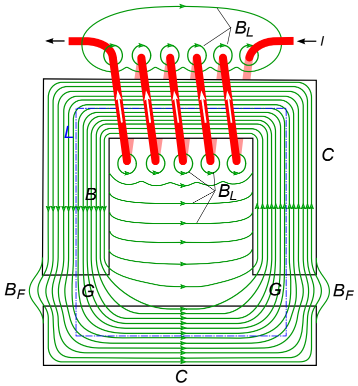
Clasification of Power converters

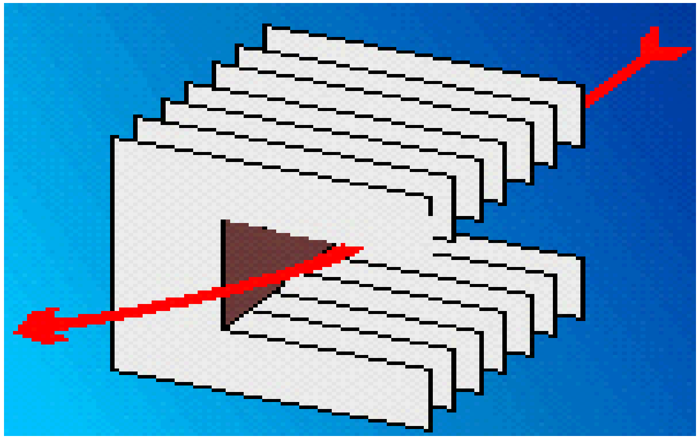


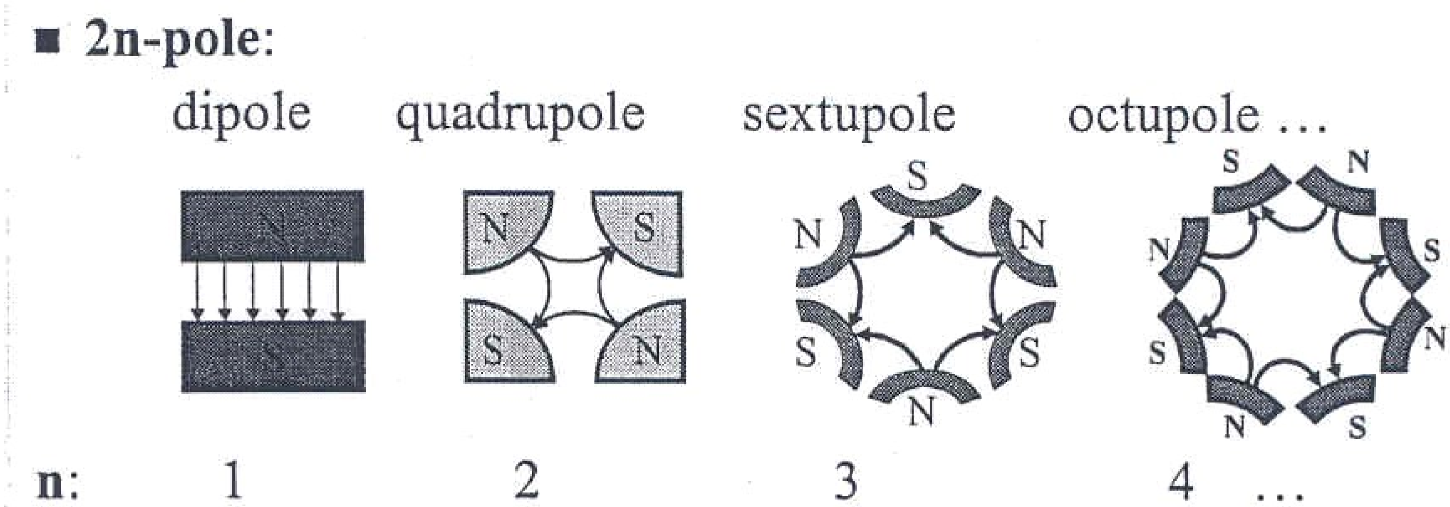
One-Quadrant Definition



One-Quadrant Power Converter in Particle Accelerators







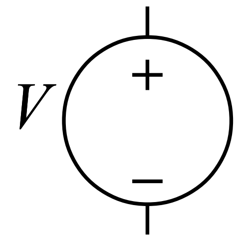
Power Electronics
Basic Definition and Rules

- Sources Definition
- Basic Rules
- Interconnection Rules

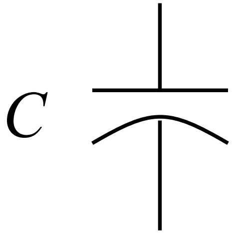
Type of Sources

Voltage Source

- A voltage source is able to impose a voltage regardless of the current flowing through it.



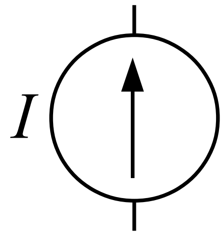
- In a more open sense, if the voltage across and element can not have discontinuities in time due to the current flowing through it



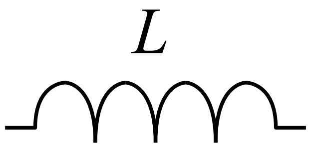
Source Type

Current Sources

A current are able to impose current regardless the voltage across its terminals.

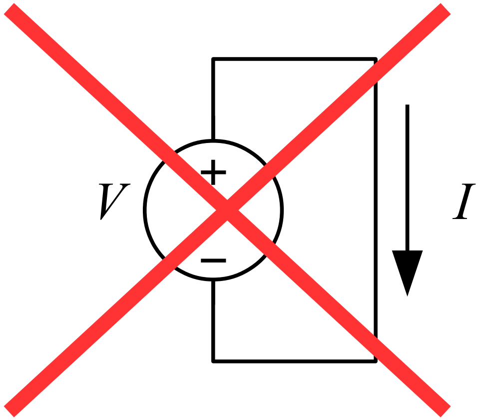


Similar to the voltage sources this can be extended to elements which current can not have discontinuities.



Basic Rules

- Rule 1: A voltage source must never be short-circuited



$I \rightarrow \infty$

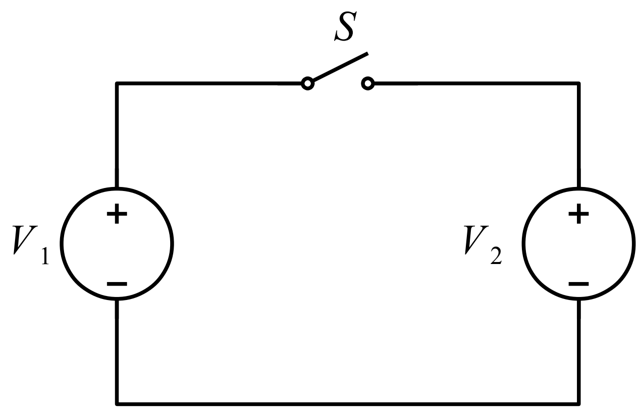
Basic Rules

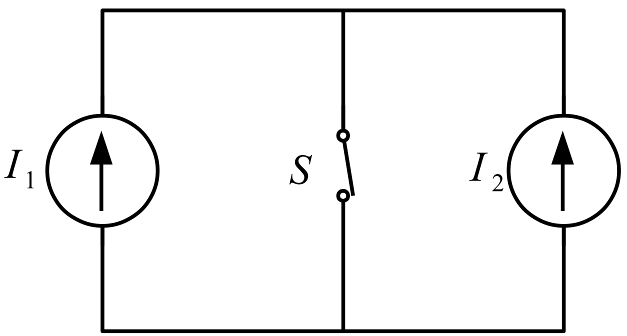
- Rule 2: A current source must never be open-circuited

$V \rightarrow \infty$

Basic Rules

- Interconection Rules

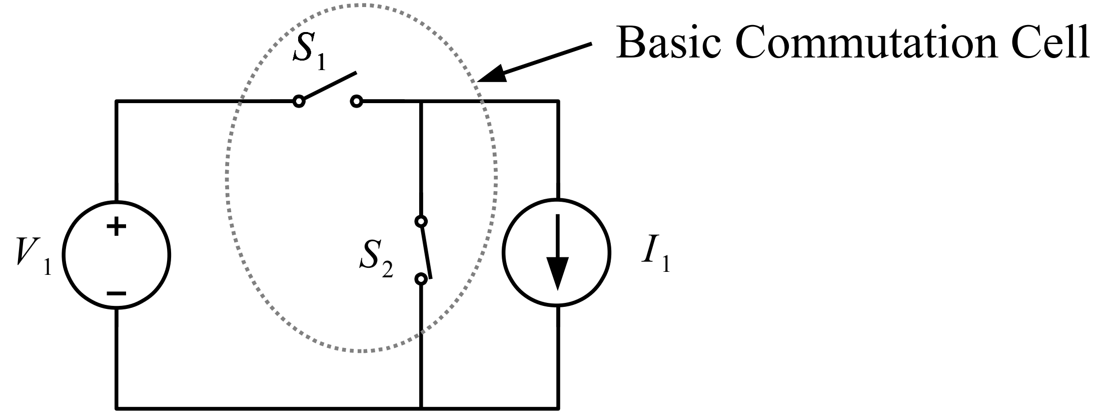




S must not be closed
Unless $V_1 = V_2$

S must not be open
Unless $I_1 = -I_2$

Interconection Rules



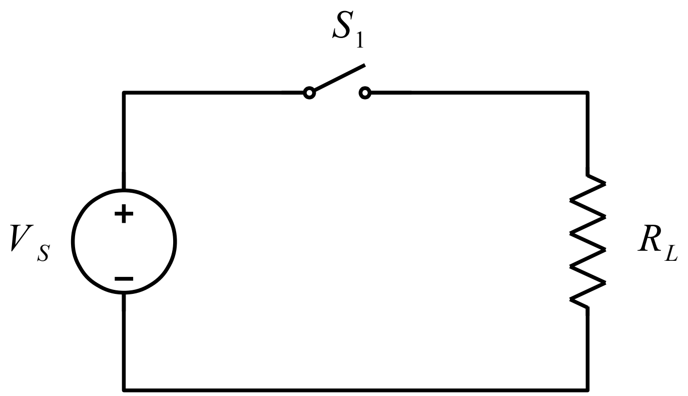
S_1	S_2	
open	*open*	Not allowed
open	*closed*	Allowed
closed	*open*	Allowed
closed	*closed*	Not allowed

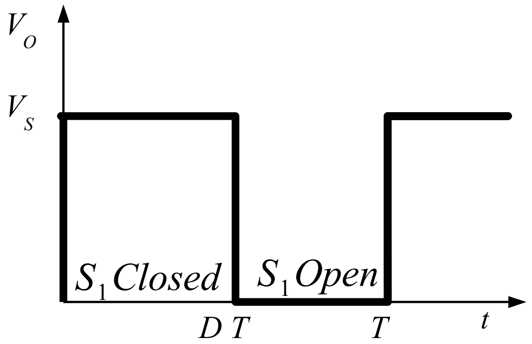
Basic DC-DC Converter

- Chopper
- Buck Converter
- Boost Converter
- Buck-Boost Converter

DC Chopper

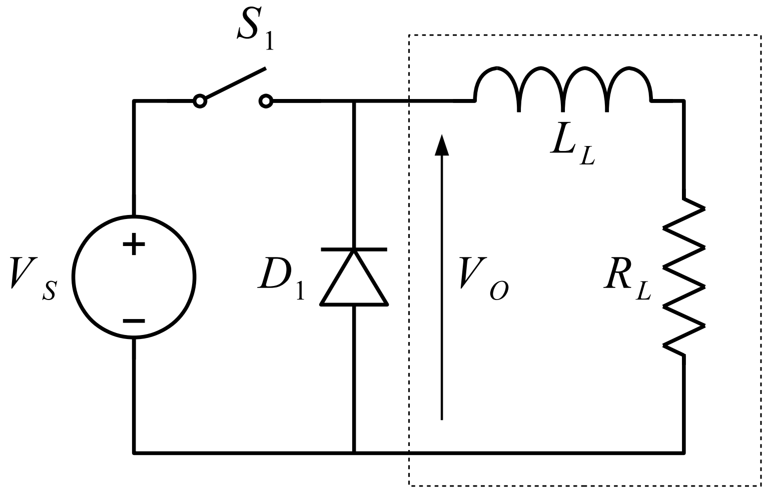
- Resistive Load





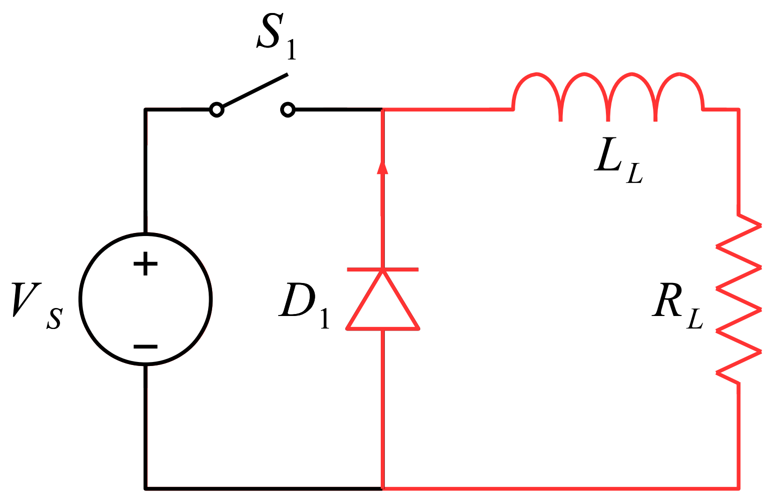
DC Chopper

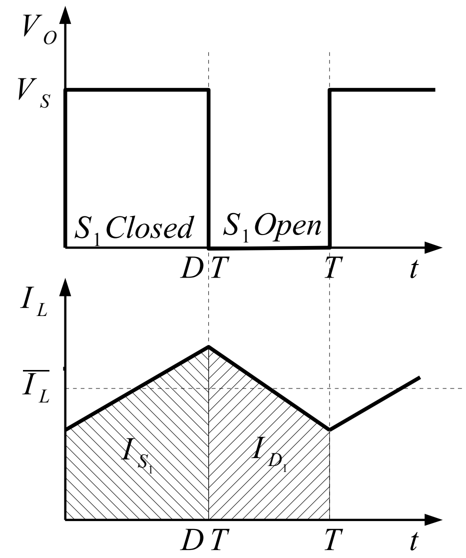
- Inductive Load



- Application: Motor control

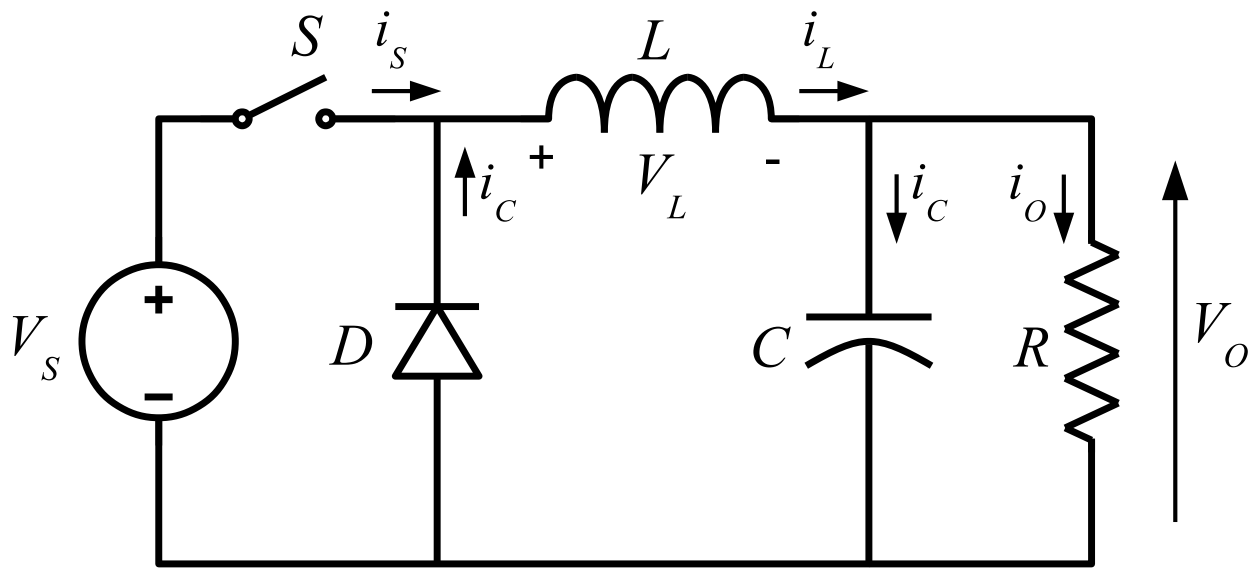
Chopper Waveforms



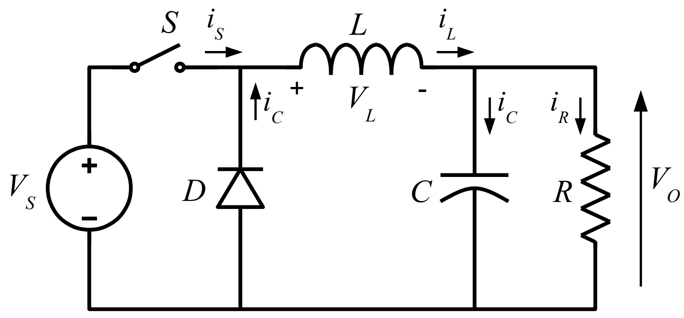


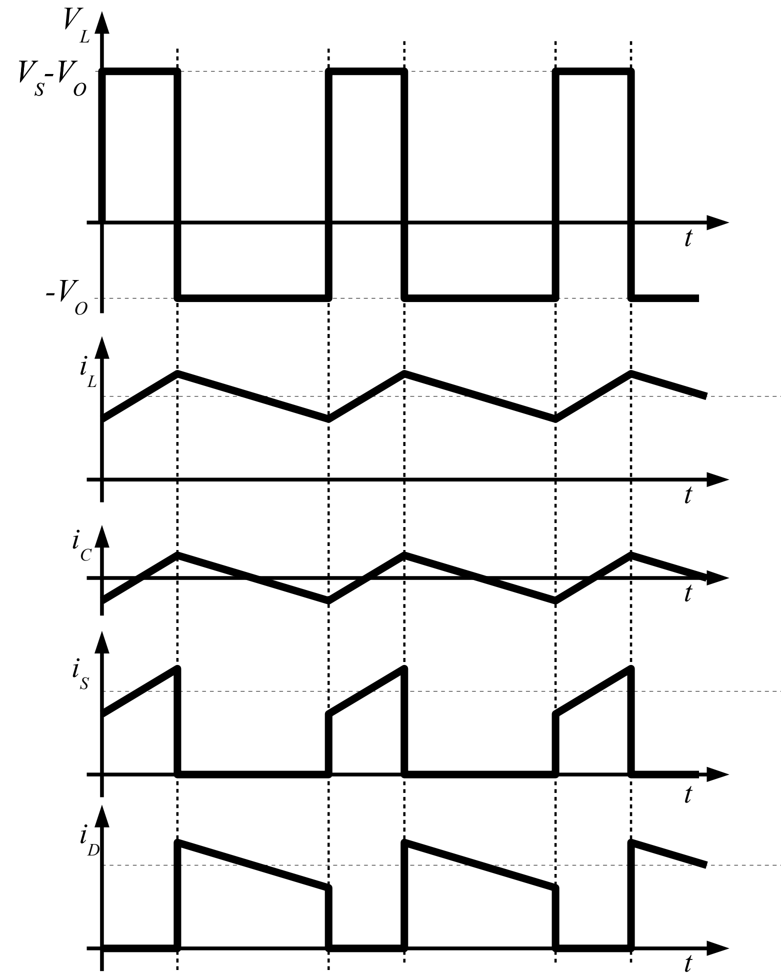
$$\overline{I_L} = \frac{V_S D}{R_L}$$

Buck Converter



Buck Converter



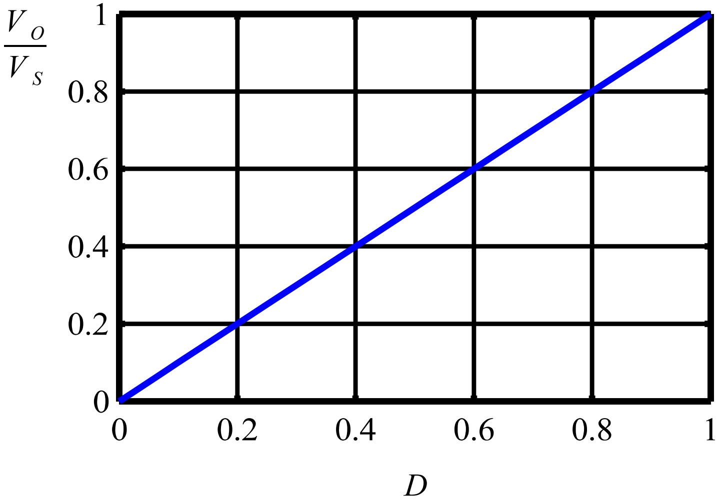


Faraday Law :
volt-second product of the inductor voltage should be zero for steady-state operation

$$(V_S - V_O) D T = V_O (1 - D) T$$

Output-Input Voltage Ratio

$$M_V \equiv \frac{V_O}{V_S} = D$$



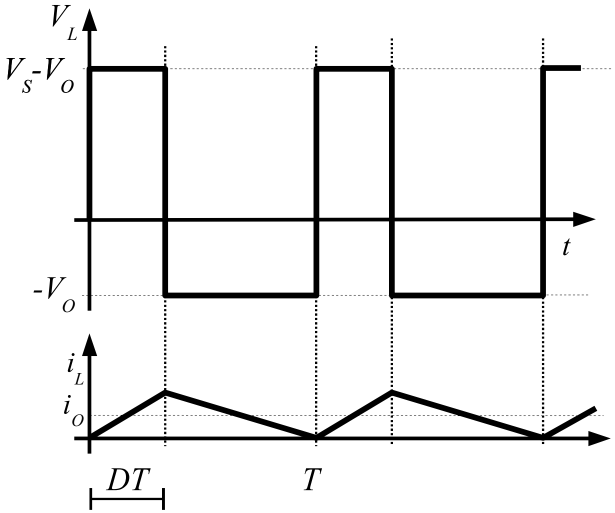
$$L_b = \frac{(1-D)R}{2f}$$

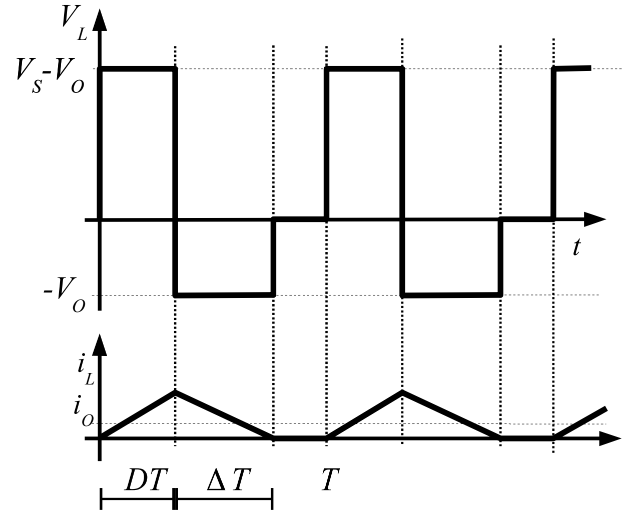
Inductance for boundary between CCM and DCM

$$C_{min} = \frac{(1-D)V_O}{8V_r L f^2}$$

Minimum capacitance for an output voltage ripple V_r

Continuous and Dis-Continuous Mode

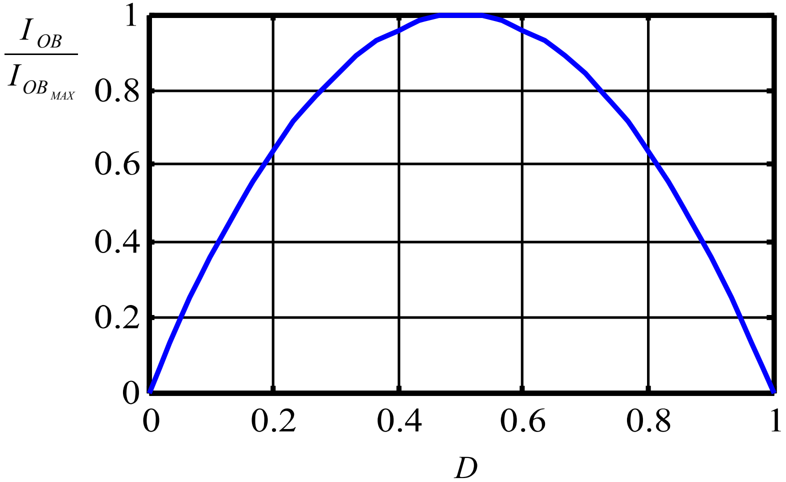




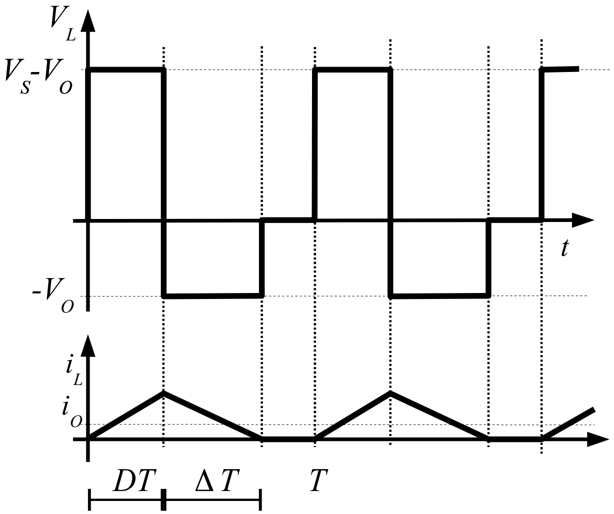
CCM and DCM Boundary

$$i_{OB} = \frac{DT}{2L}(V_S - V_O) = \frac{TV_S}{2L}(D - D^2)$$

$$I_{OB_{MAX}} = \frac{TV_S}{8L}$$



$$(V_S - V_O) D T = V_O \Delta T$$



$$\frac{V_O}{V_S} = \frac{D}{(D + \Delta)}$$

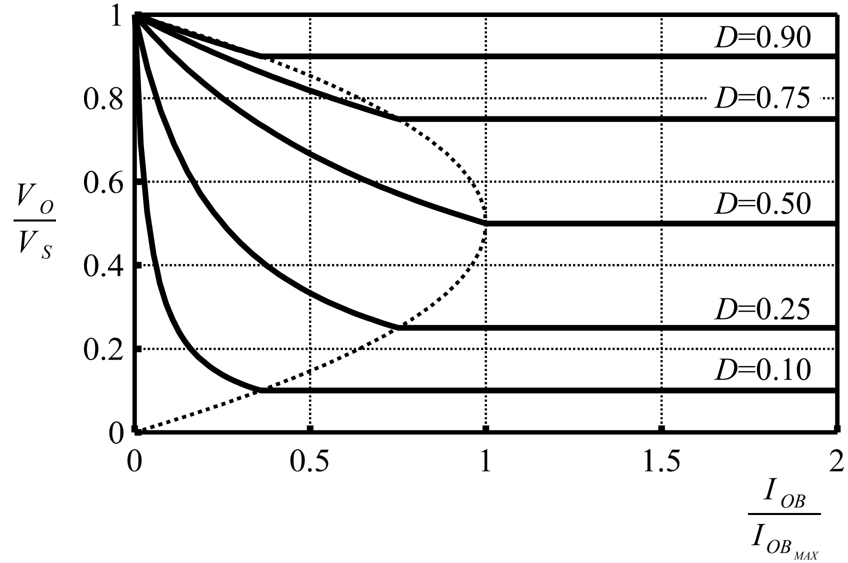
$$I_O = \frac{I_{L_{peak}} (D + \Delta) T}{2 T}$$

$$I_{L_{peak}} = \frac{V_O \Delta T}{L}$$

$$I_O = 4 I_{OB_{MAX}} D \Delta$$

Output-Input Voltage Ratio in DCM

$$\frac{V_O}{V_S} = \frac{D^2}{\left(D^2 + \frac{1}{4}\frac{I_O}{I_{OB_{MAX}}}\right)}$$

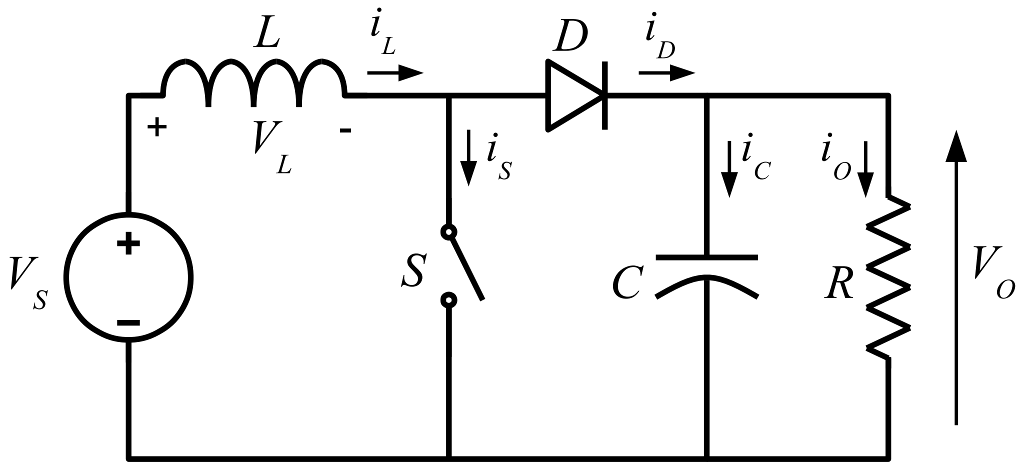


Buck Converter

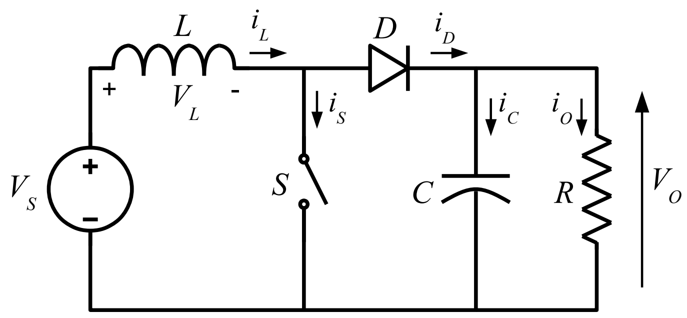
- Widely used. Even for high power converters

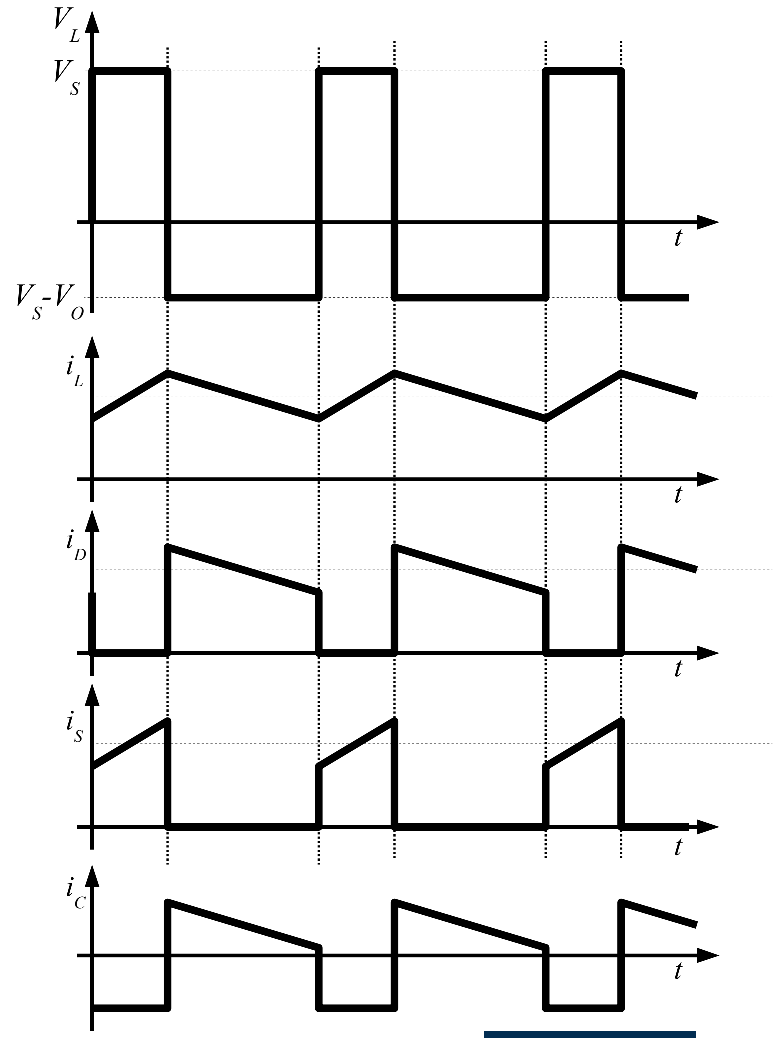
- Advantages:
  - Simple
  - Linear output-input voltage ratio. It makes easier the control.
  - Smooth output current.
- Disadvantages:
  - Discontinuous input current
  - No isolation.

Boost Converter



Boost Converter





Faraday Law :

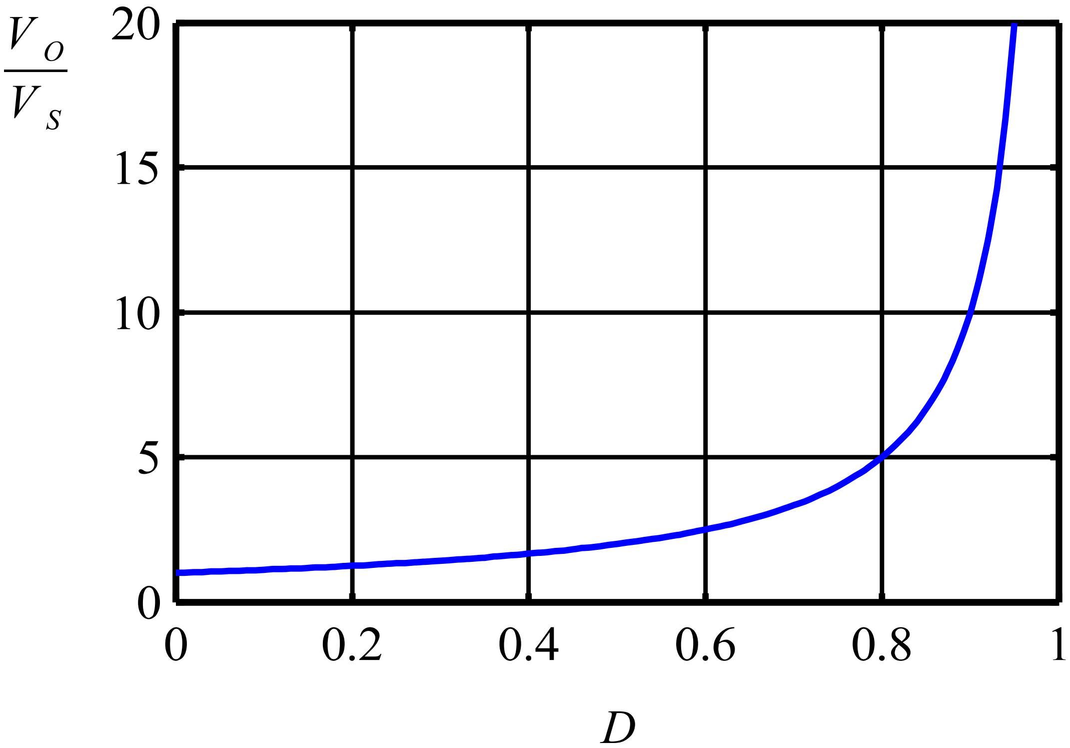
$$V_S D T = (V_O - V_S)(1 - D) T$$

$$M_V \equiv \frac{V_O}{V_S} = \frac{1}{(1-D)}$$

$$L_b = \frac{(1-D)^2 D R}{2 f} \qquad C_{min} = \frac{D V_O}{V_r R f}$$

Boost Converter: Output-Input Voltage Ratio

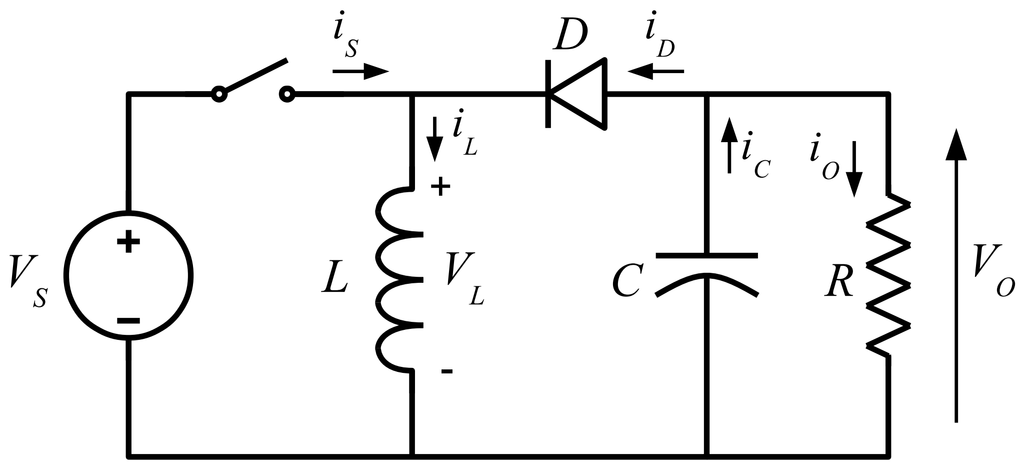
$$M_V \equiv \frac{V_O}{V_S} = \frac{1}{(1-D)}$$

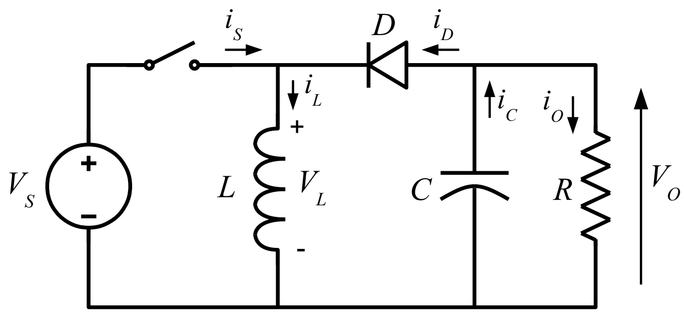


Boost Converter

- Output voltage higher than input voltage
- Advantages:
  - Simple
  - Smooth input current.
- Disadvantages:
  - Discontinuous output current. Stress the output capacitor
  - No isolation.

Buck-Boost Power Converter

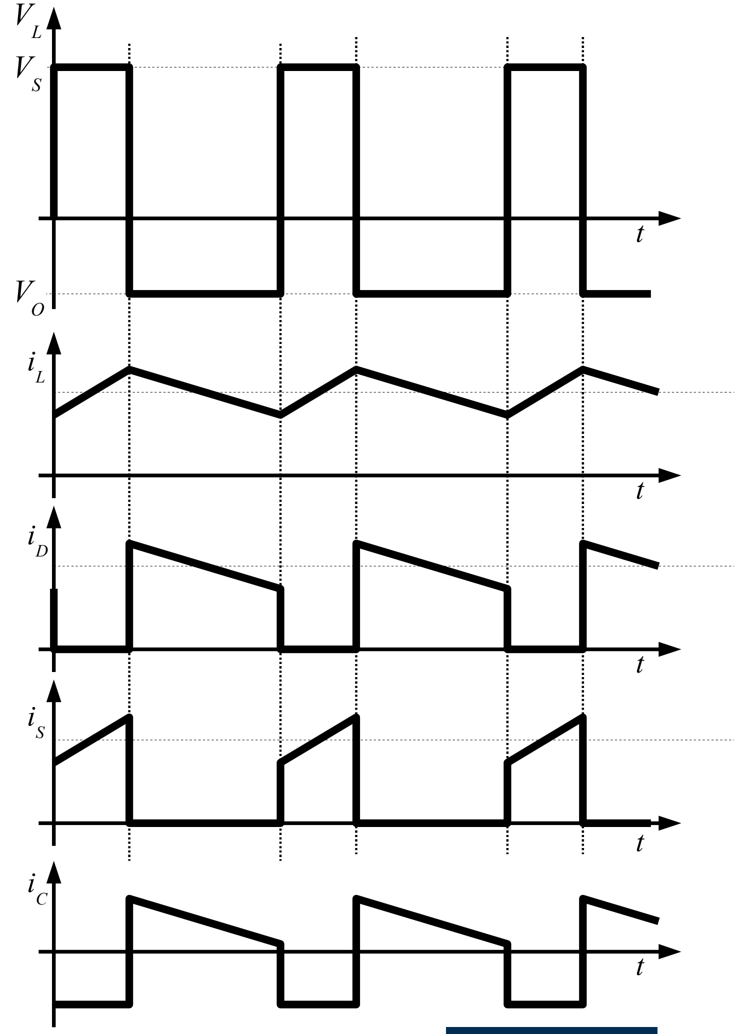




$$V_S T D = -V_O (1-D) T$$

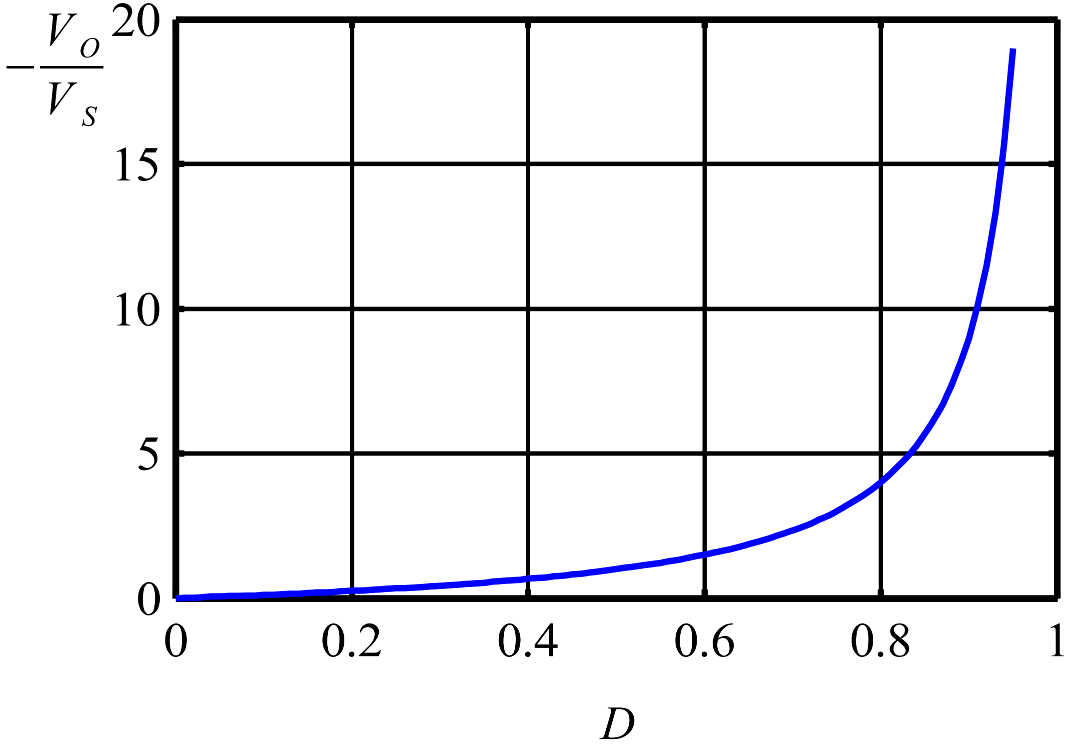
$$M_V \equiv \frac{V_O}{V_S} = -\frac{D}{(1-D)}$$

$$L_b = \frac{(1-D)^2 D R}{2 f}$$



Buck-Boost Converter: Output-Input Voltage Ratio

$$M_V \equiv \frac{V_O}{V_S} = -\frac{D}{(1-D)}$$



Buck-Boost Converter

Reverse voltage polarity

- Advantages:
  - Simple
  - Step-down and step-up
- Disadvantages:
  - Discontinuous input and output current.
  - No isolation.

Control of DC-DC Power Converters

- Regulation
- Pulse-Width Modulation. (PWM)
- Current Mode
- Variable Structure Control

Control of Switched Mode DC-DC Power Converter

Switching function.

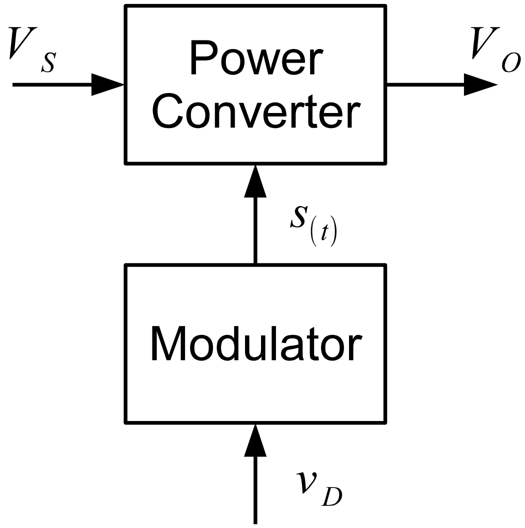
Definition:

The switching function, $S(t)$, has a value of 1 when the corresponding physical switch is *on* and 0 when it is *off*.

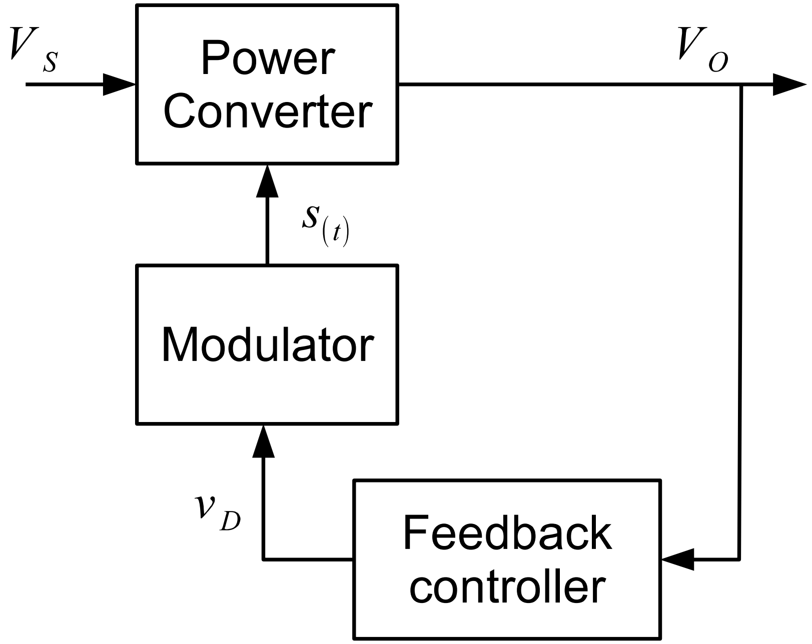
Switching functions are discrete-valued functions of time, and control of switching devices can be represented with them.

$$s(t) = \begin{cases} 1 & when\ the\ switch\ is\ on \\ 0 & when\ the\ switch\ is\ off \end{cases}$$

Power Converter Block Diagram

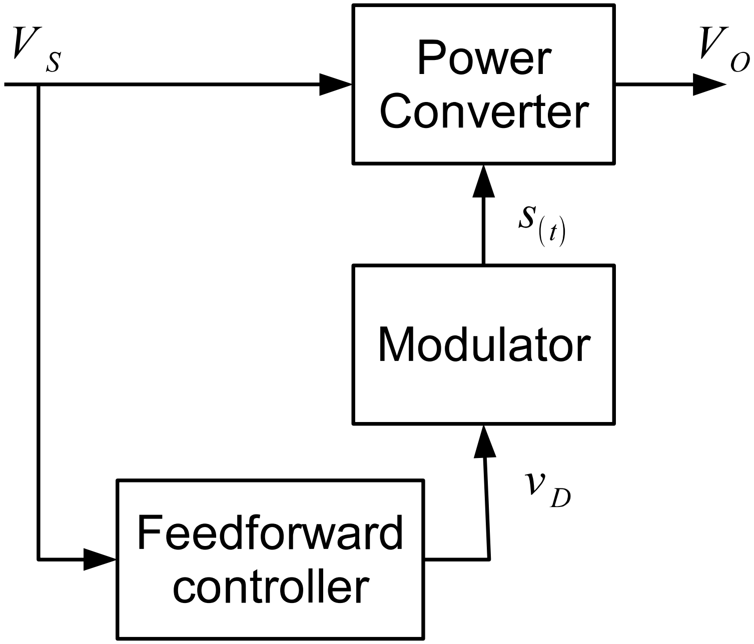


Regulation – Feedback



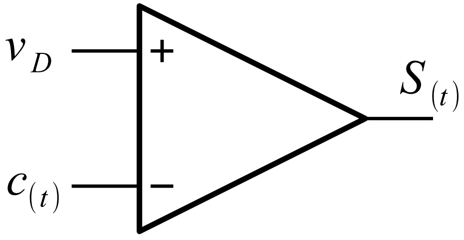
- Close loop, the output voltage is sensed and the feedback controller acts to get the wished value.
- Stability issues

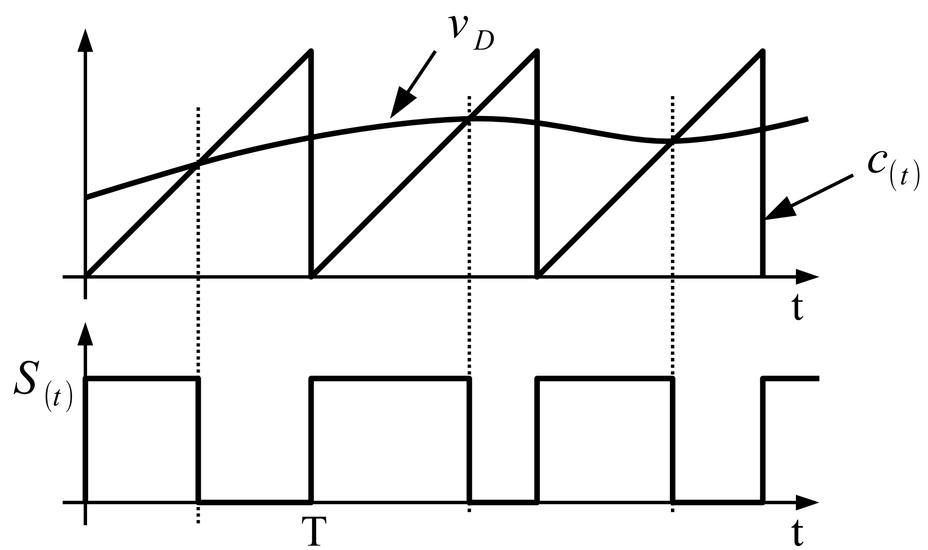
Regulation – Feed-Forward



- It is very fast. Perturbations do not have to reach the output in order to be compensated.
- It need a good model of the converter in order to design the controller.
- Usually is used together with a feedback loop.

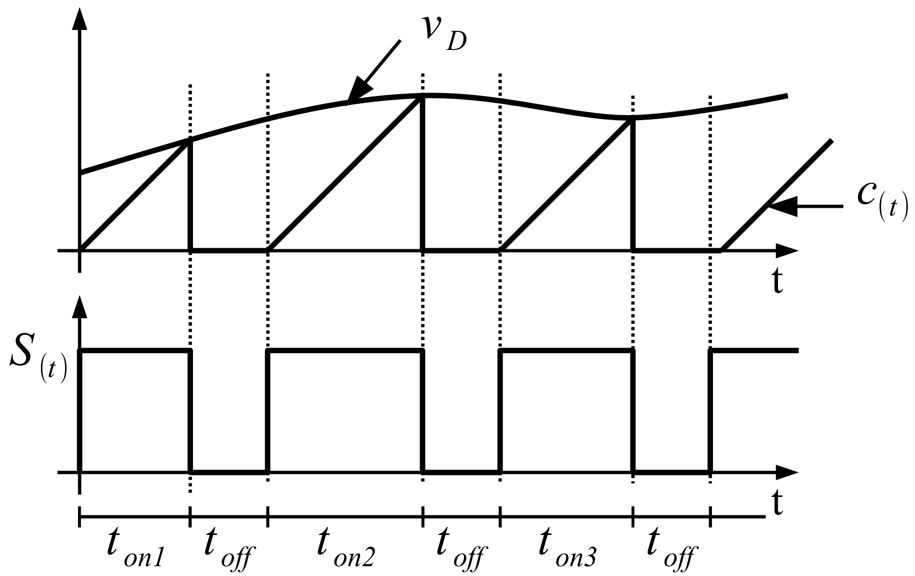
Constant Frequency PWM





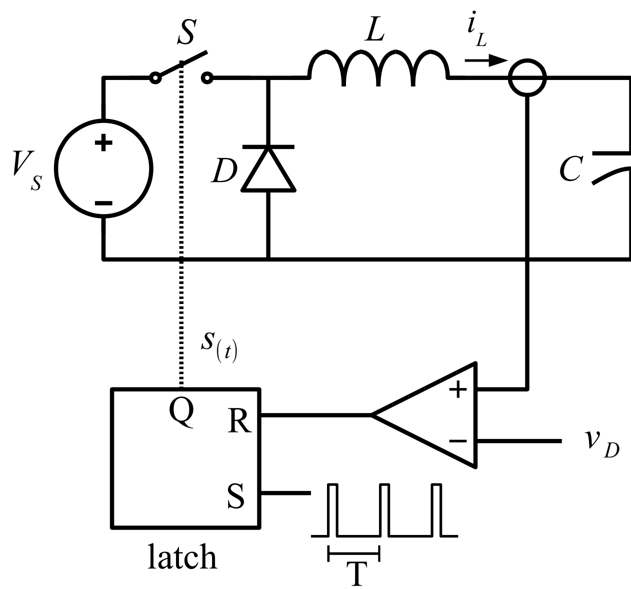
Variable Frequency PWM

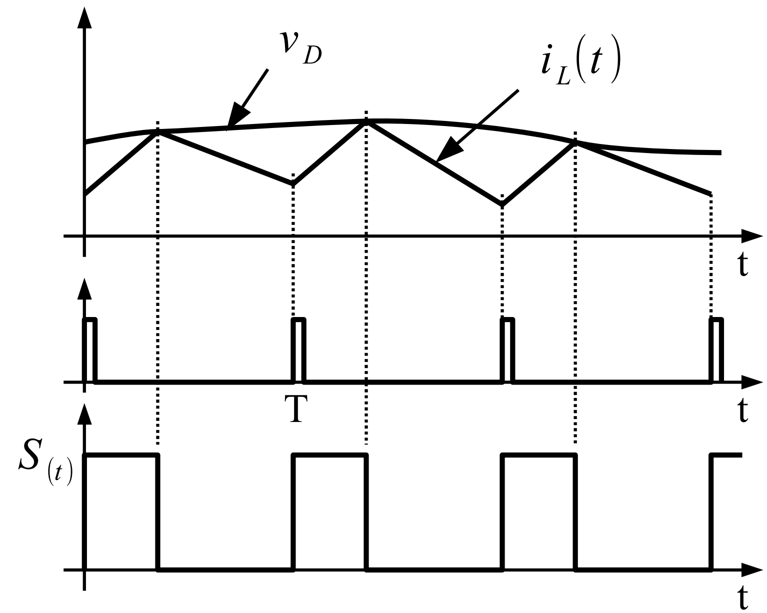
constant off-time, variable on-time



constant on-time, variable off-time

Current Mode Control (CMC)





Current Mode Control

The CMC controls the inductor current. An outer control loop is needed for output voltage regulation.

Advantages:

- Simple
- Low cost
- Easy input voltage feed-forward

Disadvantages

- Sub-harmonic oscillation for $D>0.5$. An slope compensation solves this problem.

Variable Structure Control

It is a nonlinear control which generates the switching function according to the state-space variables of the system.

Advantages:

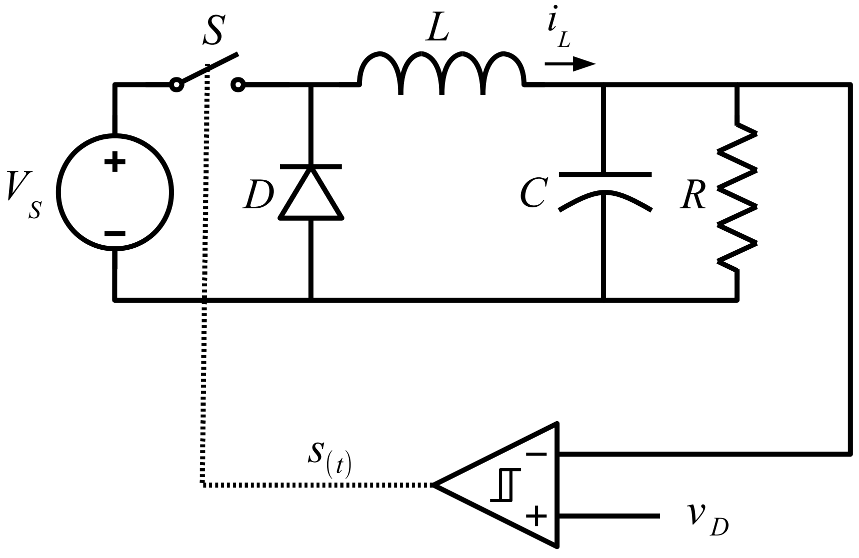
- Low sensitivity to plant parameter uncertainty
- Robustness

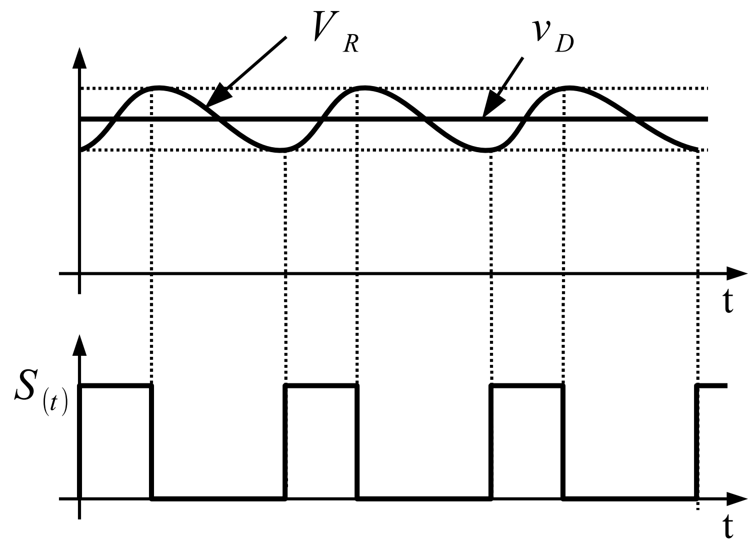
Disadvantages

- Chattering
- Variable frequency

Variable Structure Control

Hysteresis control

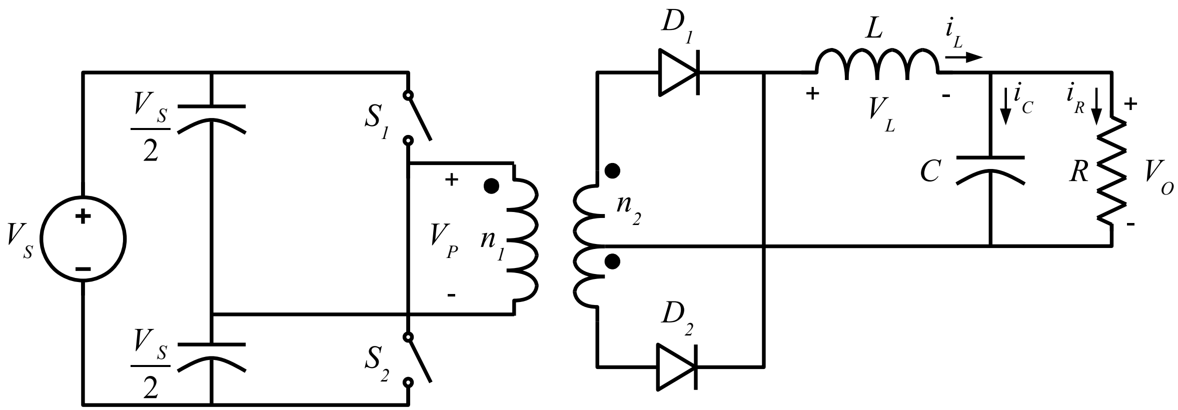




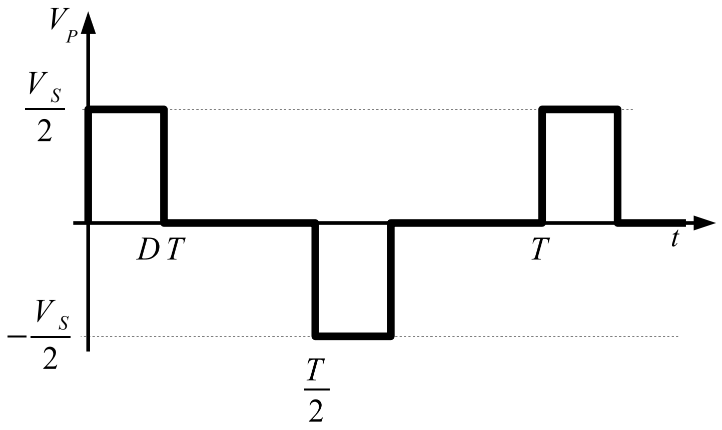
Derived Topologies

- Half Bridge Converter
- Push-Pull Converter
- Full Bridge Converter
- Forward Converter
- Flyback Converter
- Ćuk Converter

Half Bridge Converter



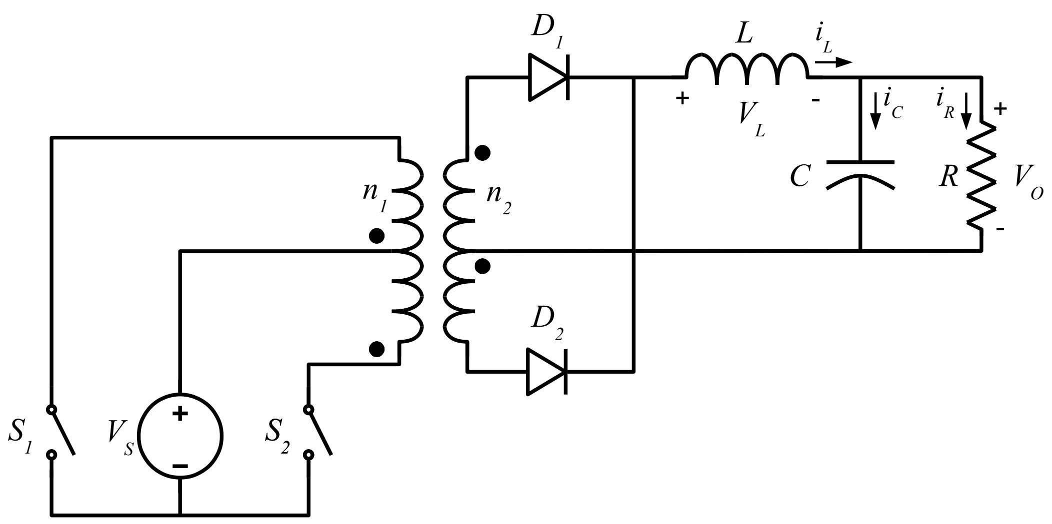
Transformer Input Waveform



- Volt-second product over a period must be zero to avoid transformer saturation

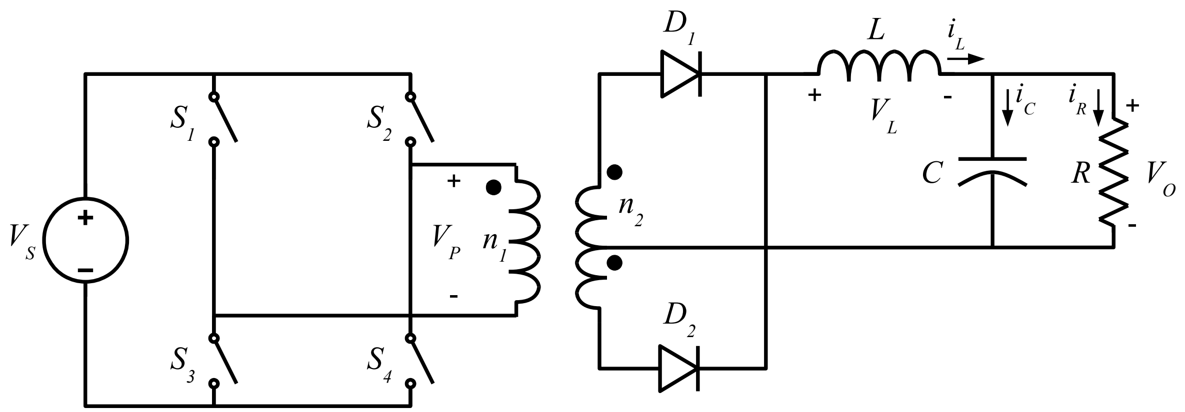
Push-Pull Converter

-



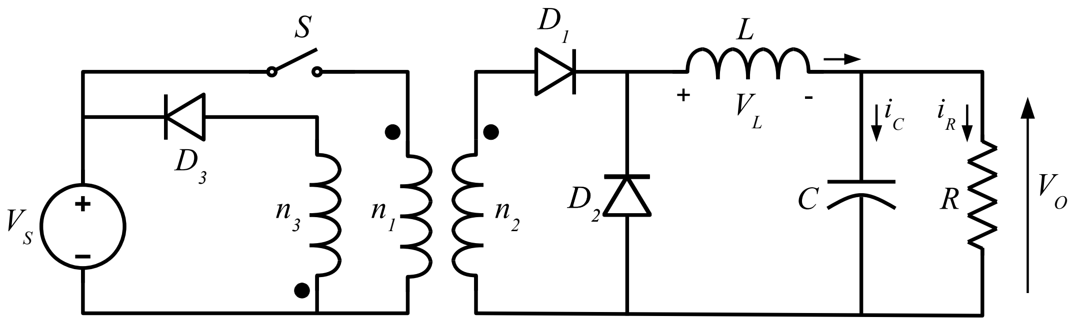
$$M_V \equiv \frac{V_O}{V_S} = 2D\frac{n_2}{n_1}$$

Full Bridge Converter



$$M_V \equiv \frac{V_O}{V_S} = 2D\frac{n_2}{n_1}$$

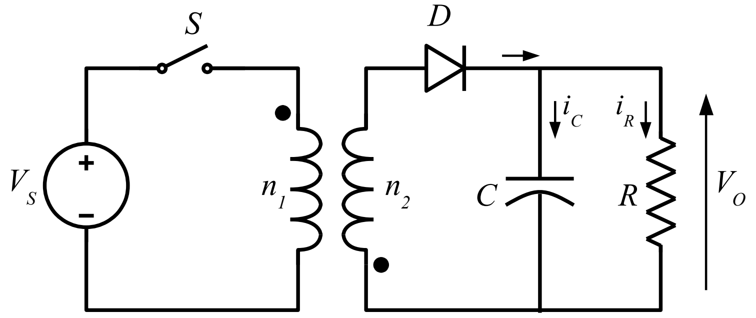
Forward Converter



$$M_V \equiv \frac{V_O}{V_S} = D\frac{n_2}{n_1}$$

$$n_1 D \leq n_3 (1 - D)$$

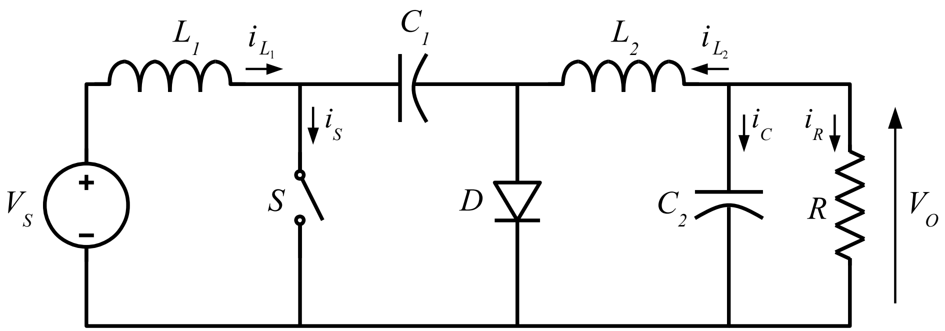
Flyback Converter



$$M_V \equiv \frac{V_O}{V_S} = \frac{n_2}{n_1}\frac{D}{1-D}$$

Derived Topologies

Ćuk Converter



$$I_{L_2} D T = I_{L_1}(1-D)T$$

$$P_{IN} = V_S I_{L_1} = -V_O I_{L_2} = P_{OUT}$$

$$M_V \equiv \frac{V_O}{V_S} = \frac{D}{(1-D)}$$

Derived Topologies

Ćuk Converter

There is also an isolated version.

The inductors can be integrated using only one magnetic core

Advantage:

- Smooth input and output current

Disadvantage:

- More components

Other Issues

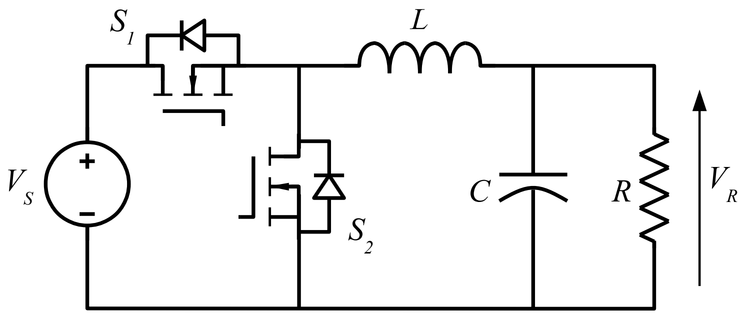
- Synchronous Rectification
- Interleaved Converters
- Hard Switching, Snubbers and Soft Switching
- DC-DC Resonant Converters
- References and Further Readings

Synchronous Rectification

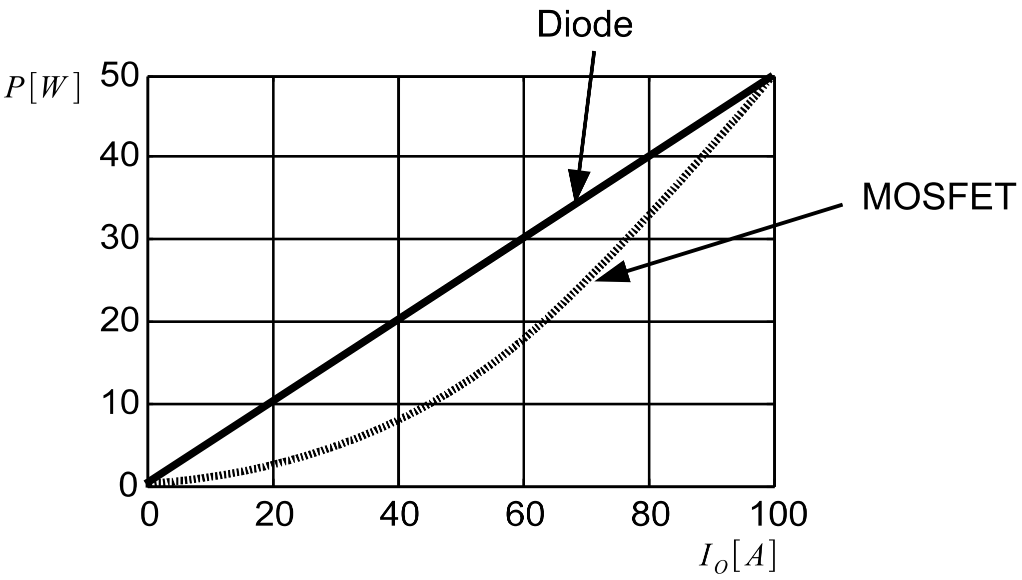
Conduction losses $P_D = V_F I_O (1-D)$ V_F = diode forward voltage drop

$$\eta = \frac{V_O I_O}{V_O I_O + V_F I_O (1-D)} = \frac{V_O}{V_O + V_F (1-D)}$$

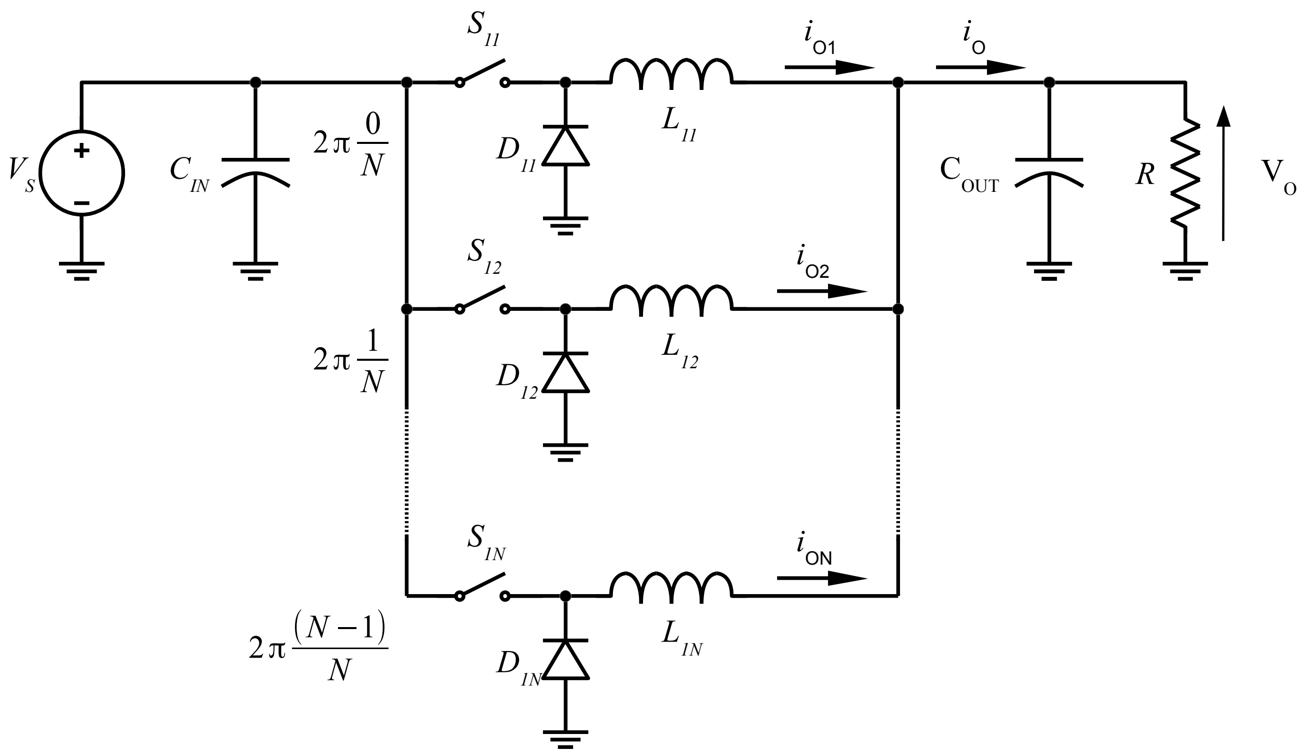
Efficiency is low for low output voltage power converters



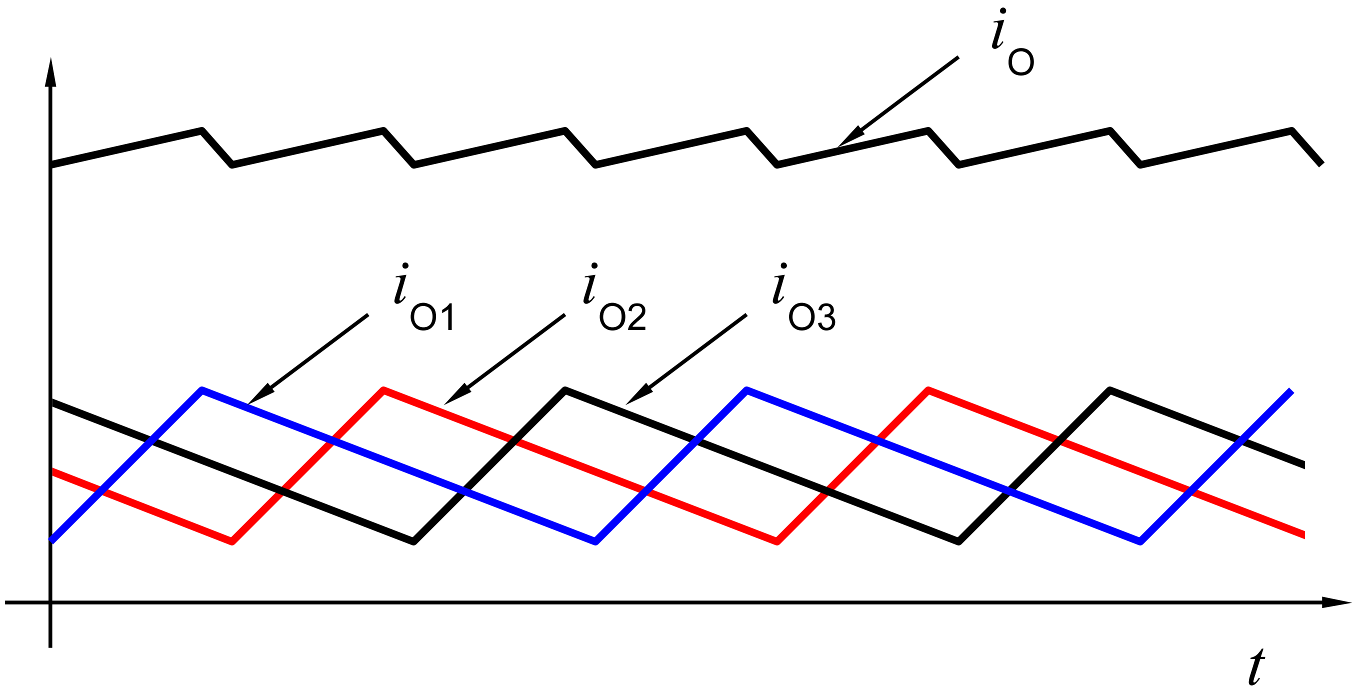
Power Losses in Diode and MOSFET



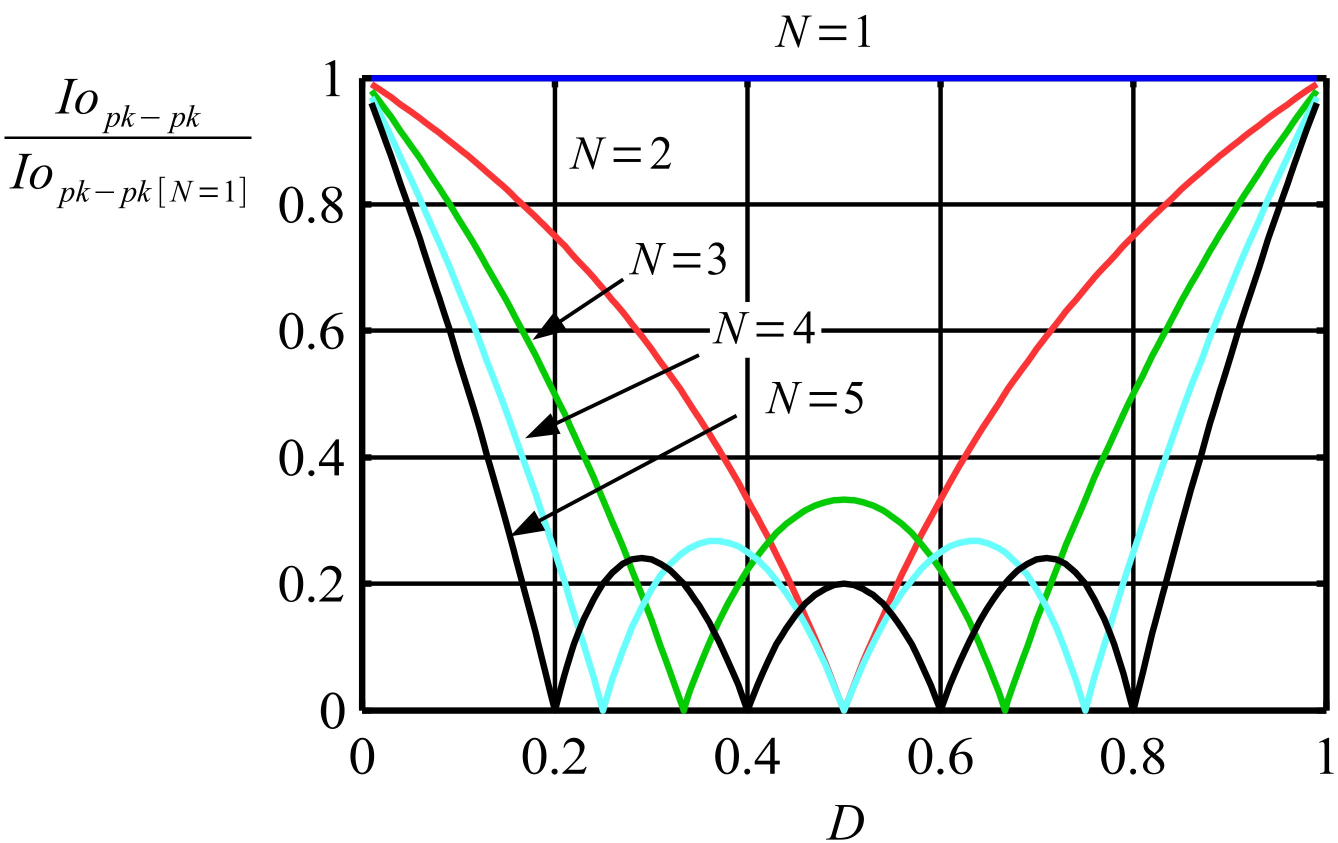
Interleaved Converters



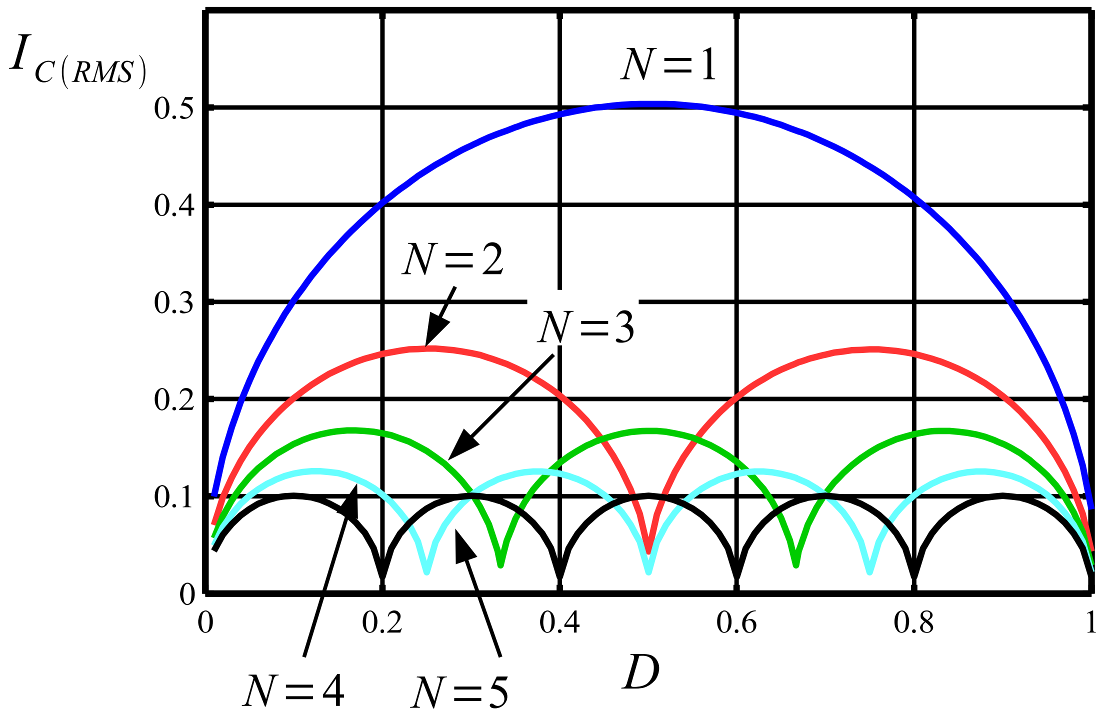
Interleaved Converters: Output Current



Normalized Output Current Ripple

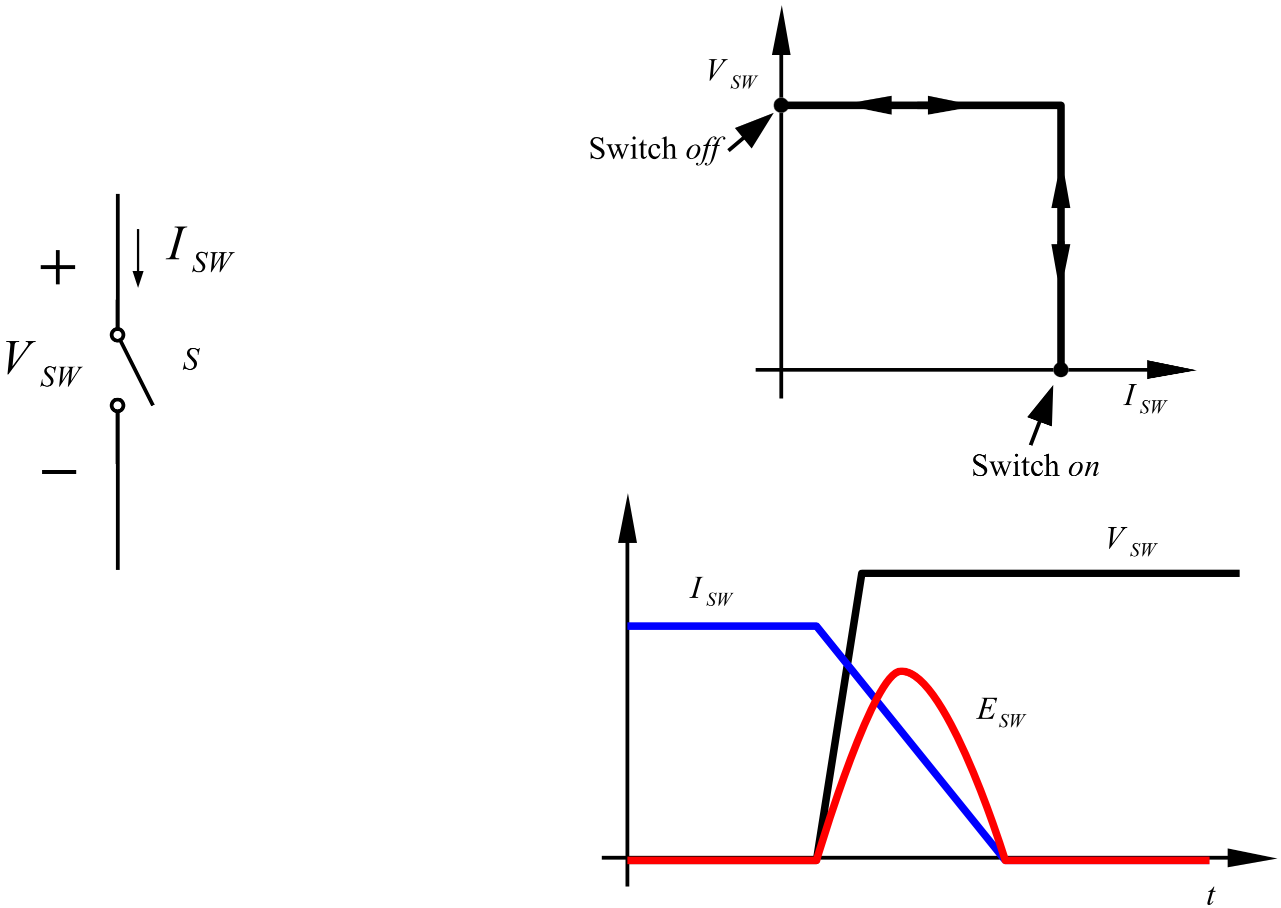


Normalized Input Capacitor RMS Current

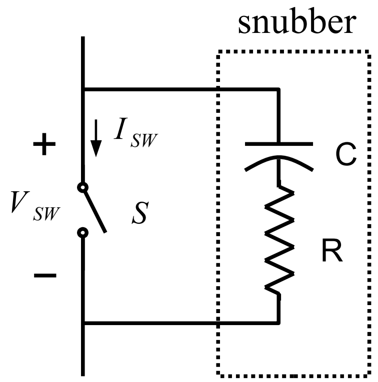


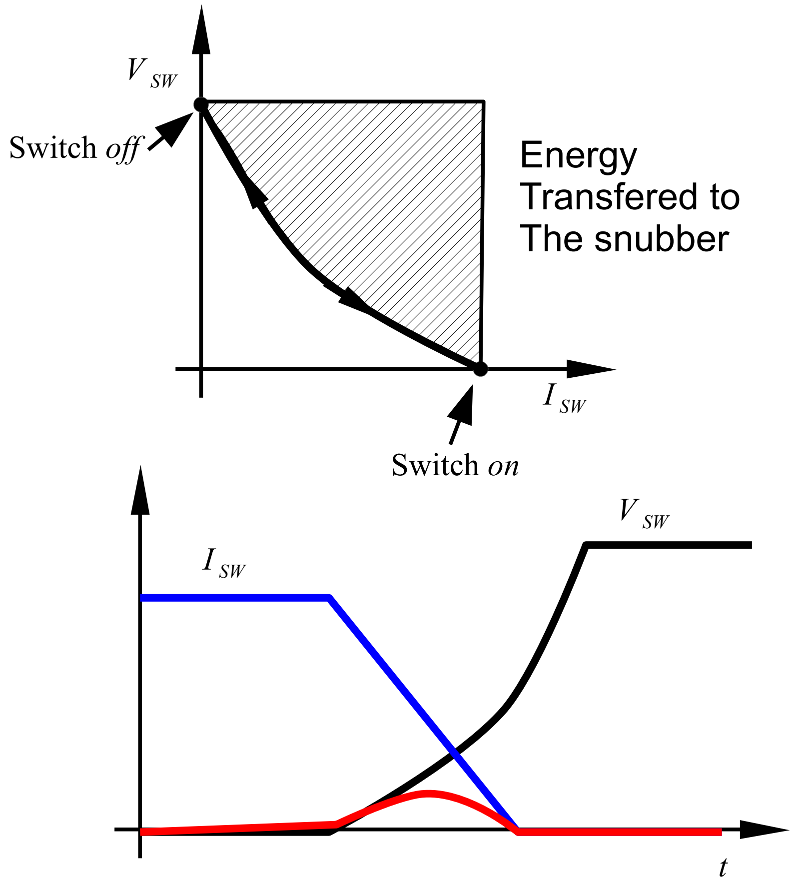
$I_O = 1\,A.$ $\Delta I_{ON} = 0.30\, I_{ON}.$

Hard Switching

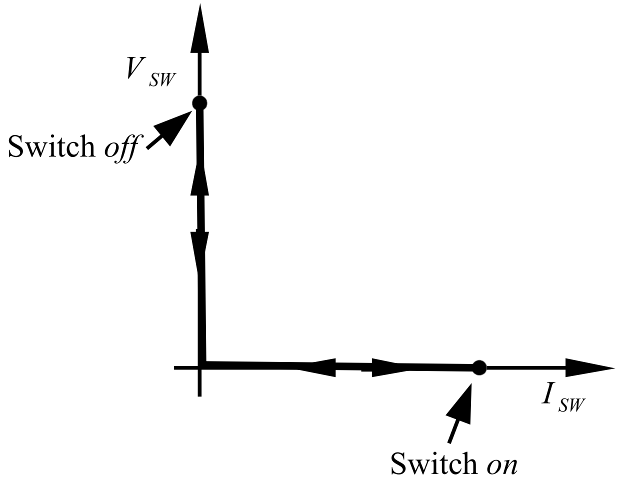


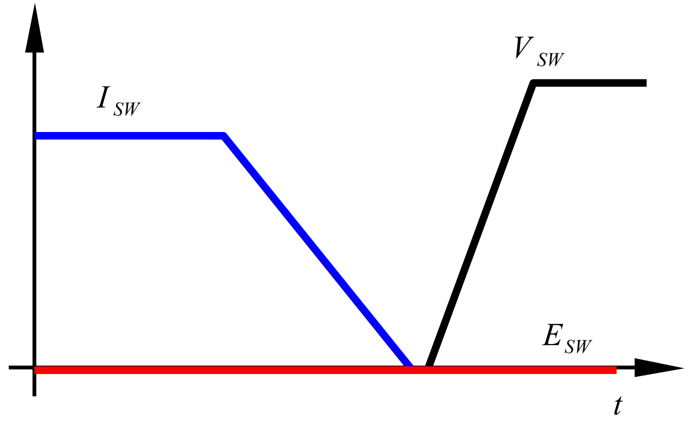
Snubbers


snubber
+
I_{SW}
V_{SW}
S
–
C
R

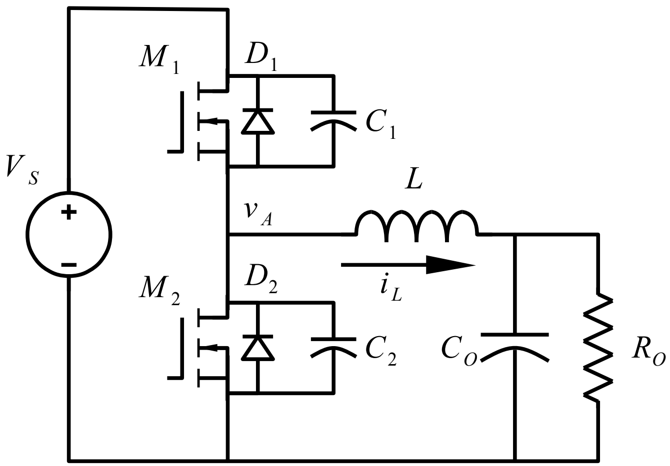

V_{SW}
Switch *off*
Energy
Transfered to
The snubber
I_{SW}
Switch *on*
V_{SW}
I_{SW}
t

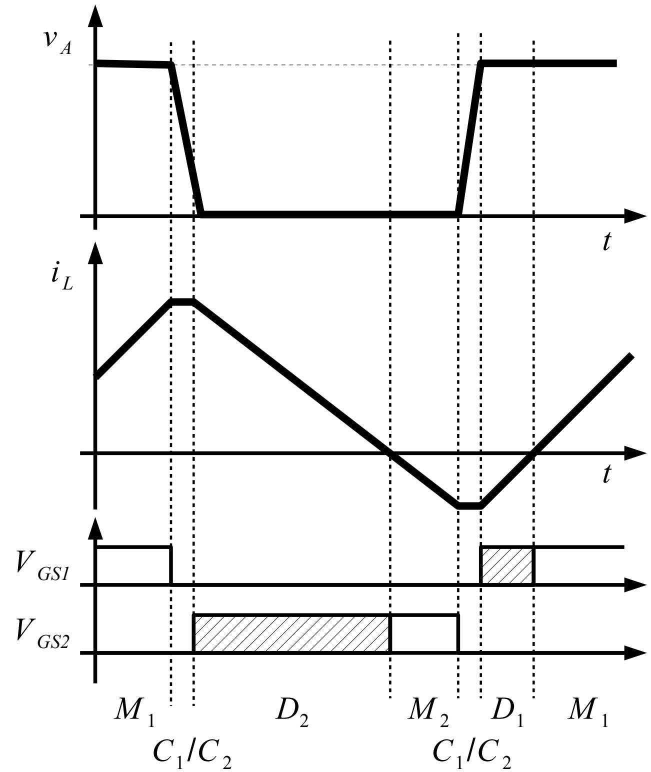
Soft Switching





Soft Switching

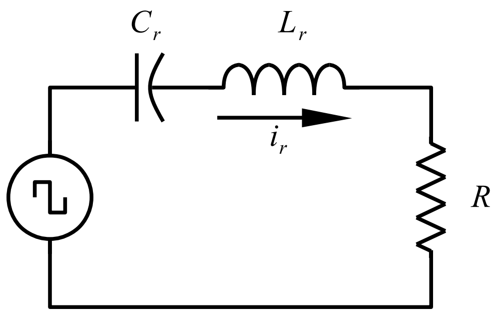




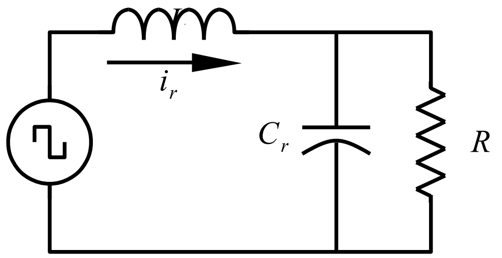
DC-DC Resonant Converters

Resonant Converters operates by applying a square voltage or current generated by switches to a a resonant circuit.

- Series resonant converter



- Parallel resonant converter

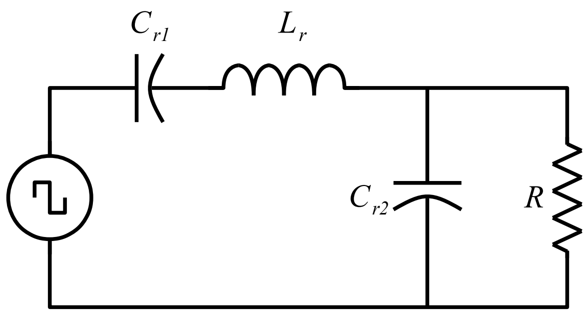


The converters operate at frequencies close to the resonant frequency.

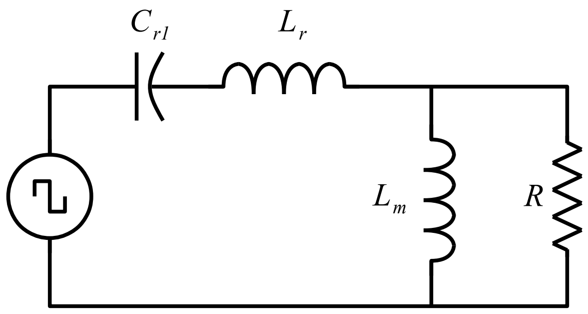
The energy transferred to the load is controlled by changing the operating frequency.

LCC and LLC Resonant Converters

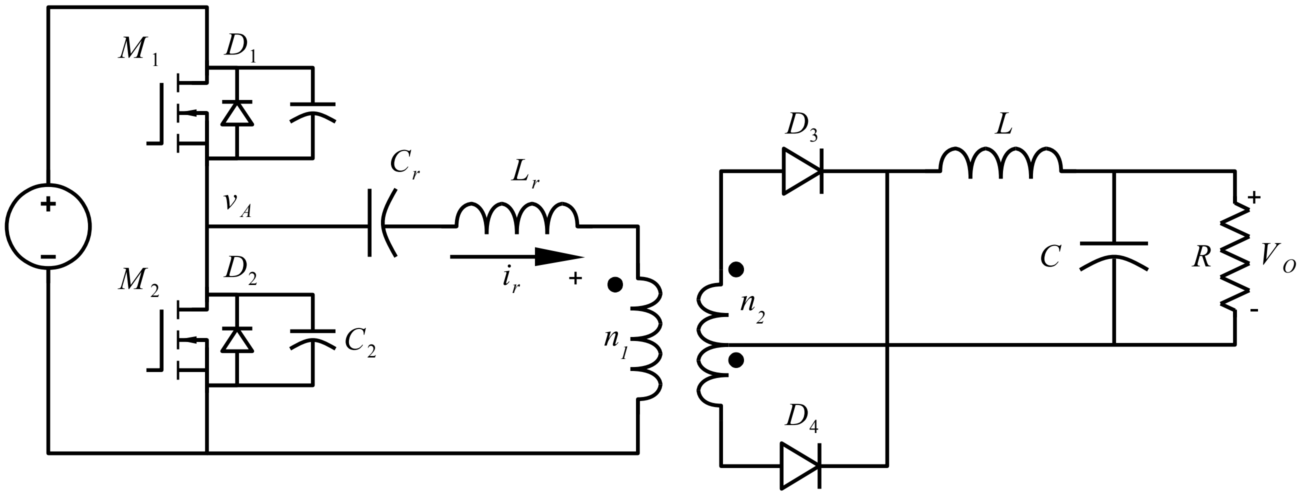
- LCC resonant converter
  - Disadvantages: two capacitors



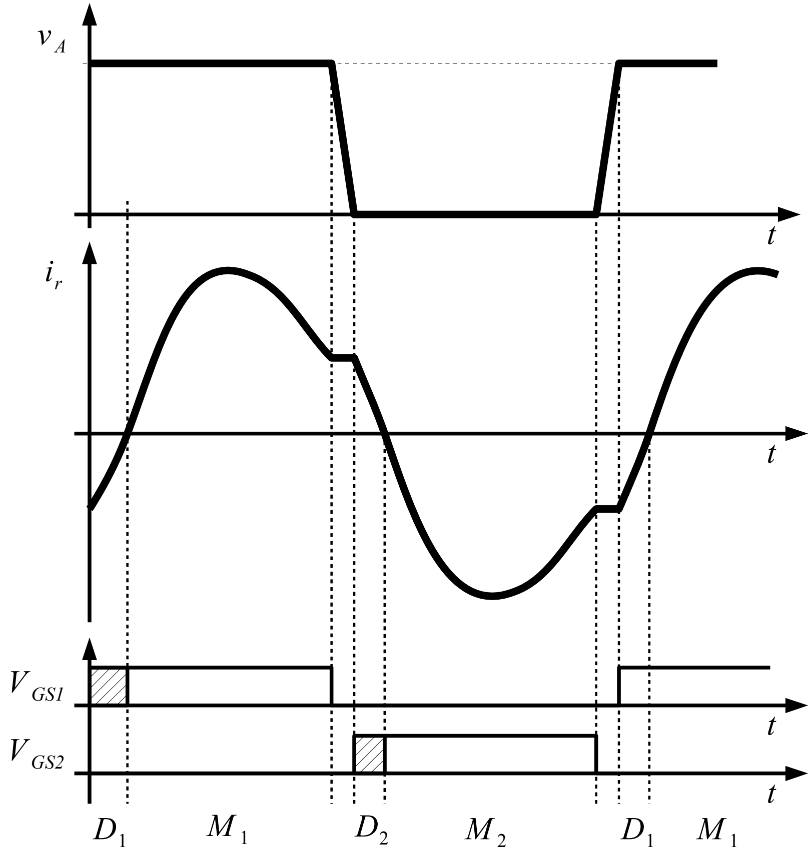
- LLC resonant converter
  - Advantage: the two inductances can be integrates into one magnetic component



LLC Resonant Converters



LLC Converter Waveforms. ZVS



DC-DC Resonant Converters

- High Efficiency – Soft switching operation
- High operating frequency – small reactive components
- High power density

- More complex control
- Stress in semiconductors (large voltages and currents)

References and Further Reading

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Thank You !