Power Electronics Education Electronic Book

Welcome to PEEEB

Lecture 5: Non-isolated DC-DC Converters

Presenter: Dr. Firuz Zare

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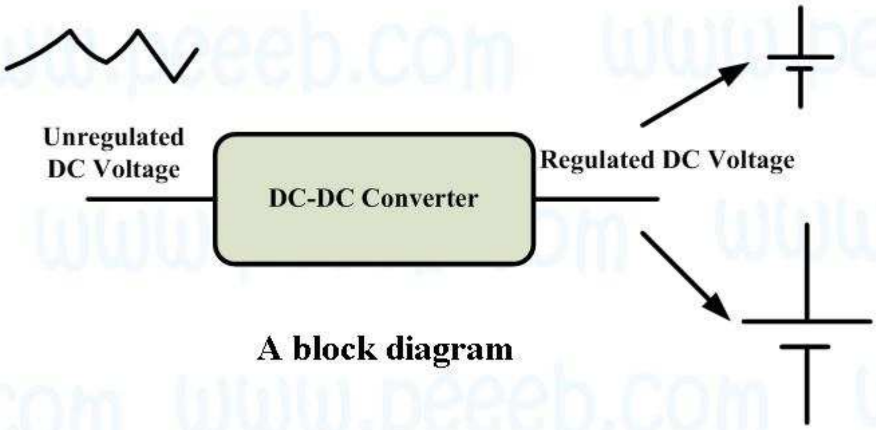
DC-DC Converters



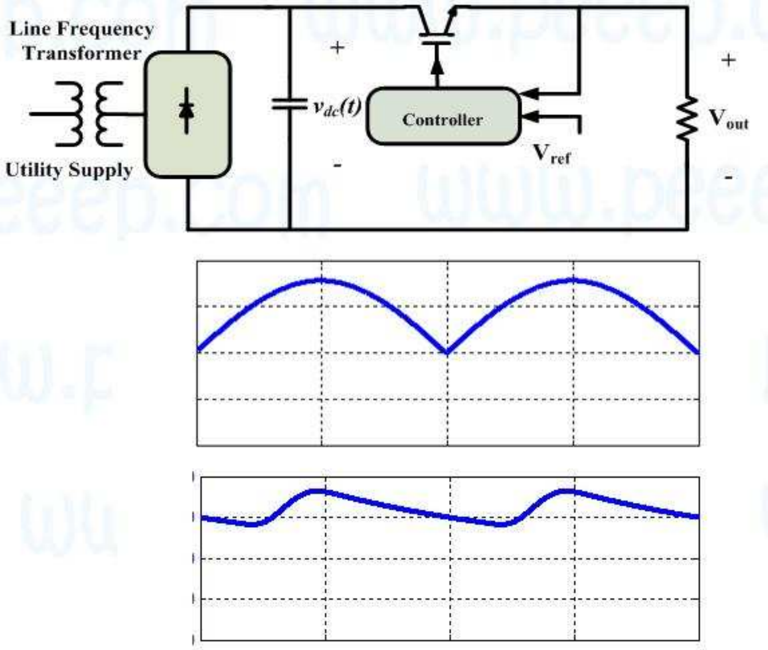
A block diagram

DC-DC Converters: Some applications

- Power Supply with Constant or Adjustable Magnitude
- DC Motor Drives
- Improving Power Factor

Low Power Linear Power Supply (Voltage Regulator)

Low efficiency
Heavy and bulky transformer



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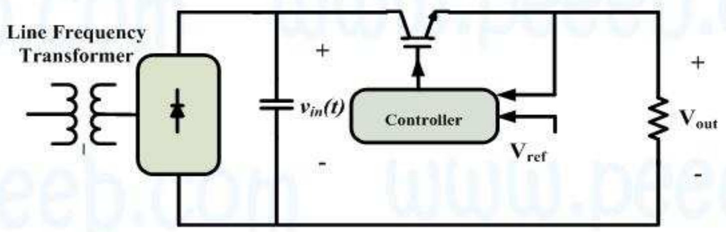
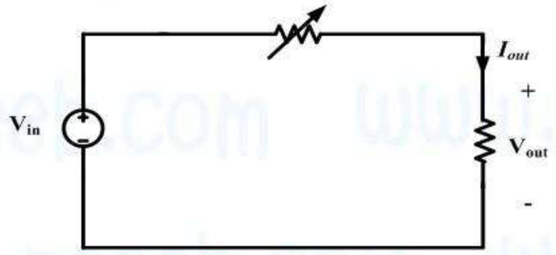
Low Power Linear Power Supply (Voltage Regulator)

Low efficiency
Heavy and bulky transformer





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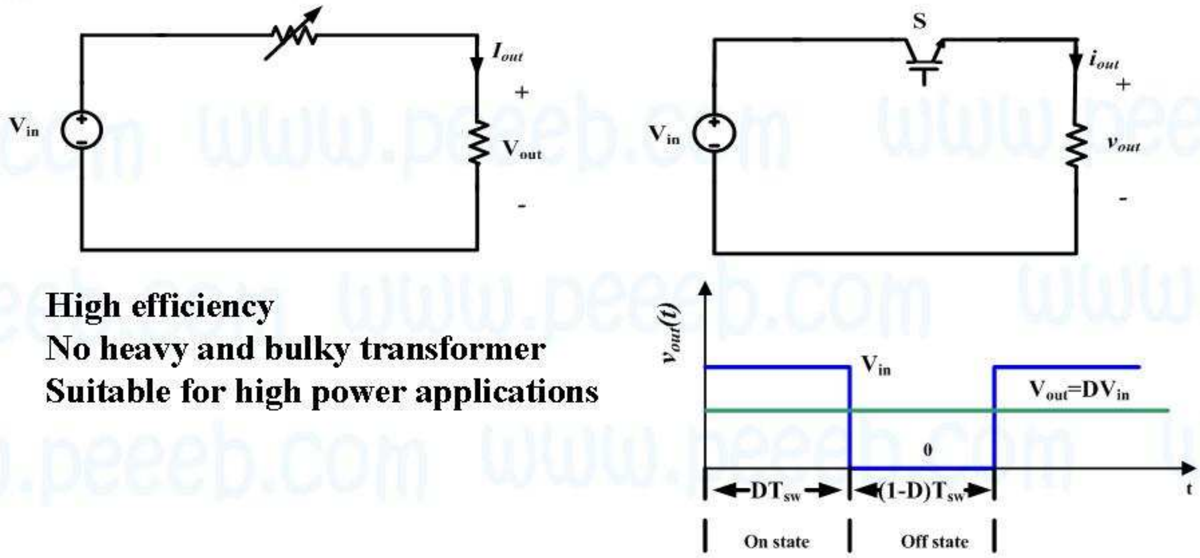
Power Supply: Linear ⇔ Switched Mode



High efficiency
No heavy and bulky transformer
Suitable for high power applications

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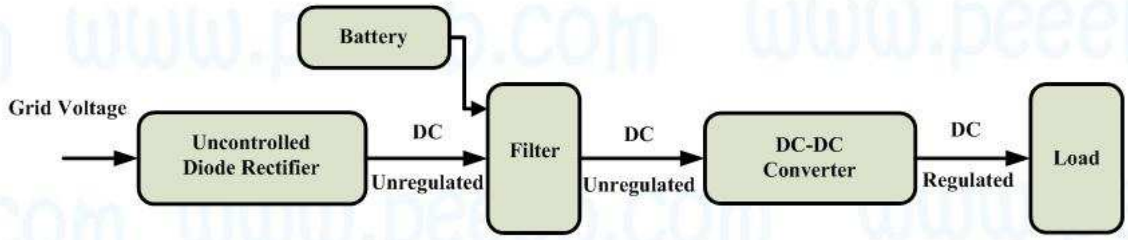
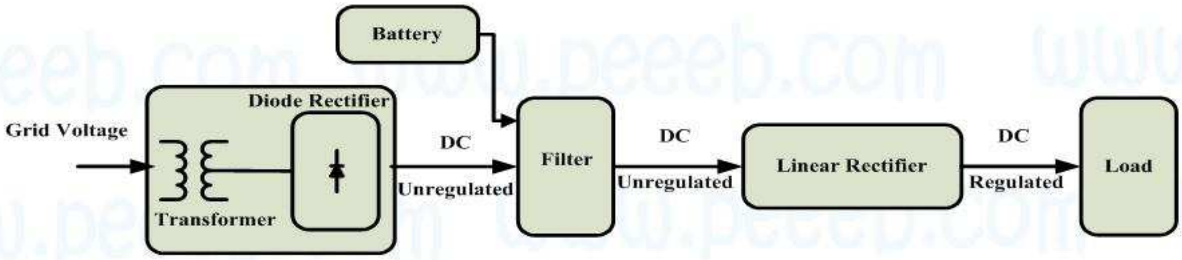
Power Supply: Linear ⇔ Switched Mode



A Switched Mode Power Supply with AC-DC and DC-DC Converters



A Linear Mode Power Supply with AC-DC Converter and Transformer

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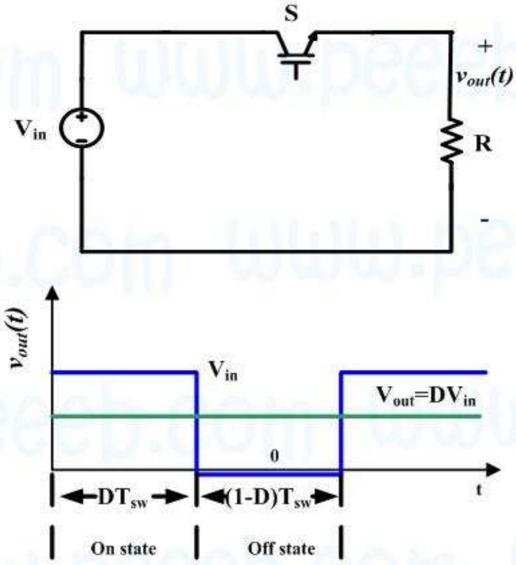
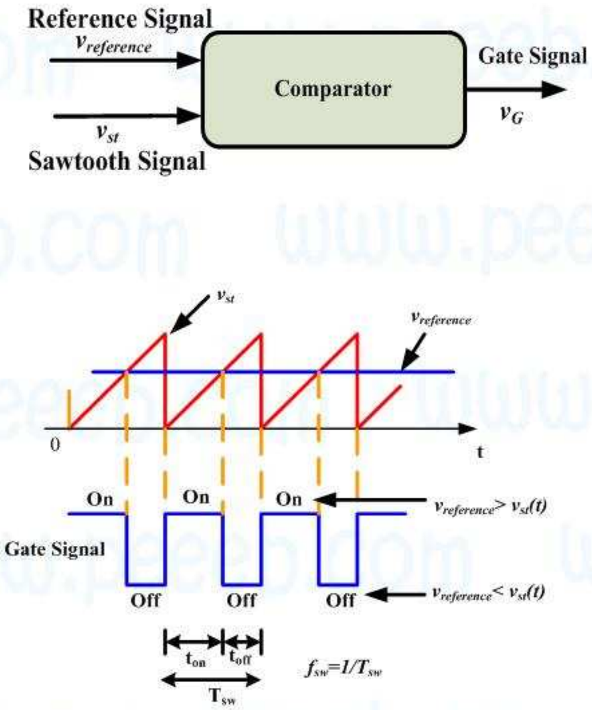
Pulse Width Modulator and Control





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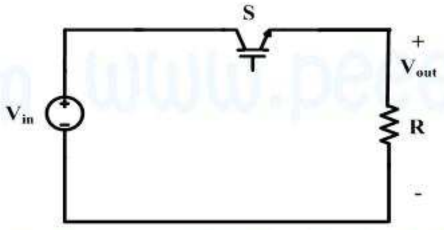
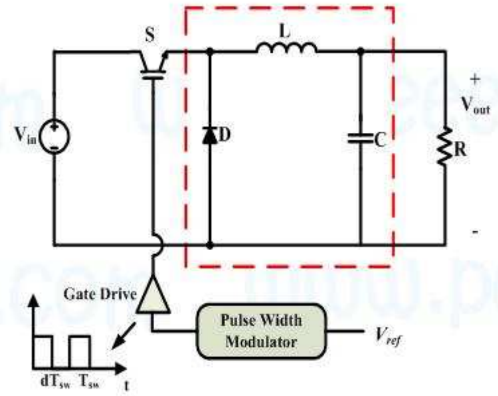
High Frequency Filter





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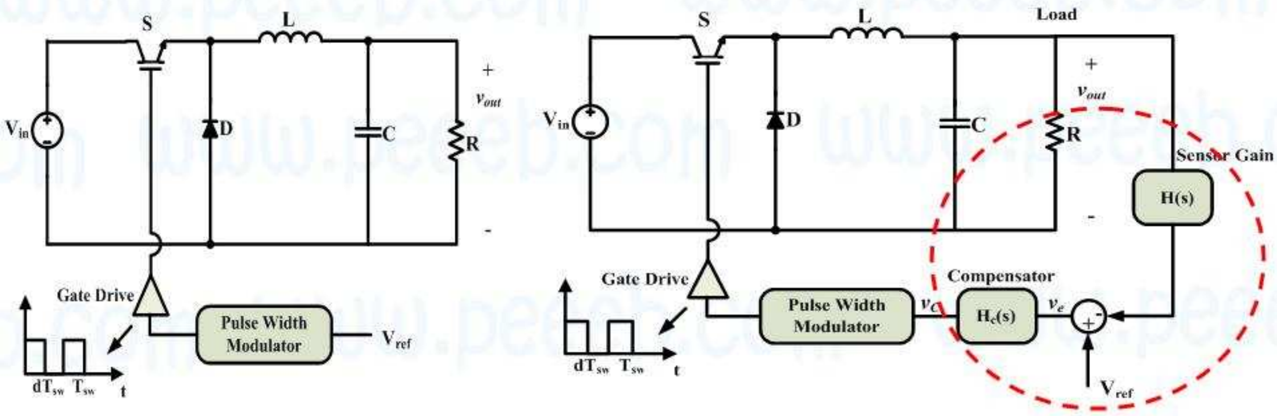
Control System: Open Loop or Close Loop



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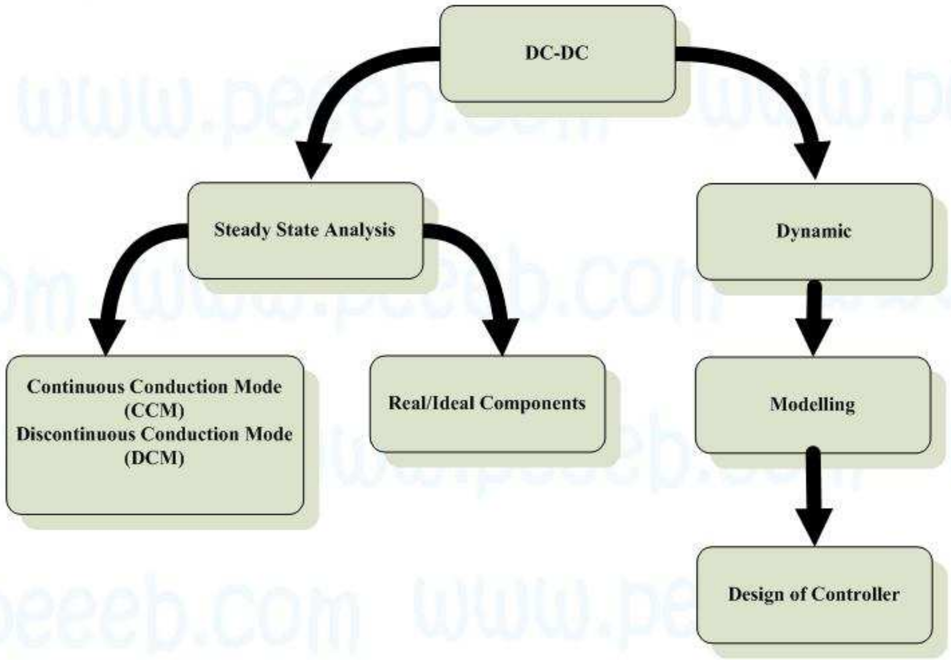
Steady State or Transient Analysis



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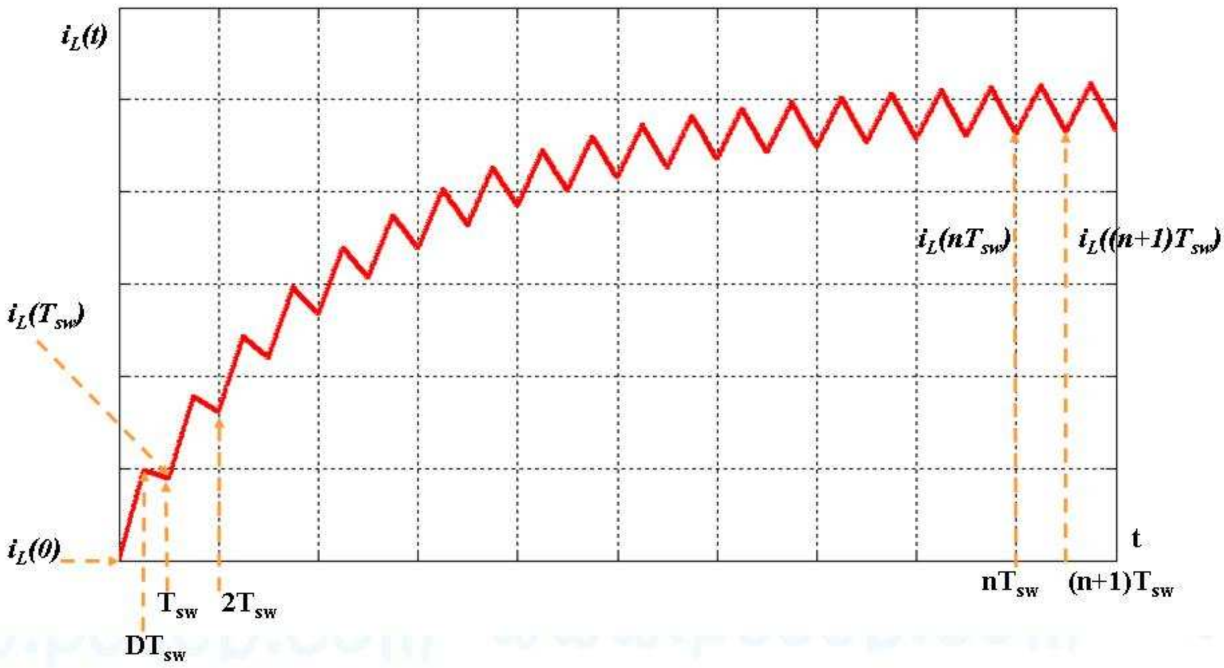
Steady State or Transient Analysis



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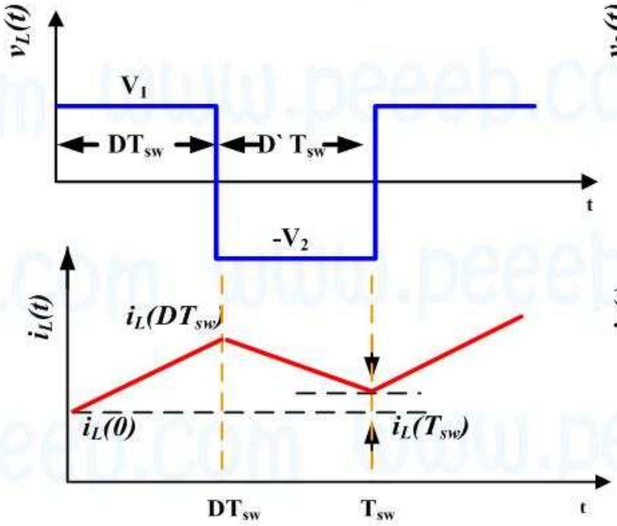
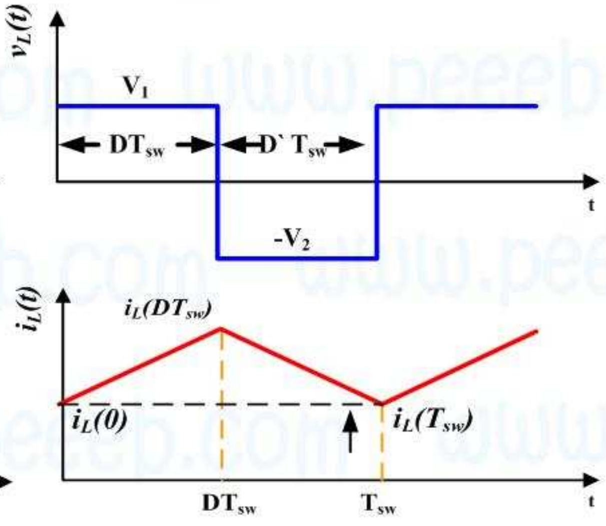
Key Rules in DC-DC Converters to Extract Steady State and Dynamic Equations





$$\overline{v_L(t)} = \frac{1}{T_{sw}}\int_0^{T_{sw}} v_L(t)\,dt \neq 0$$

$$\overline{v_L(t)} = \frac{1}{T_{sw}}\int_0^{T_{sw}} v_L(t)\,dt = 0$$

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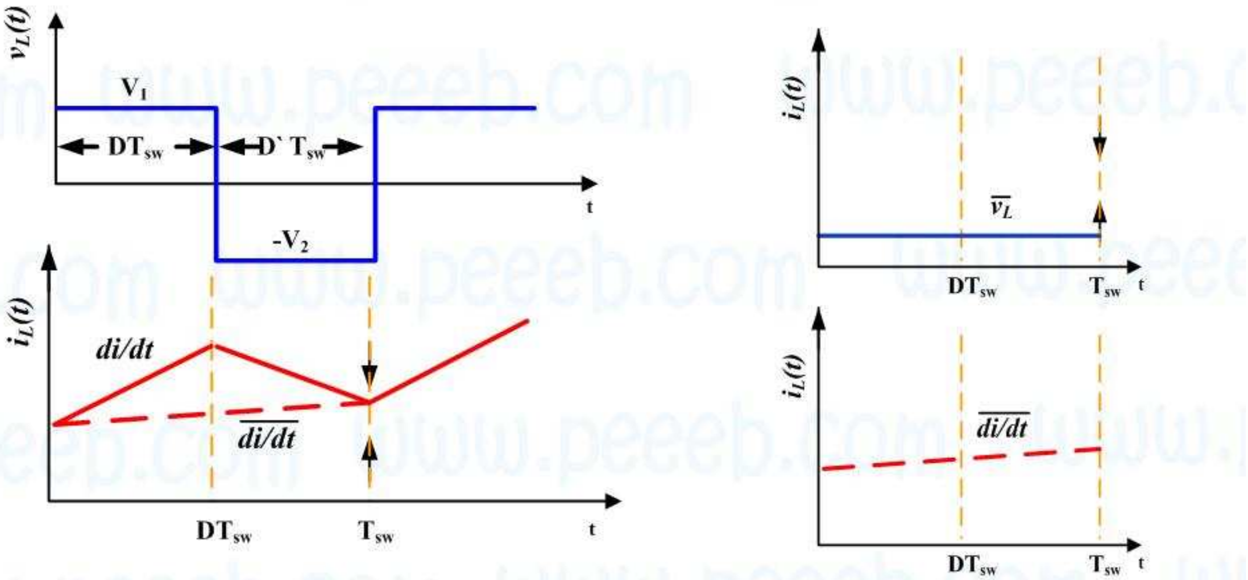
Key Rules in DC-DC Converters to Extract Steady State and Dynamic Equations



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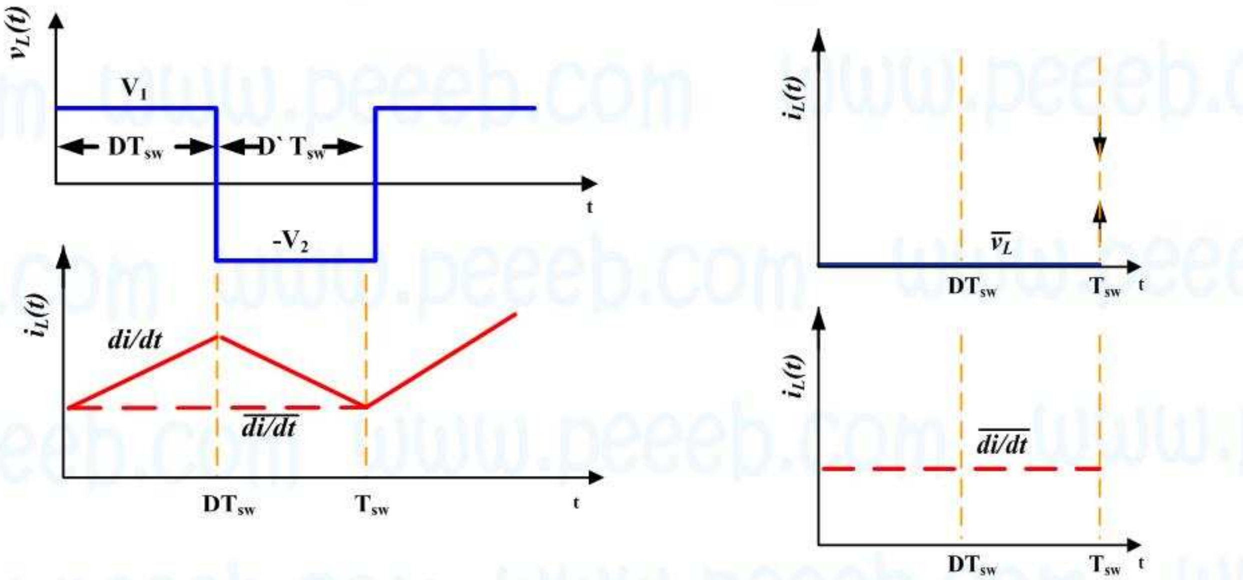
Key Rules in DC-DC Converters to Extract Steady State and Dynamic Equations



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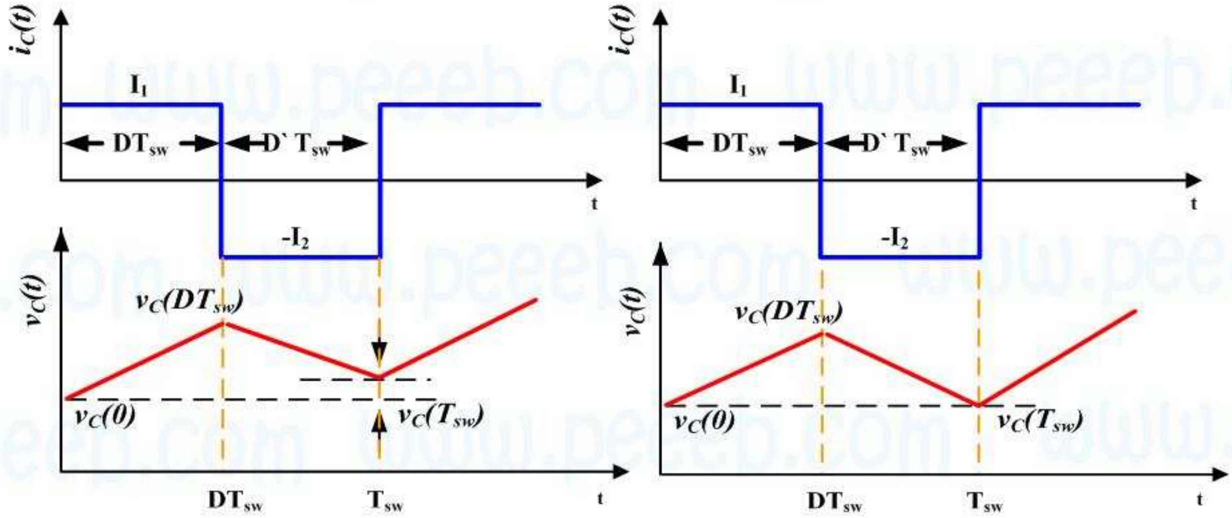
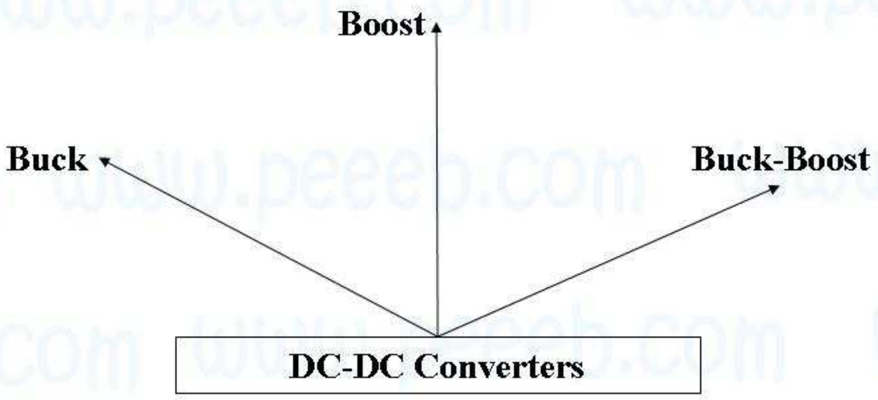
Key Rules in DC-DC Converters to Extract Steady State and Dynamic Equations



Three Different DC-DC Converters



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Buck Converter

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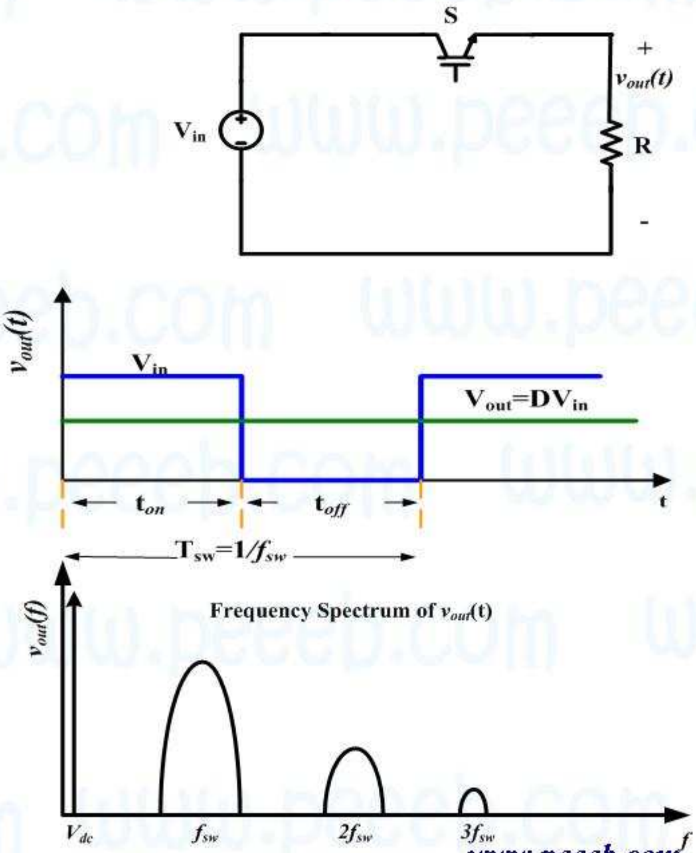

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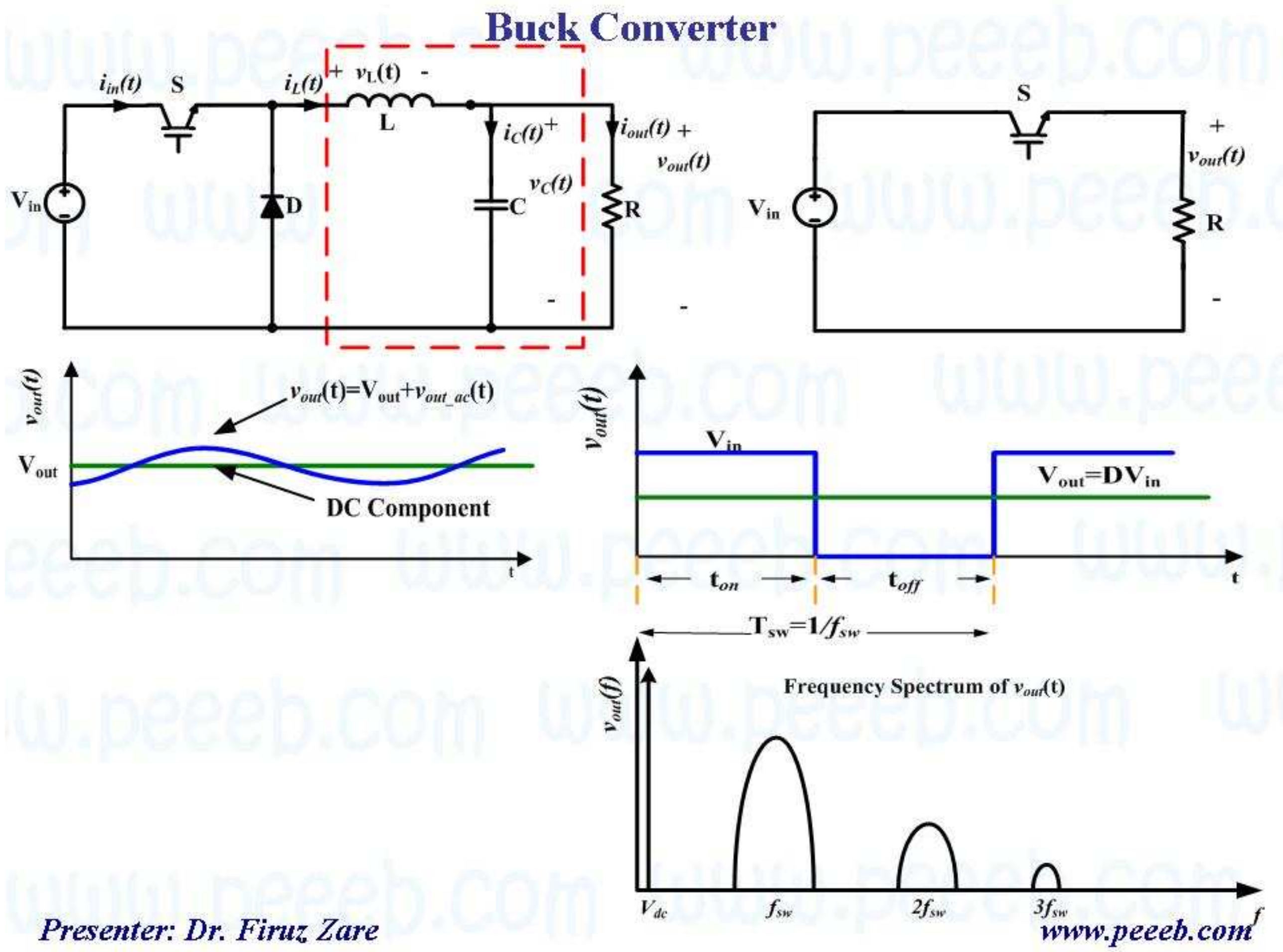

Buck Converter
$i_{in}(t)$
S
$i_L(t)$
+ $v_L(t)$ -
L
$i_C(t)$ +
$i_{out}(t)$ +
$v_{out}(t)$
$v_C(t)$
V_{in}
D
C
R
-
-
S
+
$v_{out}(t)$
V_{in}
R
-
$v_{out}(t)$
$v_{out}(t)=V_{out}+v_{out\_ac}(t)$
V_{out}
DC Component
t
$v_{out}(t)$
V_{in}
$V_{out}=DV_{in}$
t_{on}
t_{off}
t
$T_{sw}=1/f_{sw}$
$v_{out}(f)$
Frequency Spectrum of $v_{out}(t)$
V_{dc}
f_{sw}
$2f_{sw}$
$3f_{sw}$
f
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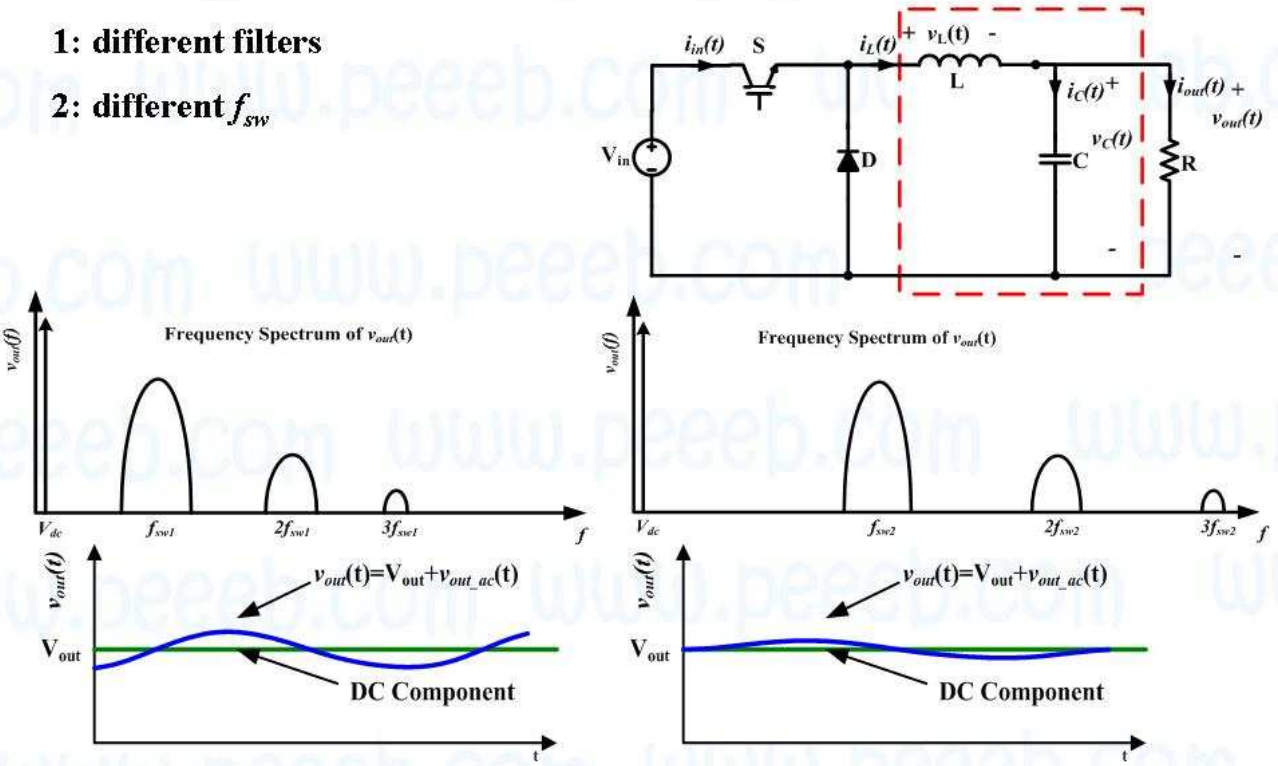
Effects of f_{sw} and filter size on output voltage ripple!

1: different filters

2: different f_{sw}



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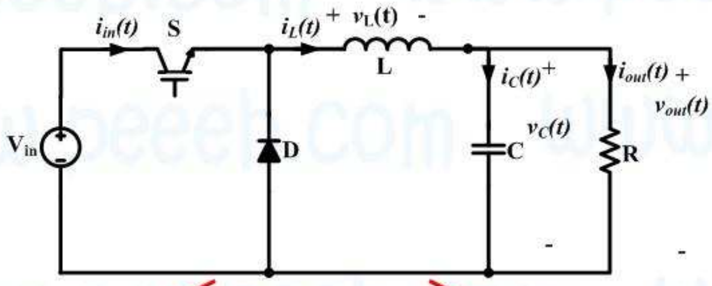
It is clear that by increasing the switching frequency, the output voltage ripple or filter size is decreased.

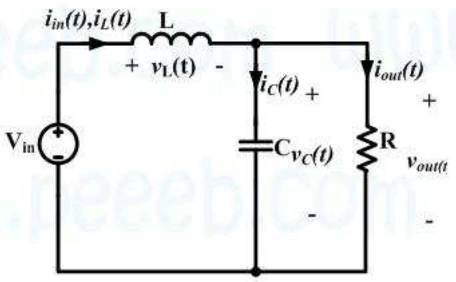
A larger LC filter can reduce the output voltage ripple magnitude but the size, cost and weight of system are increased.

Thus different applications have different requirements which almost define the system performance and cost!

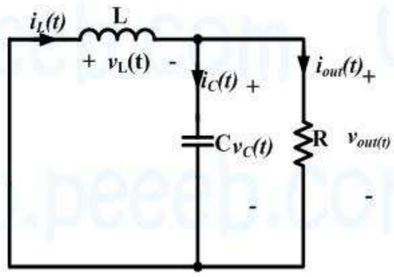
Buck Converter



When the switch is turned on, V_{in} appears across the diode and it makes if off.



When the switch is turned off, due to inductor current, the diode conducts.



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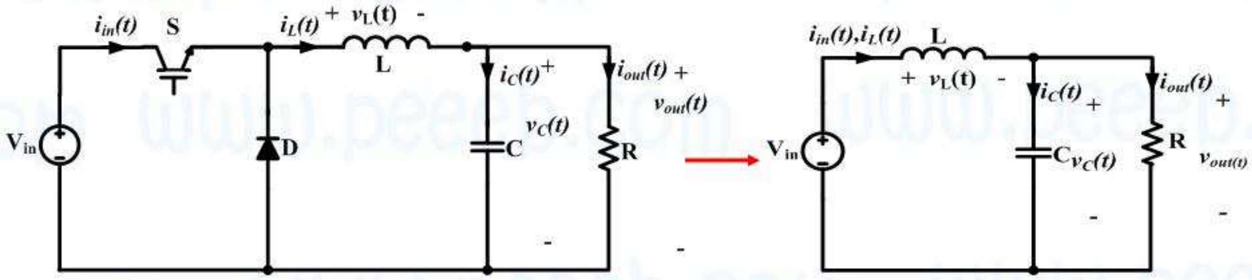

When the switch is turned on for t_{on}. $0 < t < t_{on}$

$$v_L(t) = V_{in} - v_{out}(t)$$

$$i_C(t) = i_L(t) - i_{out}(t)$$

$$\begin{cases} v_L(t) = V_{in} - V_{out} \\ i_C(t) = i_L(t) - I_{out} \end{cases}$$

Duty cycle (D) is defined as: $D = \dfrac{t_{on}}{T_{sw}}$

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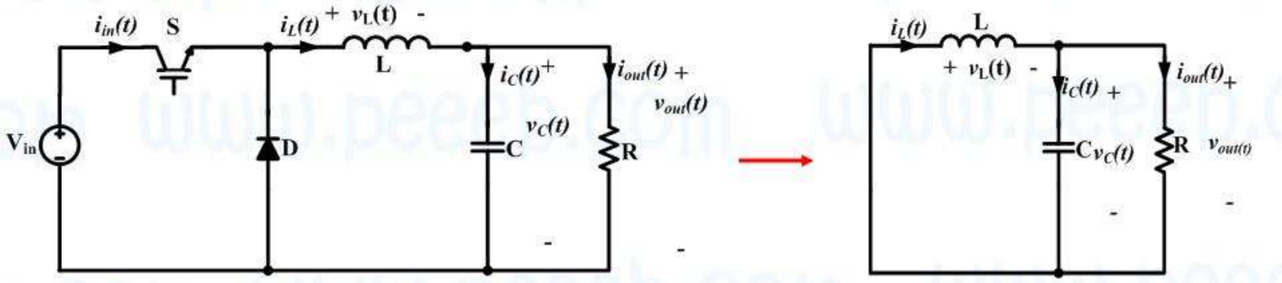
Buck Converter



When the switch is turned off for the rest of cycle, T_{sw}-t_{on}. $t_{on} < t < T_{sw}$

$$v_L(t) = -v_{out}(t)$$

$$i_C(t) = i_L(t) - i_{out}(t)$$

$$\begin{cases} v_L(t) = -V_{out} \\ i_C(t) = i_L(t) - I_{out} \end{cases}$$

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Steady State Equations

$$v_L(t) = \begin{cases} V_{in} - V_{out} & 0 < t < t_{on} \\ -V_{out} & t_{on} < t < T_{sw} \end{cases}$$

$$i_C(t) = i_L(t) - i_{out}(t) \qquad 0 < t < T_{sw}$$

$$\overline{v_L(t)} = 0 \qquad \frac{1}{T_{sw}} \int_0^{T_{sw}} v_L(t)\,dt = 0$$

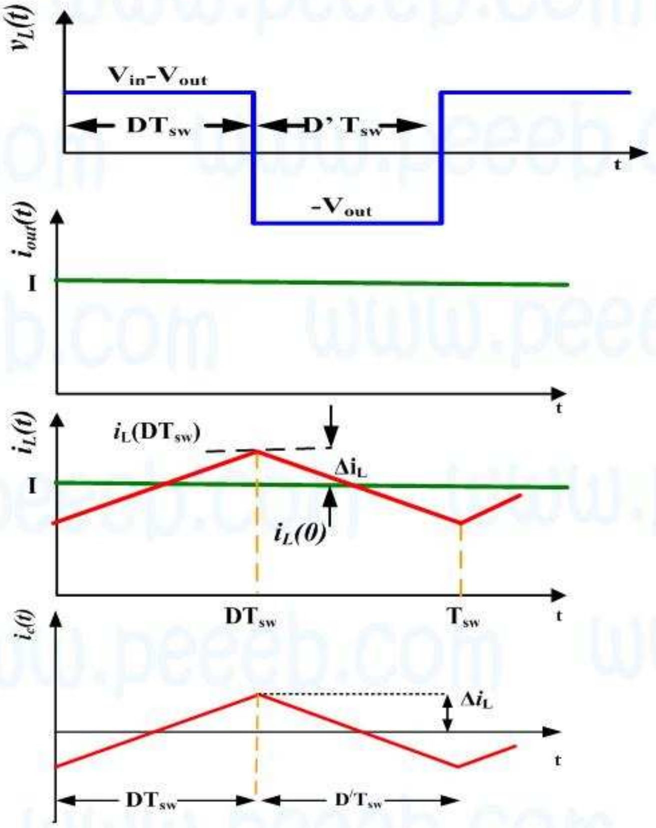
$$\int_0^{DT_{sw}} (V_{in} - V_{out})\,dt + \int_{DT_{sw}}^{T_{sw}} -V_{out}\,dt = 0$$

$$(V_{in} - V_{out})DT_{sw} + (-V_{out})(T_{sw} - DT_{sw}) = 0$$

$$V_{in}D - V_{out}(D + 1 - D) = 0$$

$$V_{in}D - V_{out} = 0$$

$$H(D) = \frac{V_{out}}{V_{in}} = D$$



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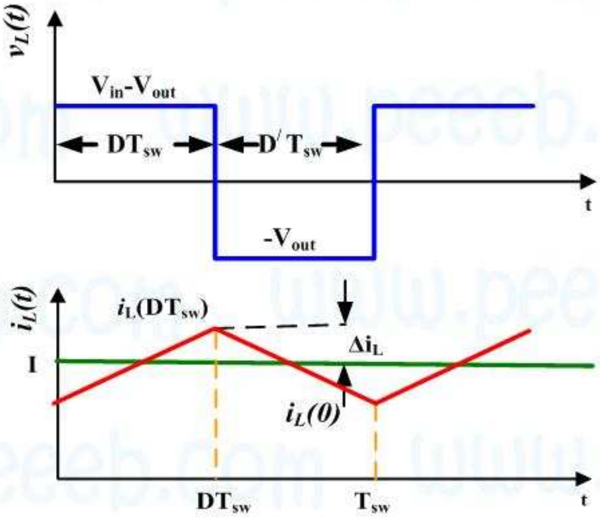
Buck Converter

How to select L and C sizes?

Once we select the switching frequency based on other design issues such as switching losses and EMI. Then we can find the inductor and capacitor values.



Buck Converter

How to select L and C sizes?

$$v_L(t) = L\frac{di_L(t)}{dt}$$

$$di_L(t) = \frac{v_L(t)dt}{L}$$

$$\int_0^t di_L(t)dt = \frac{1}{L}\int_0^t v_L(t)dt$$

$$\int_0^{DT_{sw}} di_L(t) = \frac{1}{L}\int_0^{DT_{sw}} v_L(t)dt$$

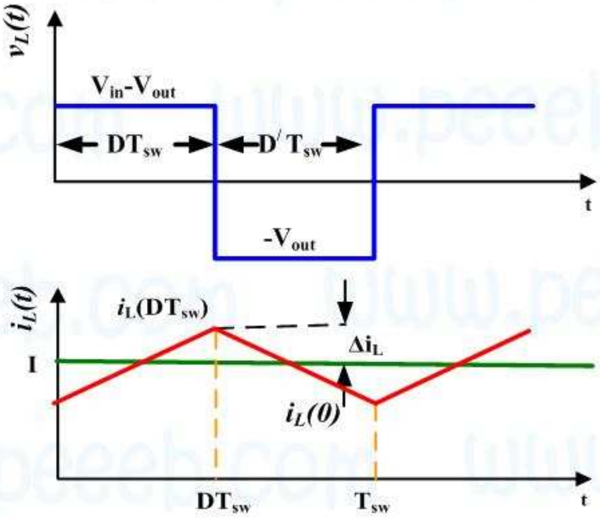
$$i_L(DT_{sw}) - i_L(0) = \frac{(V_{in} - V_{out})DT_{sw}}{L}$$

$$2\Delta i_L = \frac{DT_{sw}(V_{in} - V_{out})}{L} \qquad T_{sw} = \frac{1}{f_{sw}}$$

$$\Delta i_L = \frac{D(V_{in} - V_{out})}{2Lf_{sw}}$$

$$\Delta i_L = \frac{D(V_{in} - V_{out})}{2Lf_{sw}} = \frac{DD'V_{in}}{2Lf_{sw}}$$

$$L = \frac{DD'V_{in}}{2f_{sw}\Delta i_L}$$



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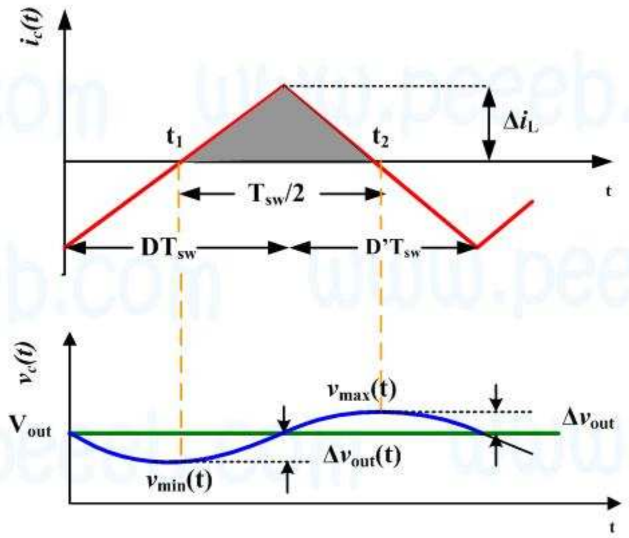
Buck Converter

How to select L and C sizes?

When $i_C(t)$ is positive, the capacitor voltage $v_C(t)$ is charged.



$$C\frac{dv_C(t)}{dt} = i_C(t)$$

$$dv_C(t) = \frac{i_C(t)dt}{C}$$

$$\int_{t_1}^{t_2} dv_C(t)dt = \frac{1}{C}\int_{t_1}^{t_2} i_C(t)dt$$

$$2\Delta v_C(t) = \frac{1}{C}\left(\frac{\Delta i_L}{2}\frac{T_{sw}}{2}\right)$$

$$\Delta v_C(t) = \frac{\Delta i_L}{8Cf_{sw}}$$

$$C = \frac{\Delta i_L}{8\Delta v_C f_{sw}}$$

$$C = \frac{DD'V_{in}}{16Lf_{sw}{}^2\Delta v_C}$$

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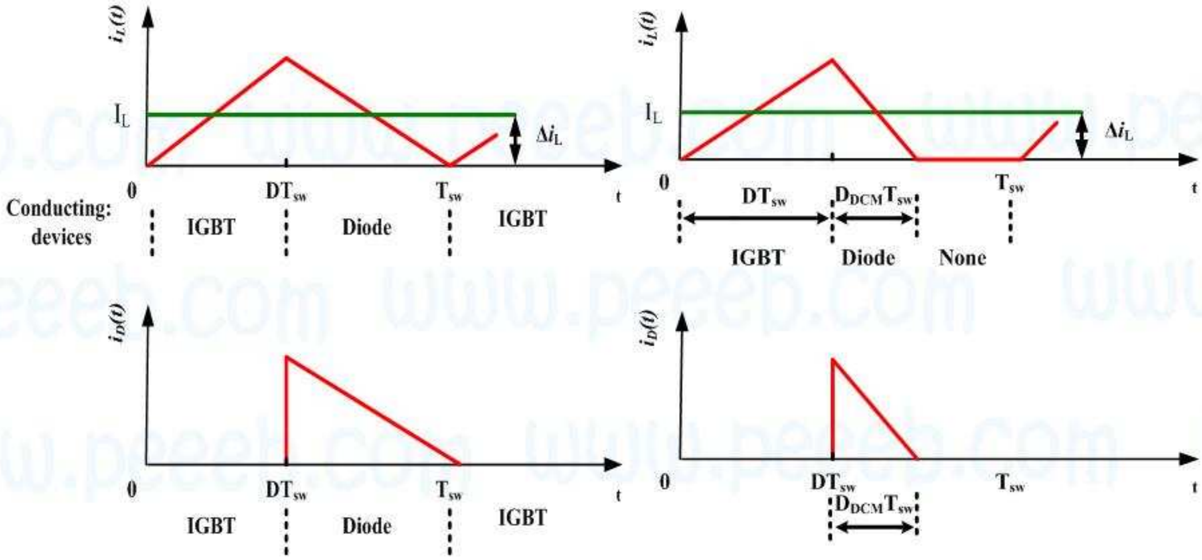
Buck Converter

Continues and Discontinues Conduction Modes
CCM & DCM



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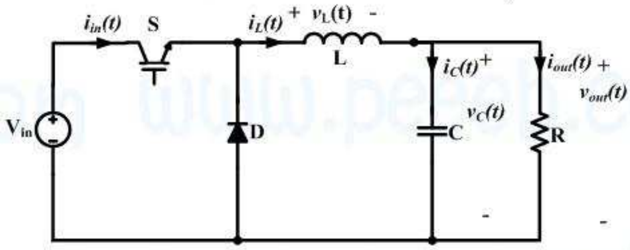
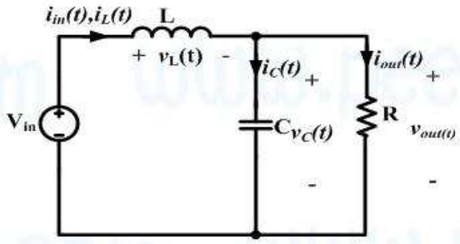
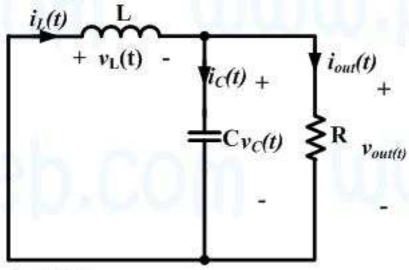
Buck Converter

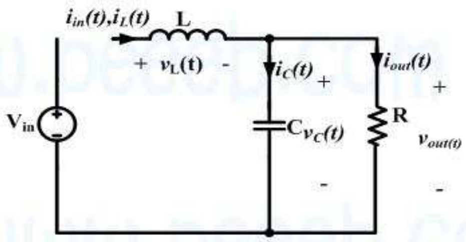
Discontinues Conduction Modes, DCM



In the DCM, the inductor current is not continues and the converter has three different states.







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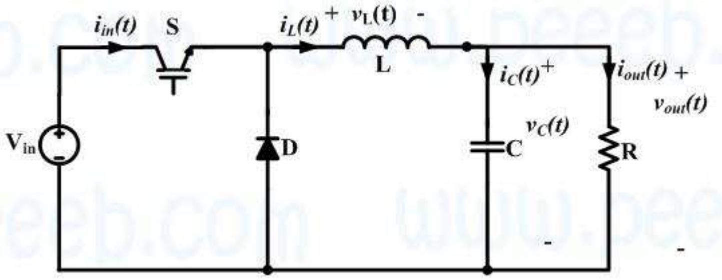
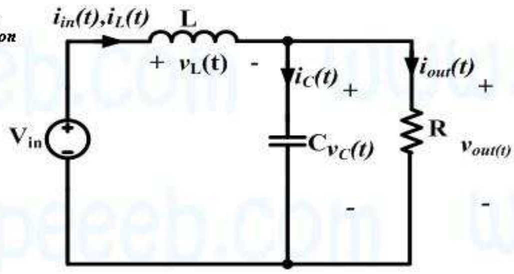
Buck Converter

Discontinues Conduction Modes, DCM
The IGBT is on and the diode is off



When the switch is turned on for t_{on}. $0<t<t_{on}$



$$v_L(t)=V_{in}-v_{out}(t)$$

$$i_C(t)=i_L(t)-i_{out}(t)$$

$$\begin{cases} v_L(t)=V_{in}-V_{out} \\ i_C(t)=i_L(t)-I_{out} \end{cases}$$

Duty cycle (D) is defined as: $D=\dfrac{t_{on}}{T_{sw}}$

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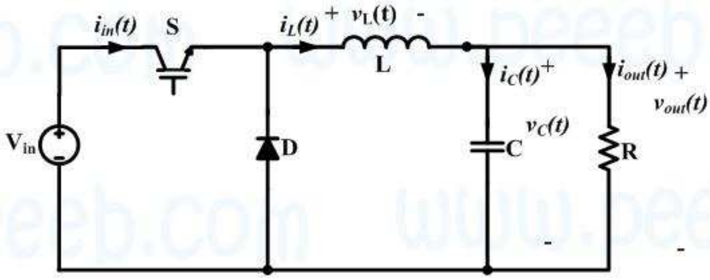
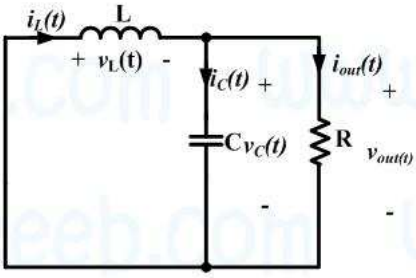
Buck Converter

Discontinues Conduction Modes, DCM
The IGBT is off and the diode is on



When the switch is turned off till the inductor current reaches to zero, $DT_{sw} < t < (D+D_{DCM})T_{sw}$



$$v_L(t) = -v_{out}(t)$$

$$i_C(t) = i_L(t) - i_{out}(t)$$

$$\begin{cases} v_L(t) = -V_{out} \\ i_C(t) = i_L(t) - I_{out} \end{cases}$$

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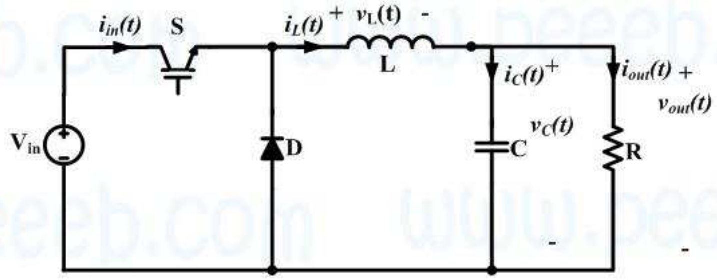
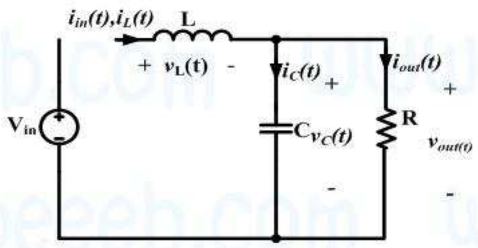
Buck Converter

Discontinues Conduction Modes, DCM

The diode and IGBT are off



The inductor current is zero.



$$v_L(t) = 0$$

$$i_C(t) = -i_{out}(t)$$

$$\begin{cases} v_L(t) = 0 \\ i_c(t) = -I_{out} \end{cases}$$

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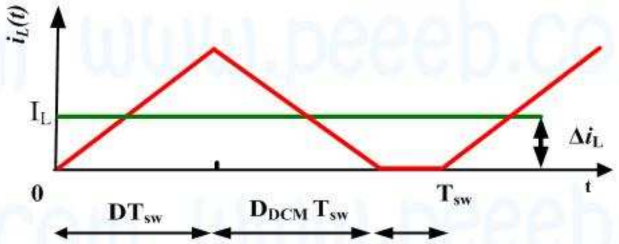
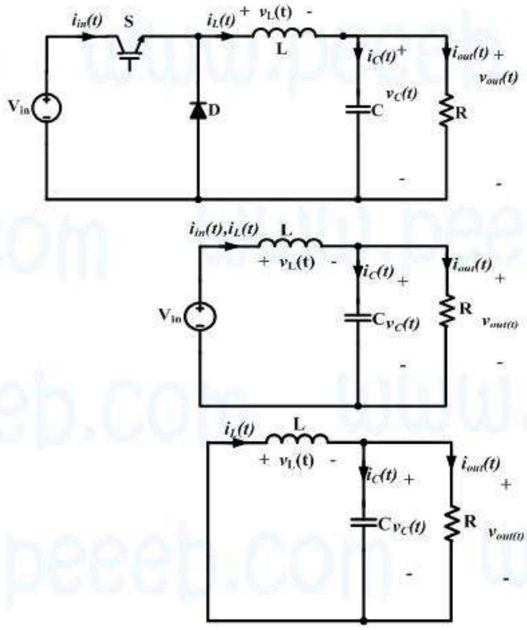
Buck Converter

Discontinues Conduction Mode, DCM





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Buck Converter

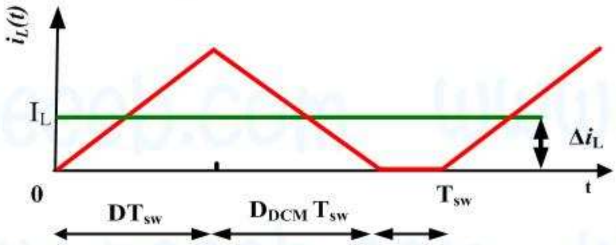
$$V_{in}I_{in} = V_{out}I_{out}$$

$$I_{in} = \overline{i_{in}(t)} = \frac{1}{T_{sw}}\int_0^{DT_{sw}} i_L(t)\,dt = \frac{DT_{sw}\times 2\Delta i_L}{2T_{sw}} = D\Delta i_L$$

$$V_{in}D\Delta i_L = \frac{V_{out}^2}{R}$$

$$L\frac{di_L}{dt} = v_L(t) \qquad L\left(\frac{2\Delta i_L}{DT_{sw}}\right) = V_{in}-V_{out} \qquad 0<t<t_{on}$$

$$\Delta i_L = \frac{(V_{in}-V_{out})DT_{sw}}{2L}$$



$$\frac{V_{in}D^2(V_{in}-V_{out})T_{sw}}{2L} = \frac{V_{out}{}^2}{R}$$

$$V_{in}{}^2 - V_{in}V_{out} = \frac{2LV_{out}^2}{RT_{sw}D^2}$$

$$\frac{V_{in}^2}{V_{out}^2} - \frac{V_{in}}{V_{out}} - K_1 = 0 \qquad K_1 = \frac{2L}{RT_{sw}D^2}$$

$$\frac{V_{in}}{V_{out}} = \frac{+1\pm\sqrt{1+4K_1}}{2}$$

$$H(D) = \frac{V_{out}}{V_{in}} = \frac{2}{+1+\sqrt{1+\frac{8L}{RT_{sw}D^2}}}$$

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Buck Converter

Assuming that the converter operates in CCM:

$\Delta i > I_L$ DCM

$\Delta i < I_L$ CCM

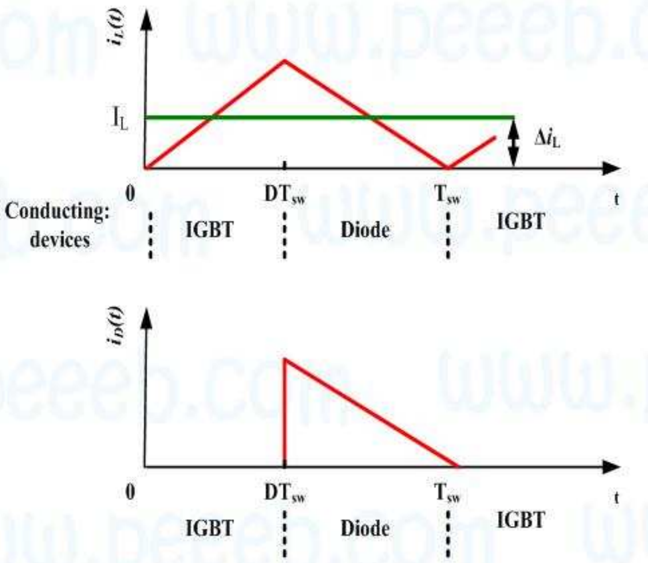
$I_L = I_{out} \quad I_L = \dfrac{V_{out}}{R}$

$$\Delta i = \frac{(V_{in} - V_{out})DT_{sw}}{2L} = \frac{(V_{in} - DV_{in})DT_{sw}}{2L}$$

$$\Delta i = \frac{V_{in}(1-D)DT_{sw}}{2L} = \frac{V_{in}DD'T_{sw}}{2L}$$

$$\Delta i < I_L \quad \Rightarrow \quad \frac{DD'V_{in}T_{sw}}{2L} < \frac{DV_{in}}{R}$$

$$\frac{D'T_{sw}}{2L} < \frac{1}{R} \quad \Rightarrow \quad D' < \frac{2L}{RT_{sw}}$$



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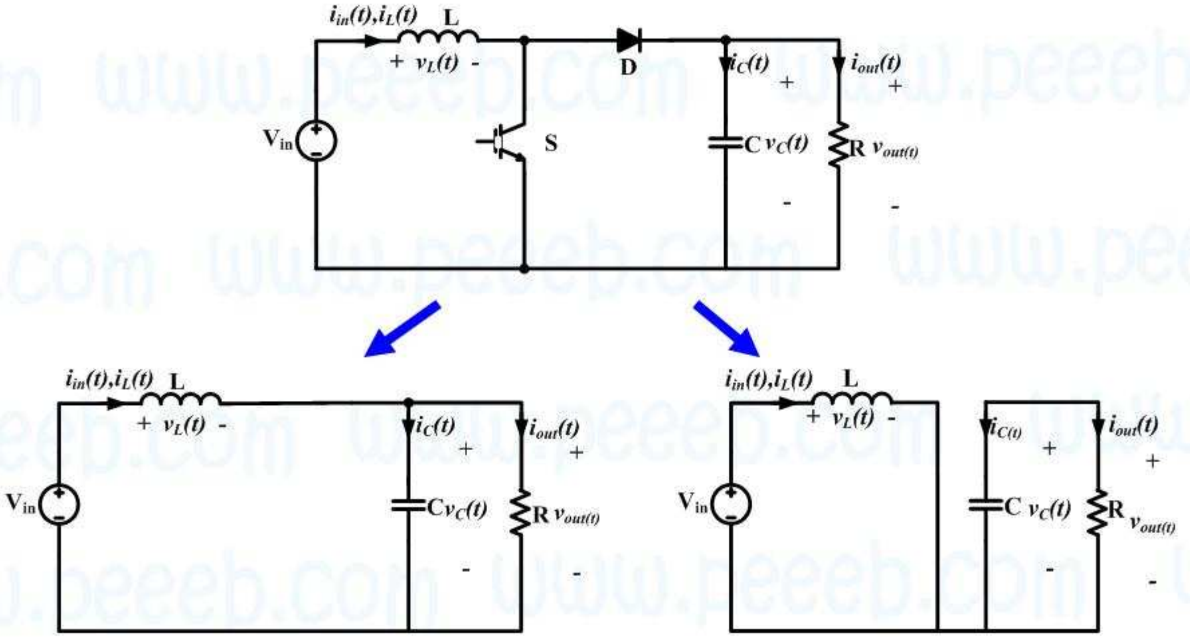
Boost Converter

Boost Converter



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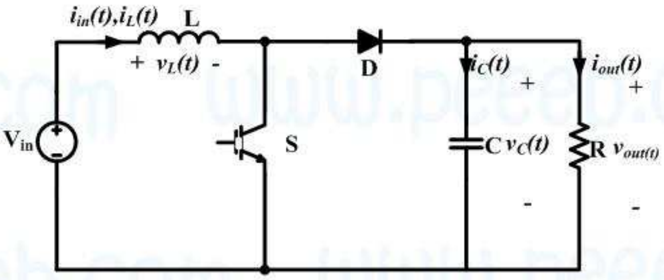
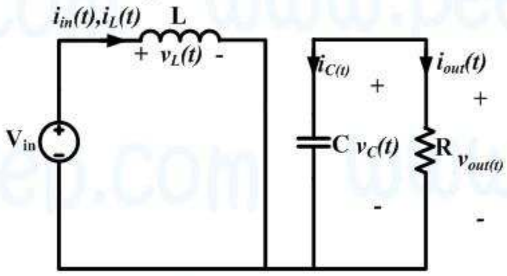
Boost Converter

$$v_L(t) = V_{in}$$

$$i_C(t) = -i_{out}(t)$$

$$\begin{cases} v_L(t) = V_{in} \\ i_C(t) = -\mathrm{I}_{out} \end{cases} \quad 0 < t < t_{on}$$



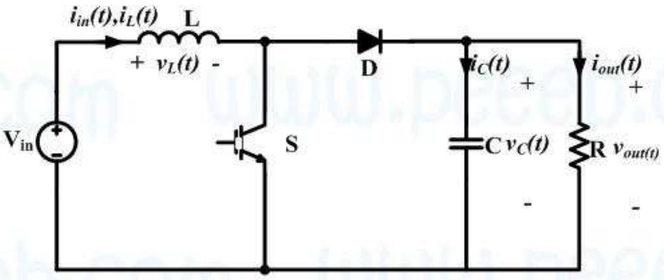


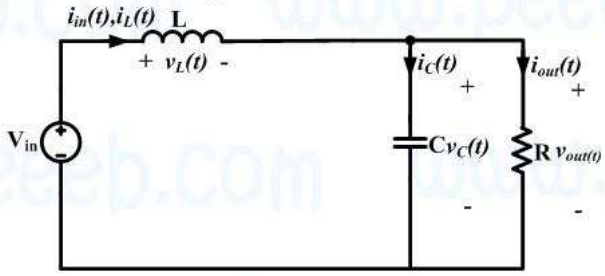
Boost Converter

$$v_L(t) = V_{in} - v_{out}(t) \qquad t_{on} < t < T_{sw}$$

$$i_C(t) = i_L(t) - i_{out}(t)$$

$$\begin{cases} v_L(t) = V_{in} - V_{out}(t) \\ i_C(t) = i_L(t) - I_{out} \end{cases}$$





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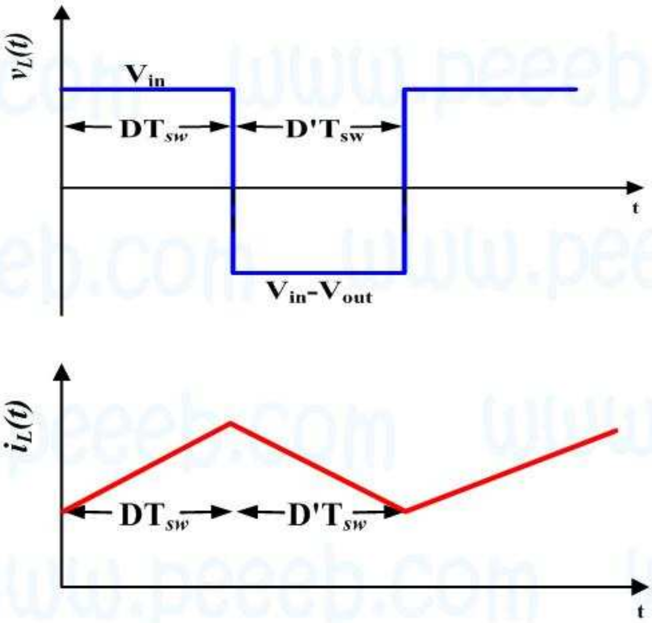
Boost Converter

$$v_L(t) = \begin{cases} V_{in} & 0 < t < t_{on} \\ V_{in} - V_{out} & t_{on} < t < T_{sw} \end{cases}$$

$$i_C(t) = \begin{cases} -I_{out} & 0 < t < t_{on} \\ i_L(t) - I_{out} & t_{on} < t < T_{sw} \end{cases}$$



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Boost Converter

$$\overline{v_L(t)} = 0$$

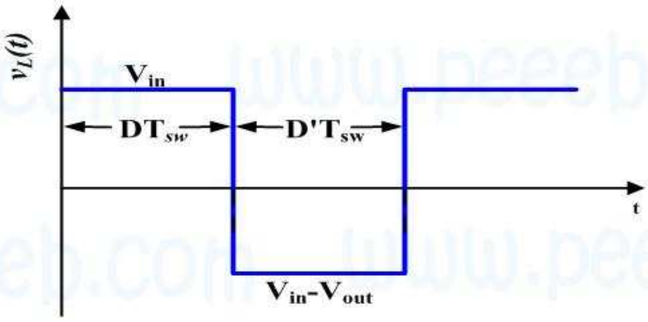
$$\int_0^{DT_{sw}} V_{in}\,dt + \int_{DT_{sw}}^{T_{sw}} (V_{in} - V_{out})\,dt = 0$$

$$V_{in} DT_{sw} + (V_{in} - V_{out})(T_{sw} - DT_{sw}) = 0$$

$$V_{in} DT_{sw} + (V_{in} - V_{out}) D'T_{sw} = 0$$

$$V_{in}(D + D') - V_{out} D' = 0$$

$$H(D) = \frac{V_{out}}{V_{in}} = \frac{1}{(1-D)} = \frac{1}{D'}$$



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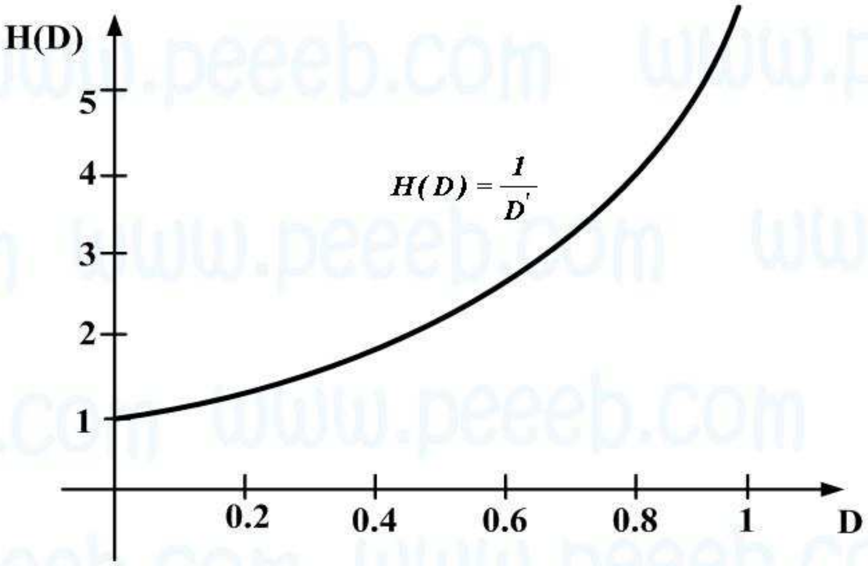

H(D)
5
4
3
2
1
$H(D) = \frac{1}{D'}$
0.2
0.4
0.6
0.8
1
D

Boost Converter

How to select L and C sizes?

$$L\frac{di_L(t)}{dt}=v_L(t)$$

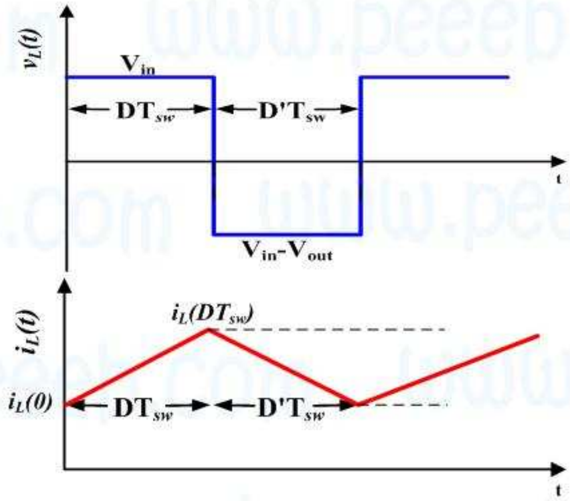
$$\int_0^{DT_{sw}} di_L(t)=\frac{1}{L}\int_0^{DT_{sw}} V_{in}\,dt$$

$$i_L(DT_{sw})-i_L(0)=\frac{V_{in}DT_{sw}}{L}$$

$$2\Delta i_L=\frac{V_{in}DT_{sw}}{L}\Rightarrow$$

$$\Delta i_L=\frac{V_{in}D}{2Lf_{sw}}$$

$$L=\frac{V_{in}D}{2f_{sw}\Delta i_L}$$



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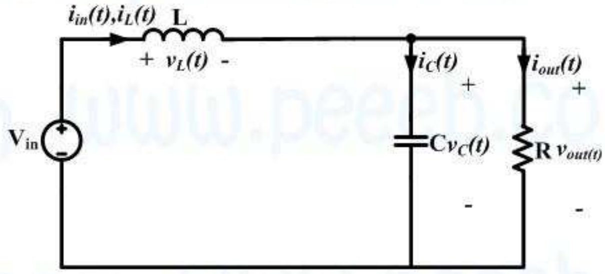
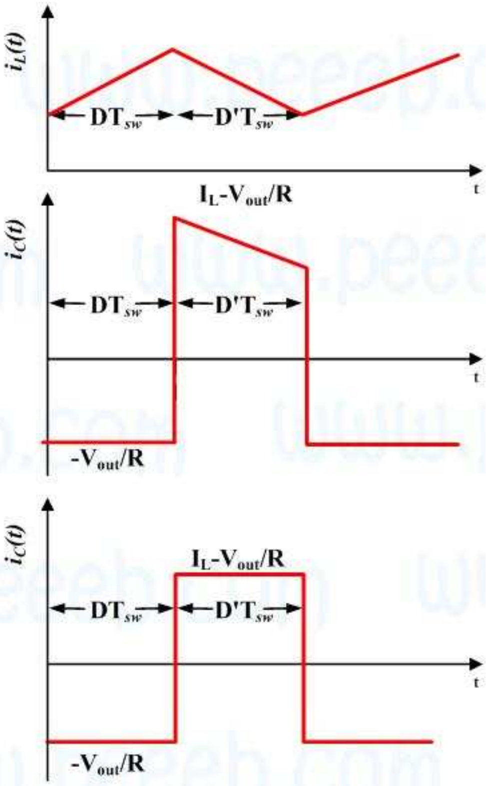
Boost Converter





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Boost Converter

How to select L and C sizes?

$$C\frac{dv_C(t)}{dt}=i_C(t)$$

$$dv_C(t)=\frac{i_C(t)dt}{C}$$

$$\int_0^{DT_{sw}} dv_C(t)=\frac{1}{C}\int_0^{DTsw} i_C(t)\,dt$$

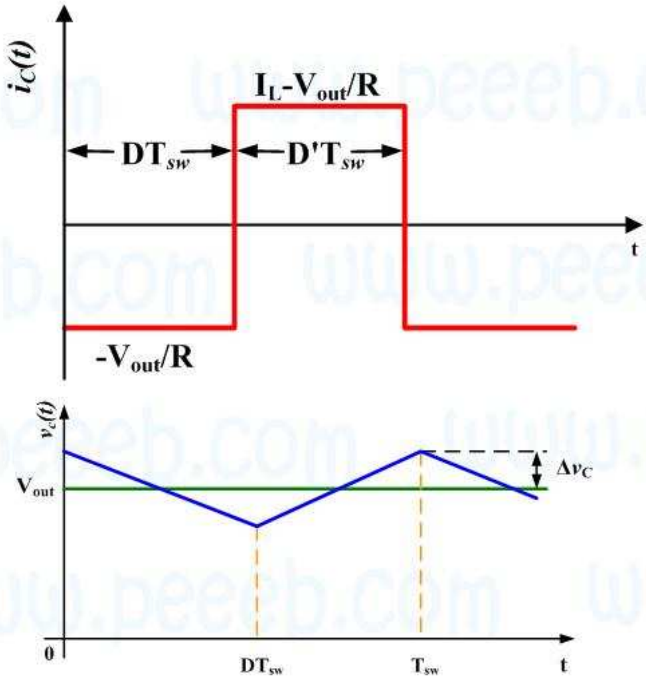
$$-2\Delta v_C=\frac{-I_{out}DT_{sw}}{C}$$

$$\Delta v_C=\frac{I_{out}DT_{sw}}{2C}$$

$$I_{out}=\frac{V_{out}}{R} \qquad T_{sw}=\frac{1}{f_{sw}}$$

$$\Delta v_C=\frac{V_{out}D}{2RCf_{sw}}$$

$$C=\frac{V_{in}D}{2RD'f_{sw}\Delta v_C}$$



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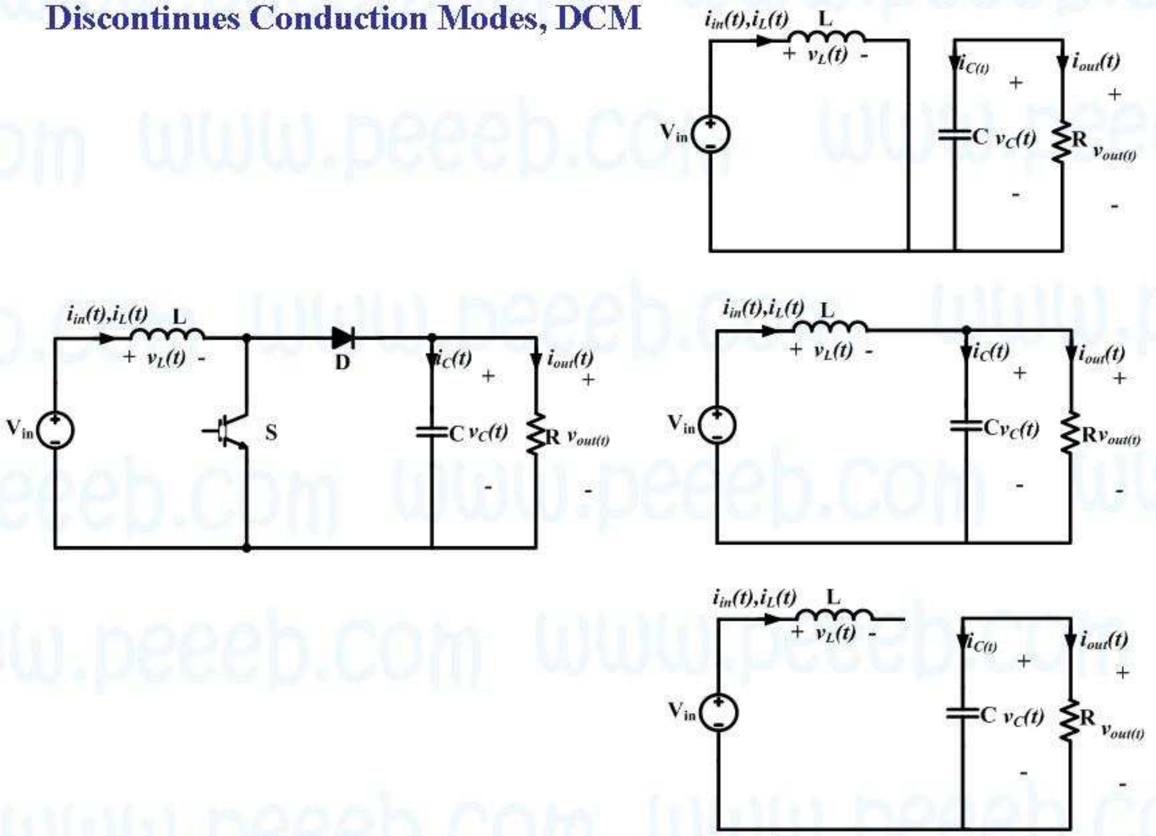
Boost Converter

Discontinues Conduction Modes, DCM



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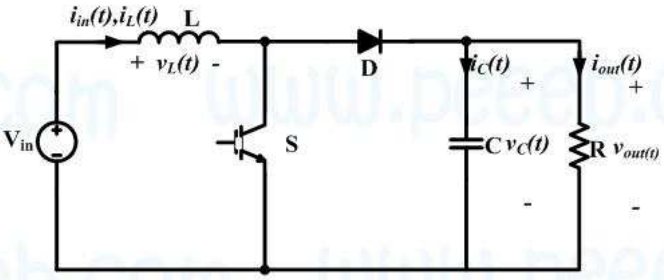
Boost Converter

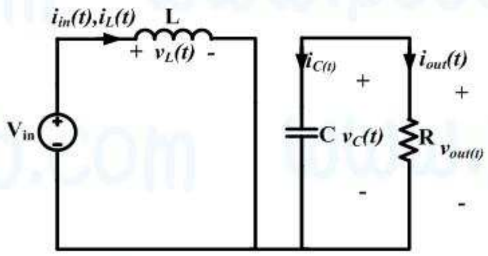
Discontinues Conduction Modes, DCM
The IGBT is on and the diode is off.



$$v_L(t) = V_{in}$$

$$i_C(t) = -i_{out}(t)$$

$$\begin{cases} v_L(t) = V_{in} \\ i_C(t) = \text{-}I_{out} \end{cases} \qquad 0 < t < t_{on}$$



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Boost Converter

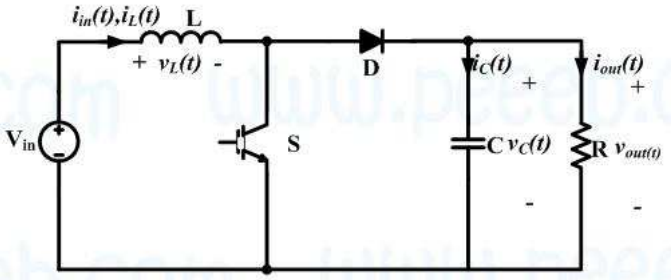
Discontinues Conduction Modes, DCM

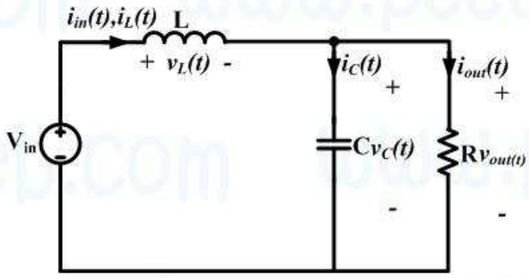
The IGBT is off and the diode is on.

$v_L(t) = V_{in} - v_{out}(t) \qquad t_{on} < t < D_{DCM} T_{sw}$

$i_C(t) = i_L(t) - i_{out}(t)$

$$\begin{cases} v_L(t) = V_{in} - V_{out}(t) \\ i_C(t) = i_L(t) - I_{out} \end{cases}$$





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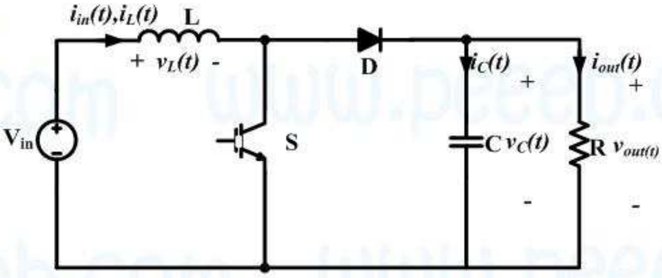
Boost Converter

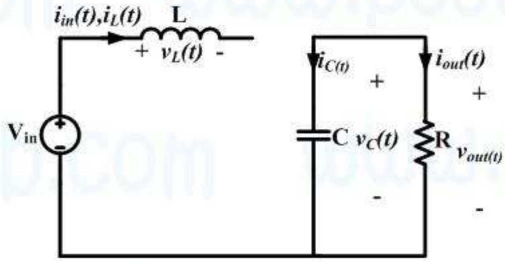
Discontinues Conduction Modes, DCM
Both the IGBT and the diode are off.

$v_L(t) = 0 \qquad D_{DCM}T_{sw} < t < T_{sw}$

$i_C(t) = i_{out}(t)$

$$\begin{cases} v_L(t) = 0 \\ i_c(t) = -I_{out} \end{cases}$$





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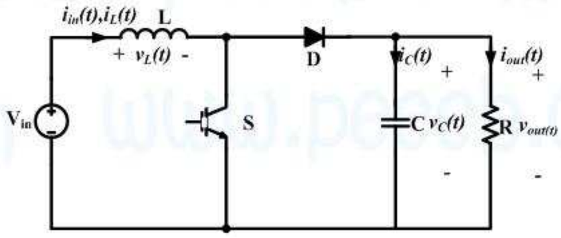
Boost Converter

Discontinues Conduction Modes, DCM



$$V_{in} I_{in} = V_{out} I_{out}$$

$$I_{in} = \overline{i_{in}(t)} = \frac{1}{T_{sw}} \int_0^{(D+D_{DCM})T_{sw}} i_L(t)\, dt = \frac{(D + D_{DCM})T_{sw} \times 2\Delta i_L}{2T_{sw}}$$

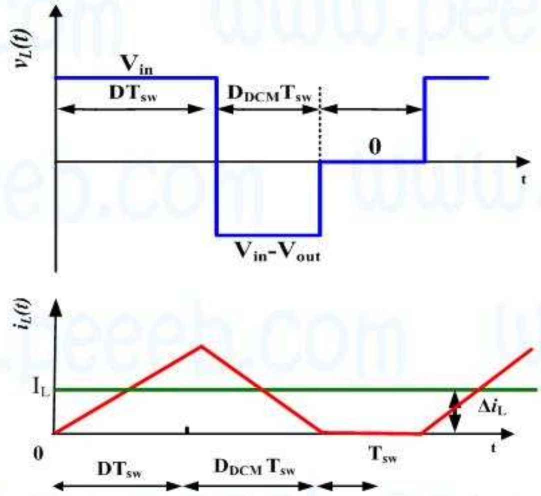
$$I_{in} = (D + D_{DCM})\Delta i_L$$

$$V_{in} \Delta i_L (D + D_{DCM}) = \frac{V_{out}^2}{R}$$

$$L\frac{di_L(t)}{dt} = v_L(t)$$

$$L\left(\frac{2\Delta i_L}{DT_{sw}}\right) = V_{in} \qquad 0 < t < t_{on}$$

$$\Delta i_L = \frac{V_{in} DT_{sw}}{2L}$$



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Boost Converter

Discontinues Conduction Modes, DCM

$$V_{in}\left(\frac{V_{in}DT_{sw}}{2L}\right)(D+D_{DCM})=\frac{V_{out}^2}{R}$$

$$V_{in}^2\left(\frac{RT_{sw}D}{2L}\right)(D+D_{DCM})=V_{out}^2$$

$$V_{in}^2\times\left(\frac{RT_{sw}D}{2L}\right)\left(D+\frac{V_{in}D}{V_{out}-V_{in}}\right)=V_{out}^2$$

$$V_{in}^2\left(\frac{RT_{sw}D}{2L}\right)(DV_{out}-DV_{in}+DV_{in})=V_{out}^2(V_{out}-V_{in})$$

$$V_{in}^2\left(\frac{RT_{sw}D}{2L}\right)(DV_{out})=V_{out}^2(V_{out}-V_{in})$$

$$V_{in}^2\left(\frac{RT_{sw}D}{2L}\right)D=V_{out}^2-V_{out}V_{in}$$

$$\frac{V_{out}^2}{V_{in}^2}-\frac{V_{out}}{V_{in}}-\left(\frac{RD^2T_{sw}}{2L}\right)=0 \qquad K_2=\frac{RD^2T_{sw}}{2L}$$

$$\frac{V_{out}^2}{V_{in}^2}-\frac{V_{out}}{V_{in}}-K_2=0$$

$$\frac{V_{out}}{V_{in}}=\frac{+1\pm\sqrt{1+4K_2}}{2} \qquad \frac{V_{out}}{V_{in}}=\frac{1+\sqrt{1+\frac{2RD^2T_{sw}}{L}}}{2}$$

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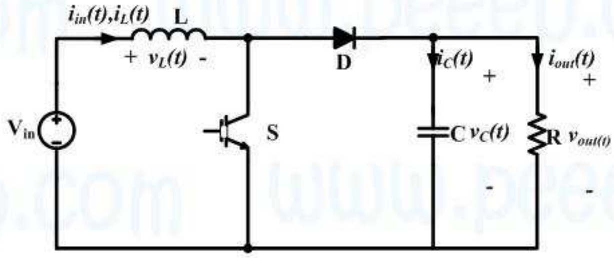
Boost Converter

Discontinues Conduction Modes, DCM

$\Delta i_L > I_L \quad DCM \qquad \Delta i_L < I_L \quad CCM$



$$\Delta i_L = \frac{V_{in} D T_{sw}}{2L} \qquad \frac{V_{in} D T_{sw}}{2L} < I_L$$

$$\frac{V_{in} D T_{sw}}{2L} < \frac{V_{in}}{(1-D)^2 R}$$

$$D(1-D)^2 < \frac{2L}{RT_{sw}}$$

$$D\left(1-2D+D^2\right) < \frac{2L}{RT_{sw}}$$

$$D^3 - 2D^2 + D < \frac{2L}{RT_{sw}}$$

$$f(D) = D^3 - 2D^2 + D$$

$$\frac{df(D)}{dD} = 0 \Rightarrow 3D^2 - 4D + 1 = 0 \Rightarrow D = \frac{1}{3}$$

$$f\left(\frac{1}{3}\right)\bigg|_{max} = \frac{4}{27} < \frac{2L}{RT_{sw}}$$

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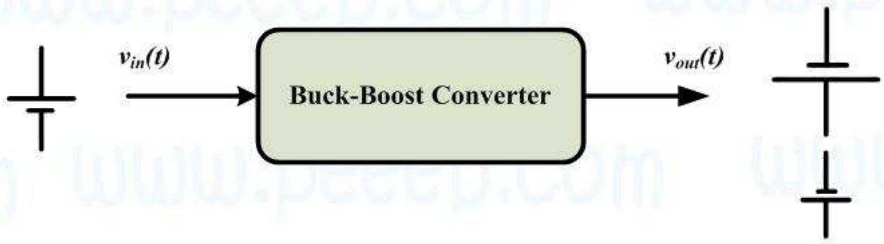
Buck-Boost Converter



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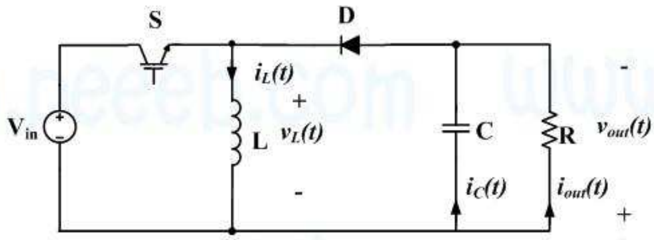
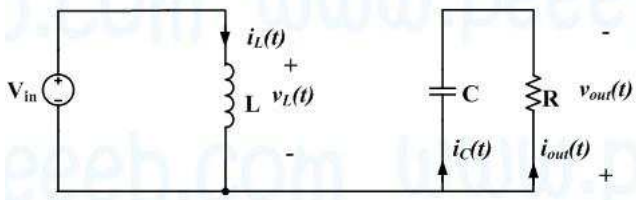
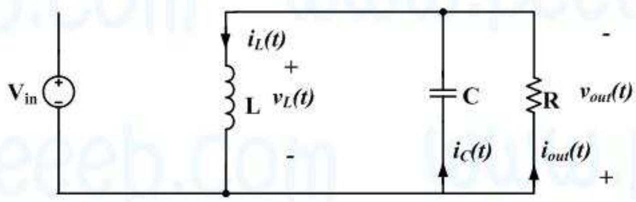
Buck-Boost Converter





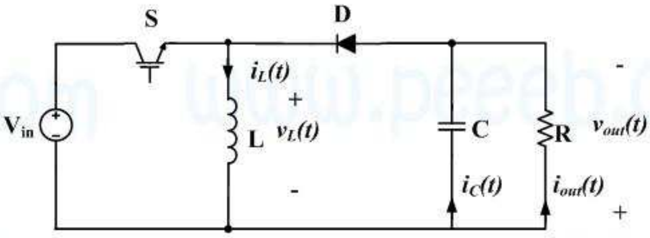


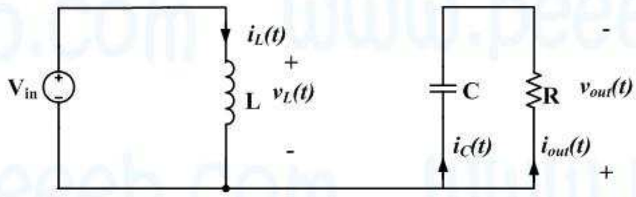
Buck-Boost Converter

$$v_L(t) = V_{in} \qquad 0 < t < t_{on}$$

$$i_C(t) = -i_{out}(t)$$

$$\begin{cases} v_L(t) = V_{in} \\ i_C(t) = -I_{out} \end{cases} \qquad 0 < t < t_{on}$$





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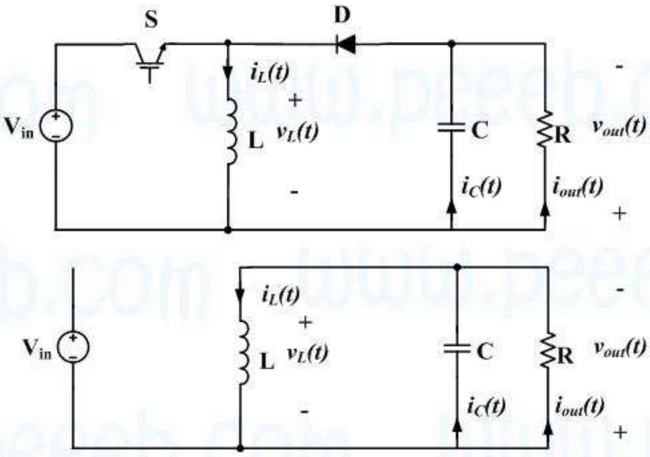
Buck-Boost Converter

$$v_L(t) = -v_{out}(t) \qquad t_{on} < t < T_{sw}$$

$$i_C(t) = i_L(t) - i_{out}(t)$$

$$\begin{cases} v_L(t) = -V_{out} \\ i_C(t) = i_L(t) - I_{out} \end{cases}$$



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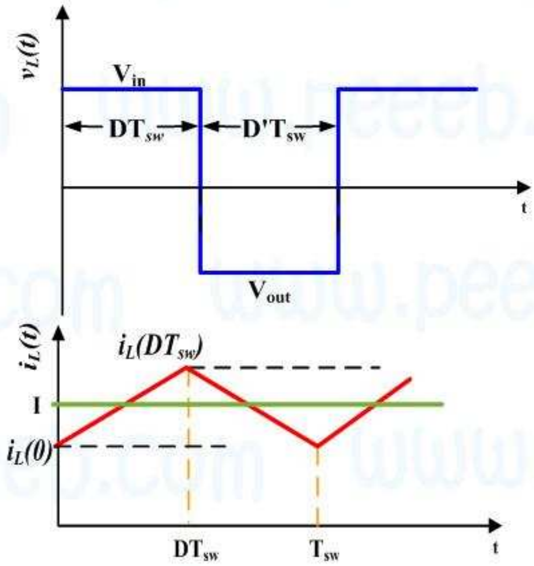
Buck-Boost Converter

$$v_L(t) = \begin{cases} V_{in} & 0 < t < t_{on} \\ -V_{out} & t_{on} < t < T_{sw} \end{cases}$$

$$i_C(t) = \begin{cases} -I_{out} & 0 < t < t_{on} \\ i_L(t) - I_{out} & t_{on} < t < T_{sw} \end{cases}$$



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Buck-Boost Converter

$$\overline{v_L(t)} = 0$$

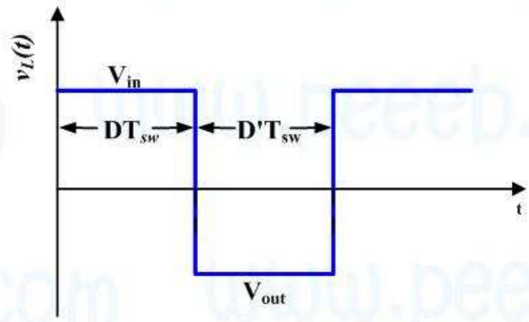
$$\int_0^{DT_{sw}} V_{in}\, dt + \int_{DT_{sw}}^{T_{sw}} V_{out}\, dt = 0$$

$$V_{in} DT_{sw} + (-V_{out})(T_{sw} - DT_{sw}) = 0$$

$$DV_{in} + (-V_{out})(T_{sw} - DT_{sw}) = 0$$

$$DV_{in} = (1 - D)V_{out}$$

$$H(D) = \frac{V_{out}}{V_{in}} = \frac{D}{(1-D)} = \frac{D}{D'}$$



Buck-Boost Converter

How to select L and C sizes?

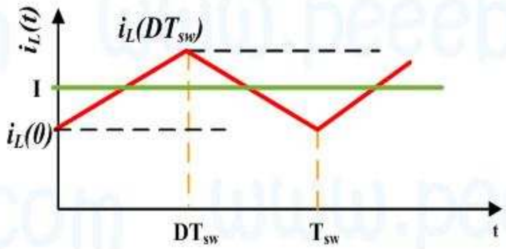
$$L\frac{di_L}{dt} = v_L(t)$$

$$\int_0^{DT_{sw}} di_L(t) = \frac{1}{L}\int_0^{DT_{sw}} V_{in}\,dt$$

$$i_L(DT_{sw}) - i_L(0) = \frac{V_{in}DT_{sw}}{L}$$

$$2\Delta i_L = \frac{V_{in}DT_{sw}}{L}$$

$$L = \frac{V_{in}D}{2f_{sw}\Delta i_L}$$



Buck-Boost Converter

How to select L and C sizes?

$$C\frac{dv_C(t)}{dt}=i_C(t)$$

$$\int_0^{DT_{sw}} dv_C(t)=\frac{1}{C}\int_0^{DT_{sw}} i_C(t)dt$$

$$-2\Delta v_C=\frac{(-I_{out})DT_{sw}}{C}$$

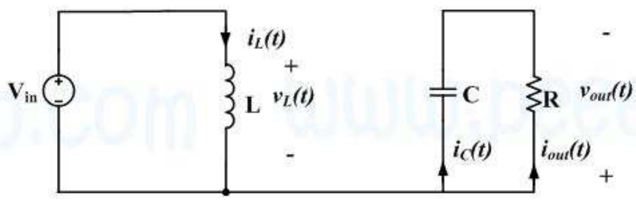
$$\Delta v_C=\frac{I_{out}DT_{sw}}{2C}$$

$$\Delta v_C=\frac{V_{out}D}{2RCf_{sw}}=\frac{V_{in}D^2}{2RCf_{sw}D'}$$

$$C=\frac{V_{in}D^2}{2Rf_{sw}D'\Delta v_C}$$

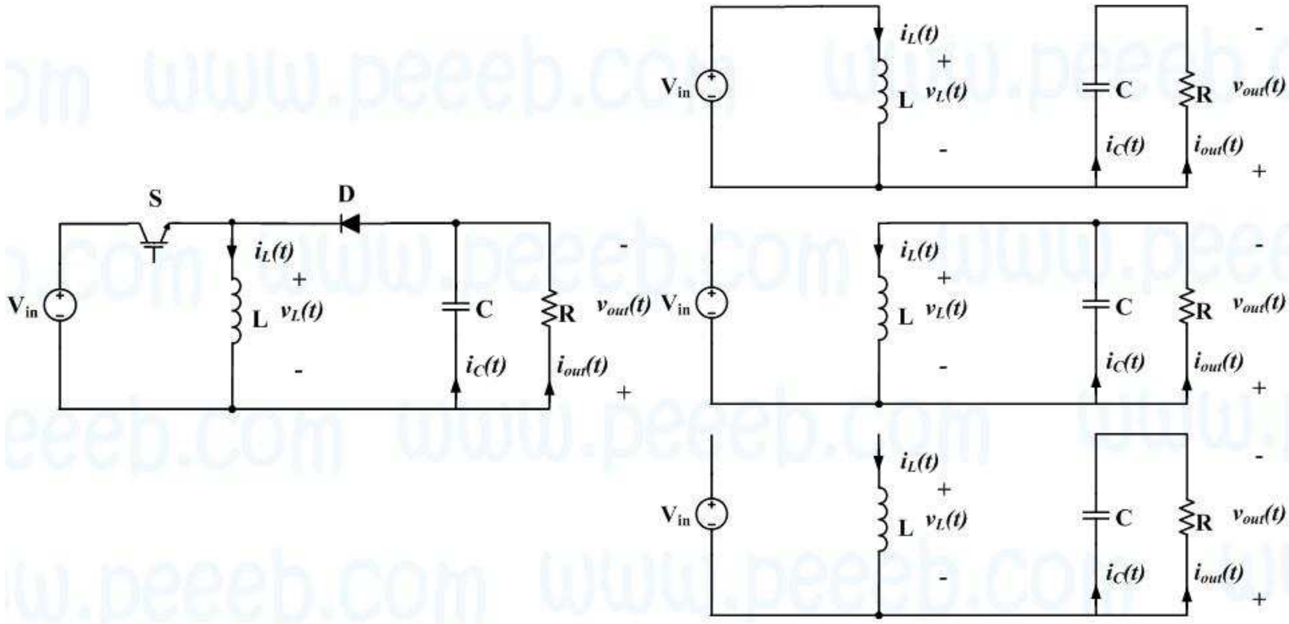
$$i_C(t)=-i_{out}(t) \qquad 0<t<t_{on}$$

$$i_C(t)=-I_{out}$$



Buck-Boost Converter

Discontinues Conduction Modes, DCM



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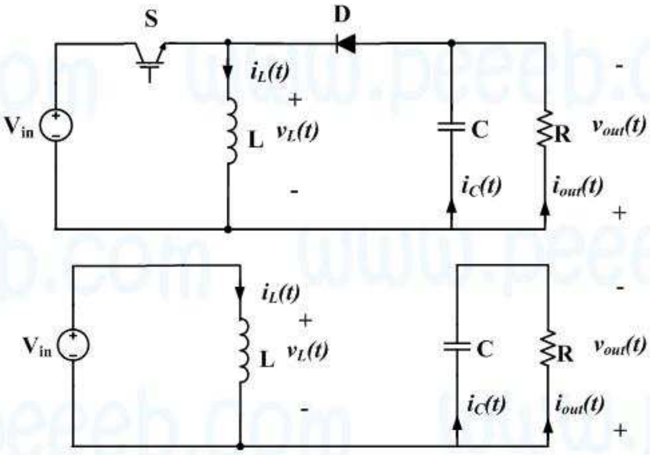
Buck-Boost Converter

Discontinues Conduction Modes, DCM

$$v_L(t) = V_{in} \qquad 0 < t < t_{on}$$

$$i_C(t) = -i_{out}(t)$$

$$\begin{cases} v_L(t) = V_{in} \\ i_C(t) = -I_{out} \end{cases} \qquad 0 < t < t_{on}$$



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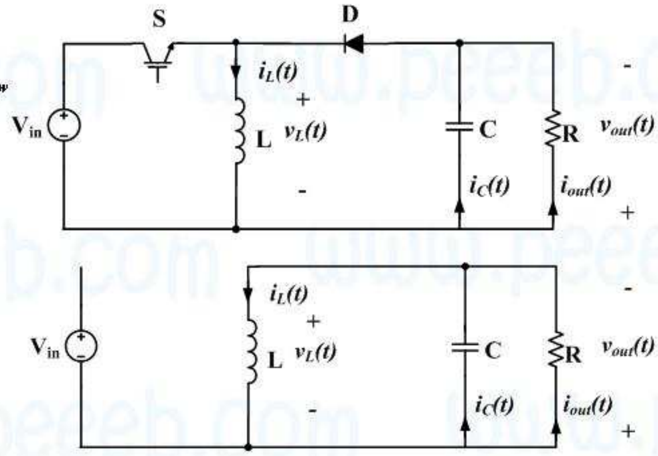
Buck-Boost Converter

Discontinues Conduction Modes, DCM

$$v_L(t) = -v_{out}(t) \qquad t_{on} < t < D_{DCM}T_{sw}$$

$$i_C(t) = i_L(t) - i_{out}(t)$$

$$\begin{cases} v_L(t) = -V_{out} \\ i_C(t) = i_L(t) - I_{out} \end{cases}$$



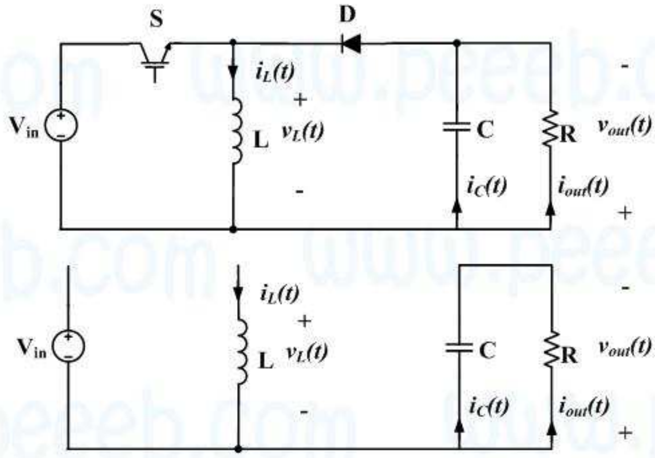
Buck-Boost Converter

Discontinues Conduction Modes, DCM

$v_L(t) = 0 \qquad D_{DCM}T_{sw} < t < T_{sw}$

$i_C(t) = -i_{out}(t)$

$$\begin{cases} v_L(t) = 0 \\ i_c(t) = -I_{out} \end{cases}$$



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$$V_{in} I_{in} = V_{out} I_{out}$$

$$I_{in} = \overline{i_{in}(t)} = \frac{1}{T_{sw}} \int_0^{DT_{sw}} i_L(t) dt = \frac{DT_{sw} \times 2\Delta i_L}{2T_{sw}} = D\Delta i_L$$

$$V_{in} D\Delta i_L = V_{out} I_{out}$$

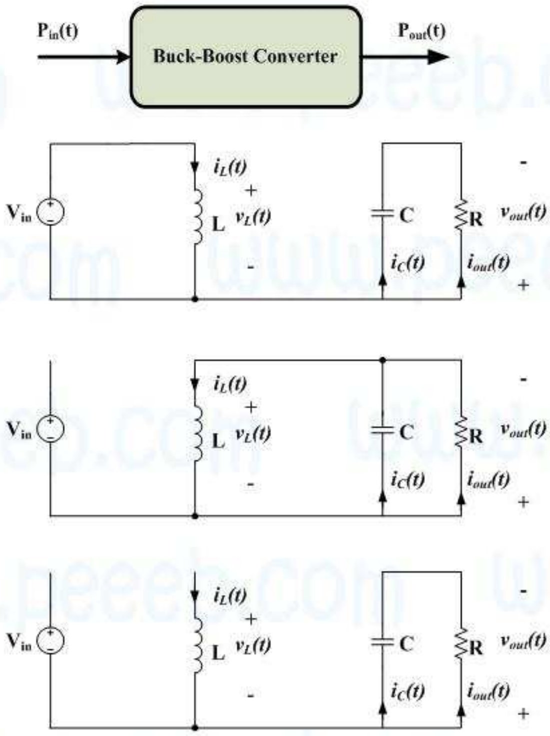
$$L \frac{di_L(t)}{dt} = v_L(t)$$

$$L\left(\frac{2\Delta i_L}{DT_{sw}}\right) = V_{in} \qquad \Delta i_L = V_{in}\left(\frac{DT_{sw}}{2L}\right)$$

$$V_{in} D V_{in}\left(\frac{DT_{sw}}{2L}\right) = \frac{V_{out}^2}{R}$$

$$\left(\frac{V_{out}}{V_{in}}\right)^2 = D^2\left(\frac{RT_{sw}}{2L}\right)$$

$$H(D) = \frac{V_{out}}{V_{in}} = D\sqrt{\frac{RT_{sw}}{2L}}$$



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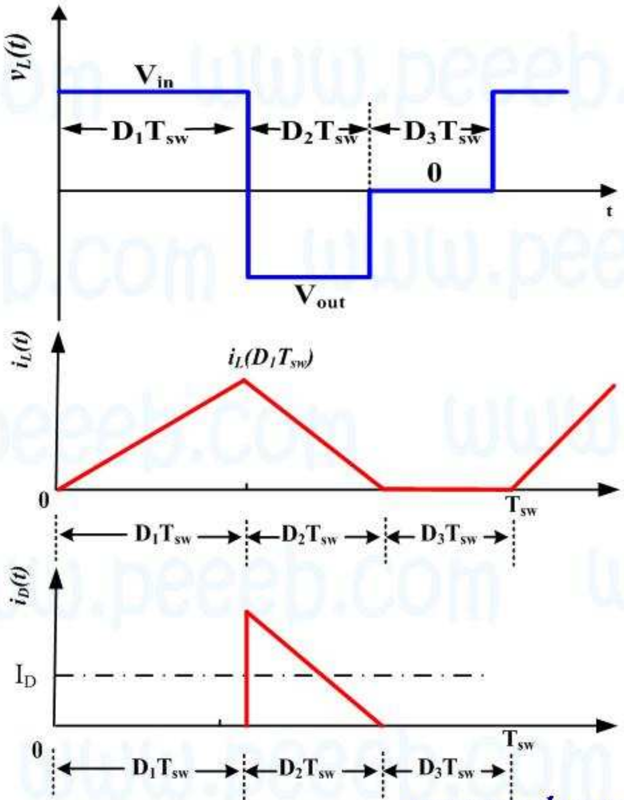
Discontinues Conduction Modes, DCM



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Buck-Boost Converter

Assuming that the converter operates in CCM:

$$\Delta i_L > I_L \qquad DCM$$

$$\Delta i_L < I_L \qquad CCM$$

$$I_{out} = \frac{1}{T_{sw}}\int_{DT_{sw}}^{T_{sw}} i_L(t)dt$$

$$I_{out} = \frac{(T_{sw} - DT_{sw})I_L}{T_{sw}}$$

$$I_{out} = (1 - D)I_L$$

$$I_L = \frac{I_{out}}{D'} = \frac{V_{out}}{RD'}$$

$$\Delta i_L = V_{in}\left(\frac{DT_{sw}}{2L}\right)$$

$$\Delta i_L < I_L \qquad CCM$$

$$V_{in}\left(\frac{DT_{sw}}{2L}\right) < \frac{V_{out}}{RD'}$$

$$V_{in}\left(\frac{DT_{sw}}{2L}\right) < \frac{V_{in}D}{D'}\frac{1}{RD'}$$

$$\frac{T_{sw}}{2L} < \frac{1}{R(D')^2}$$

$$(D')^2 < \frac{2L}{RT_{sw}}$$

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