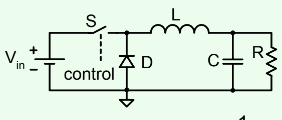
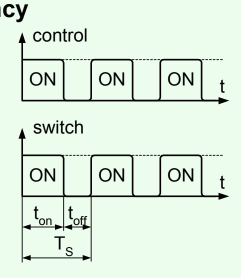
BUCK, BOOST, BUCK-BOOST, DCM

Buck Converter Constant Switching Frequency





Switch frequency: $f_S = \frac{1}{T_S}$

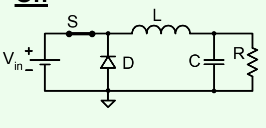
Duty Cycle:

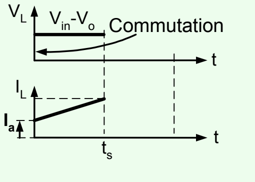
$$\frac{t_{on}}{T_s} = D_{on} \quad \text{or} \rightarrow D$$

$$\frac{t_{off}}{T_S} = D_{off} \quad \rightarrow 1 - D$$

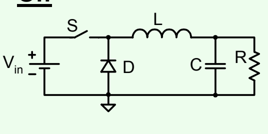
Operation modes

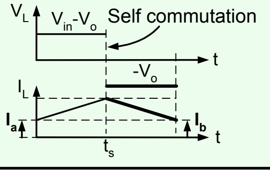
On





Off

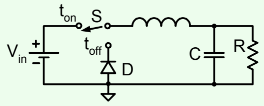




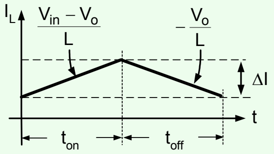
At steady state $I_a=I_b$

Buck

In this case



Inductor current waveform at steady state

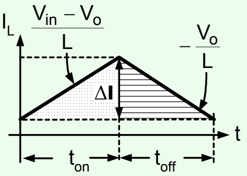


Voltage transfer function

The ΔI method

Left triangle

$$\Delta I = \frac{V_{in} - V_o}{L} \cdot t_{on}$$



Right triangle

$$\Delta I = \frac{V_o}{L} \cdot t_{off}$$

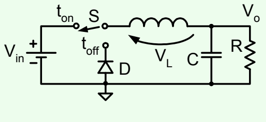
$$\left(\frac{V_{in} - V_o}{L}\right) t_{on} = \frac{V_o}{L} t_{off}$$

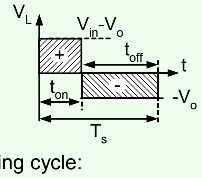
$$\frac{V_o}{V_{in}} = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T_s} = D_{on}$$

Independent of L !

Voltage transfer function

The average voltage method





At steady state, over one switching cycle:

$$\overline{V_L} = 0;$$

$$S_+ = (V_{in} - V_o) \cdot t_{on};$$

$$S_- = (-V_o) \cdot t_{off};$$

$$S_+ + S_- = 0 \Rightarrow \frac{V_o}{V_{in}} = D_{on}$$

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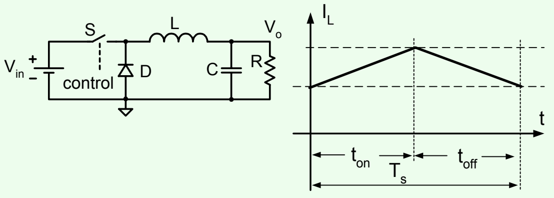
Load Change with Fixed D



How will I_L change if R is getting smaller?

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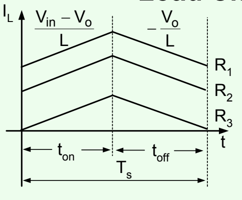
Load Change



$R_1 < R_2 < R_3$

CCM - Continues Conductor Current Mode

DCM - Discontinues Conductor Current Mode

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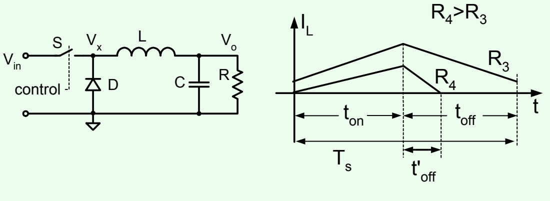
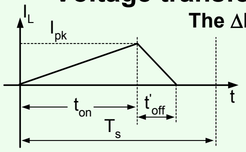
Discontinuous Inductor Current Mode (DCM)



- Different voltage transfer ratio $\neq D_{on}$
- Higher ripple current

Voltage transfer function (DCM)

The ΔI method



$$I_{pk} = \frac{V_{in} - V_o}{L} t_{on} = \frac{V_o}{L} t'_{off}$$

$$D_{off} = \frac{(V_{in} - V_{out})D_{on}}{V_{out}}$$

$$I_{AV} = \frac{1}{T_S}\left(\frac{1}{2}\frac{V_{in} - V_o}{L} T_{on} \cdot T_S (D_{on} + D_{off})\right)$$

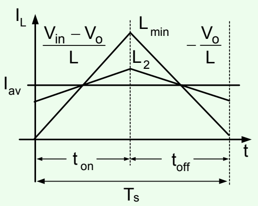
$$I_{AV} = \frac{1}{2}\frac{V_{in} - V_o}{L} T_{on} \cdot D_{on}\left(1 + \frac{V_{in} - V_o}{V_o}\right)$$

$$I_{AV} = \frac{V_o}{R}$$

$$\longrightarrow \quad R(V_{in} - V_o) D_{on}^2 T_S V_{in} = 2LV_o^2$$

$$\frac{V_o}{V_{in}} = \frac{R D_{on}^2 T_s}{4L}\left(\sqrt{1 + \frac{8L}{R D_{on}^2 T_s}} - 1\right)$$

Boundary of CCM and DCM



- For CCM $L > L_{min}$
- In Buck $\frac{V_o}{L_{min}} t_{off} = I_{pk} = 2I_{av}$ $\quad L_{min} = \frac{V_o D_{off}}{2 I_{av} f_s} = \frac{R D_{off}}{2 f_s}$

Example

A BUCK converter has a following characteristics:

Output voltage: $V_o = 5\,V$ Output current: $I_{out} = I_{av} = 10\,A$

Input voltage: $V_{in} = 10\,V$ Frequency: $f_s = 100\,kHz$

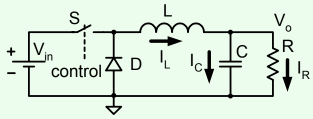
Current mode: CCM

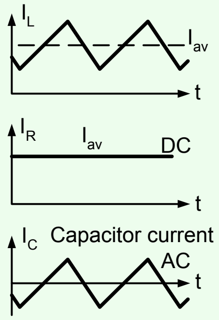
Find: L_{min}

$$\frac{V_o}{V_{in}} = D_{on} = 0.5 \xrightarrow{\text{CCM}} D_{off} = 1 - D_{on} = 0.5$$

$$L_{min} = \frac{V_o D_{off}}{2 I_{av} f_s} = \frac{5 \cdot 0.5}{2 \cdot 10 \cdot 10^5} = 1.2\,\mu H$$

Capacitor current

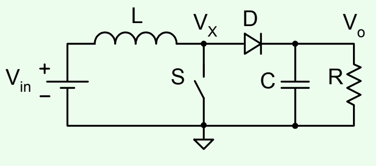




- Assumption:
  V_0 has small ripple

$$I_C = I_L - I_R$$

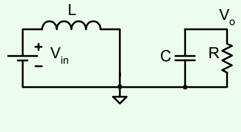
BOOST Step-Up

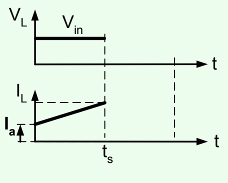


- $V_o > V_{in}$ **Why ??**

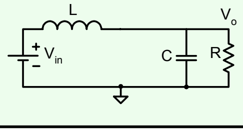
Boost Operation modes

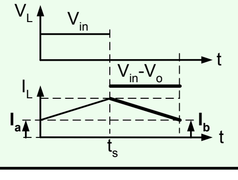
ON $V_L=V_{in}$





OFF $V_L=V_{in}-V_o$





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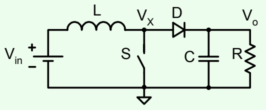
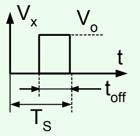
Voltage transfer function

The average voltage method





$$\overline{V}_L = 0; \quad \overline{V}_{in} - \overline{V}_x = 0; \quad \overline{V}_{in} = \overline{V}_x;$$

$$V_{in} = \overline{V}_{in};$$

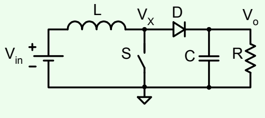
$$\overline{V}_x = \frac{V_o t_{off}}{T_s} = V_o D_{off};$$

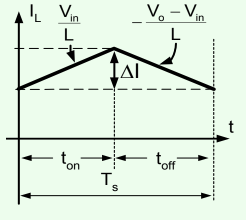
$$V_{in} = V_o D_{off} \rightarrow \frac{V_o}{V_{in}} = \frac{1}{D_{off}}$$

Prof. S. Ben-Yaakov , DC-DC Converters [2- 17]

Voltage transfer function

The ΔI method





$$\frac{V_{in}}{L} \cdot t_{on} = \frac{V_o - V_{in}}{L} \cdot t_{off}$$

$$V_{in} \cdot (t_{on} + t_{off}) = V_o \cdot t_{off}$$

$$\frac{V_o}{V_{in}} = \frac{1}{D_{off}}$$

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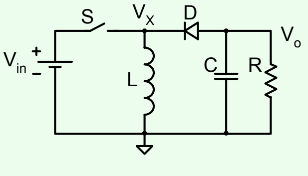
BUCK-BOOST

Step-Up Step-Down



- Find V_o/V_{in}

  Hint: Average of V_x ?

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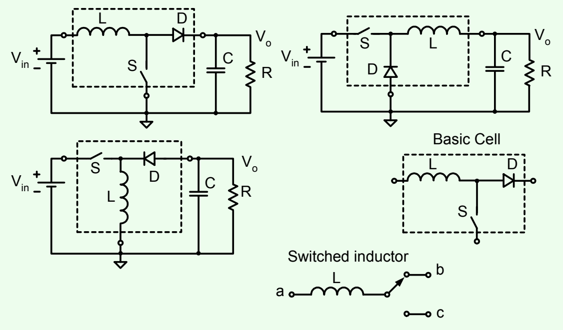
Comparison between basic topologies CCM



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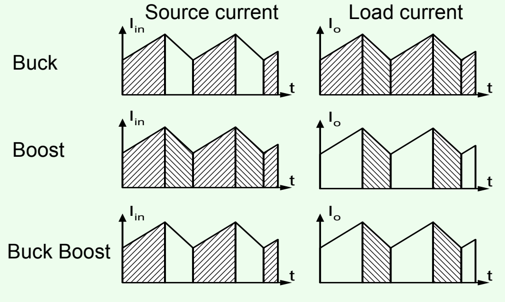
Input and Output Currents



Continues current -> Low ripple component

Discontinues current -> High ripple component

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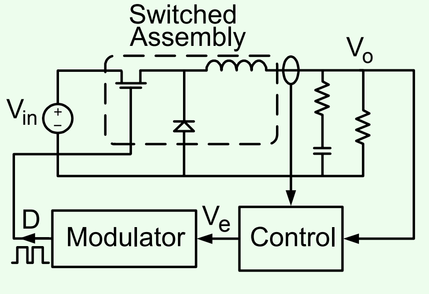
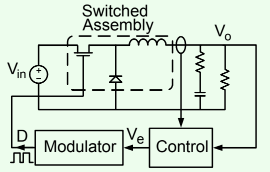
The simulation problem

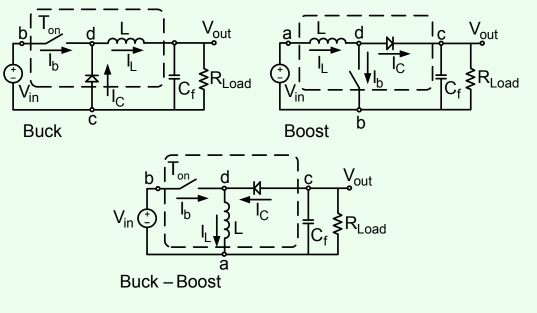


The simulation problem

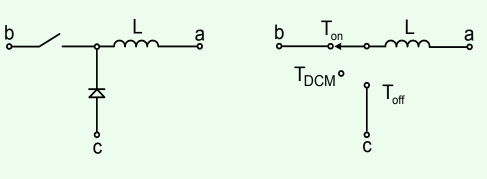


- The problematic part : Switched Assembly
- Rest of the circuit continuous - SPICE compatible
- Only possible simulation :
  Time domain (cycle-by-cycle) -Transient
- The objective : translate the
  Switched Assembly into an equivalent
  circuit which is SPICE compatible

Average Simulation of PWM Converters



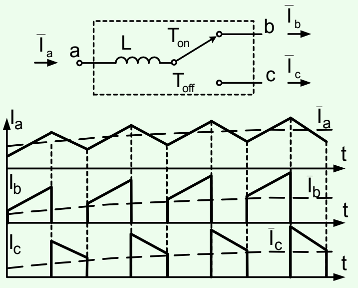
The Switched Inductor Model



T_{on} - switch conduction time
T_{off} - diode conduction time
T_{DCM} - no current time (in DCM)

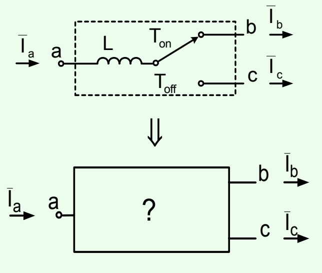
The Switched Inductor Model (SIM) (CCM)

The concept of average signals

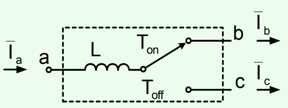


The SIM

Objective : To replace the switched part by a continuous network



Average current



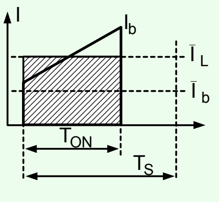
$$\bar{I}_b = \frac{\bar{I}_L T_{on}}{T_S} = \bar{I}_L D_{on}$$

$$D_{on} = \frac{T_{ON}}{T_S}$$

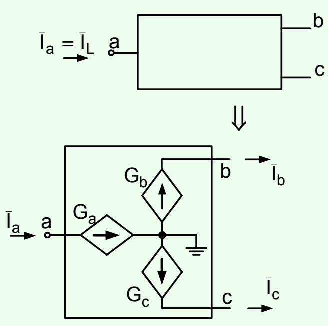
$$\bar{I}_a = \bar{I}_L$$

Similarly :

$$\bar{I}_c = \frac{\bar{I}_L T_{off}}{T_S} = \bar{I}_L D_{off}$$



Toward a continuous model



$\bar{I}_b = \bar{I}_L \cdot D_{on}$

$\bar{I}_c = \bar{I}_L \cdot D_{off}$

G_a, G_b, C_c - current dependent sources

$G_a \equiv \bar{I}_L$

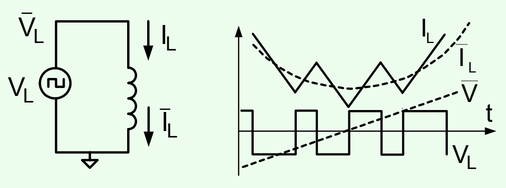
$G_b \equiv \bar{I}_L \cdot D_{on}$

$G_c \equiv \bar{I}_L \cdot D_{off}$

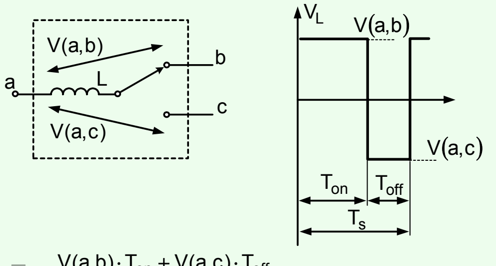
Average inductor current

Deriving $\bar{I}_L$

$$\frac{dI_L}{dt} = \frac{V_L}{L} \quad \Rightarrow \quad \frac{d\bar{I}_L}{dt} = \frac{\bar{V}_L}{L}$$



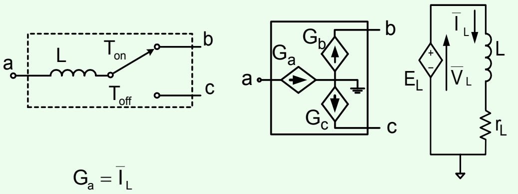
Average inductor current



$$\bar{V}_L = \frac{V(a,b) \cdot T_{on} + V(a,c) \cdot T_{off}}{T_S} =$$

$$= V(a,b) \cdot D_{on} + V(a,c) \cdot D_{off}$$

The Generalized Switched Inductor Model (GSIM)



$G_a = \overline{I}_L$

$G_b = \overline{I}_L \cdot D_{on}$

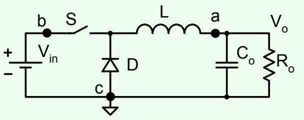
$G_c = \overline{I}_L \cdot D_{off}$

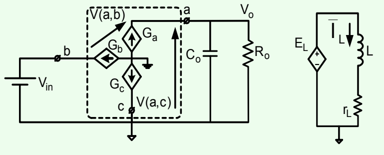
$E_L = V(a,b) \cdot D_{on} + V(a,c) \cdot D_{off}$

Topology independent !

<u>Example</u> Implementation in Buck Topology

1. The formal approach



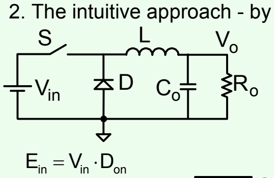


$G_a = \overline{I}(L) \quad G_b = \overline{I}(L) \cdot D_{on} \quad G_c = \overline{I}(L) \cdot D_{off}$

$E_L = [V_o - V_{in}] \cdot D_{on} + [0 - V_o] \cdot D_{off}$

Implementation in Buck Topology

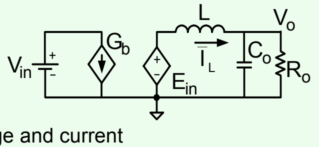
2. The intuitive approach - by inspection



$E_{in} = V_{in} \cdot D_{on}$

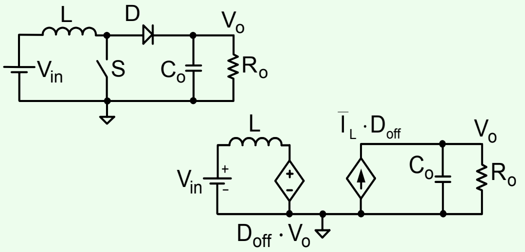
$G_b = \overline{I}_L \cdot D_{on}$

$E_{in} - V_o \rightarrow \overline{V}_L$



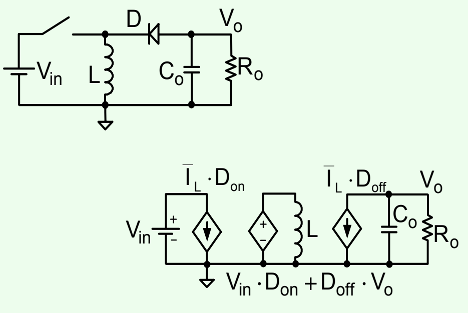
Polarity: (voltage and current sources) selected by inspection

Boost

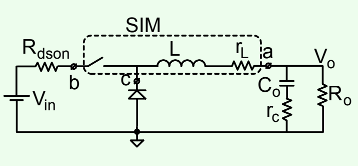


- Emulate average voltage on inductor
- Create $\bar{I}_L$ dependent current sources

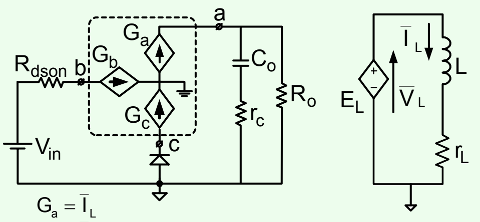
Buck-Boost



Partially accounting for parasitics



Modified Average Model



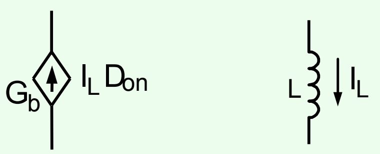
$G_a = \bar{I}_L$

$G_b = \bar{I}_L \cdot D_{on}$

$G_c = \bar{I}_L \cdot D_{off}$

$E_L = (V_a - V_b) \cdot D_{on} + (V_a - V_c) \cdot D_{off}$

Making the model SPICE compatible

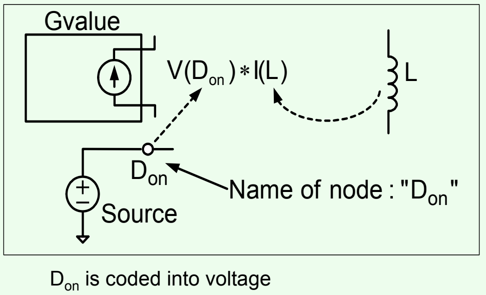


I_L and D_{on} are time dependent variables $\{I_L(t), D_{on}(t)\}$

D_{on} is not an electrical variable

In SPICE environment

$\Downarrow$



D_{on} is coded into voltage

Simulation

Running SPICE simulation

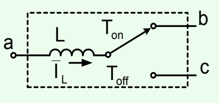
DC (steady state points) - as is

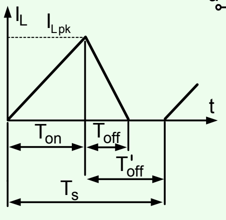
TRAN (time domain) - as is

AC (small signal) - as is

* Linearization is done by simulator !

Discontinuous Model (DCM)



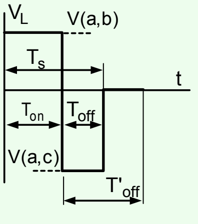


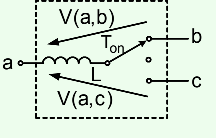
$$T'_{off} = T_s - T_{on}$$

$$D'_{off} = \frac{T_s - T_{on}}{T_s} = 1 - D_{on}$$

Combining CCM / DCM

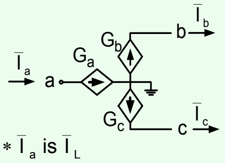
1.The average inductor current in DCM

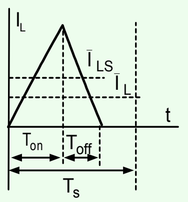




$\bar{V}_L = V(a,b)D_{on} + V(a,c)D_{off}$ as in CCM

Combining CCM / DCM

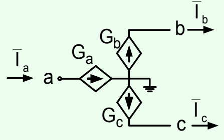


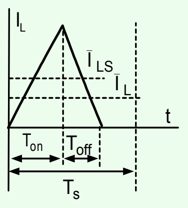


- $\bar I_a$ is $\bar I_L$
- $\bar I_b$ is sampled during T_{on}
- $\bar I_c$ is sampled during T_{off}
- $\bar I_b$ is $\bar I_c$ are sampling $\bar I_{Ls}$

$$\bar I_{Ls} = \frac{\bar I_L T_s}{T_{on}+T_{off}} = \frac{\bar I_L}{D_{on}+D_{off}}$$

Combining CCM / DCM





$$G_a = \bar I_L$$

$$G_b = \frac{\bar I_L D_{on}}{D_{on}+D_{off}}$$

$$G_c = \frac{\bar I_L D_{off}}{D_{on}+D_{off}}$$

in CCM: $(D_{on}+D_{off})=1$

Doff in DCM

$$I_{pk} = \frac{V(a,b)T_{on}}{L}$$

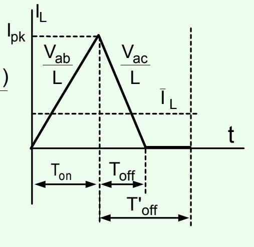
$$\bar I_L = \frac{1}{2}\left(\frac{V(a,b)T_{on}}{L}\right)\frac{(T_{on}+T_{off})}{T_S}$$

$$\bar I_L = \frac{V(a,b)D_{on}}{2Lf_s}(D_{on}+D_{off})$$

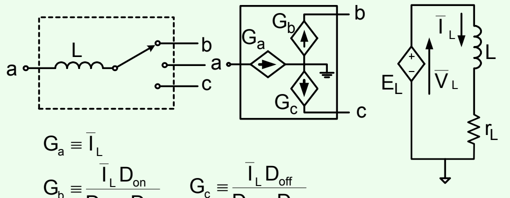
$$D_{off} = \frac{2\bar I_L L f_s}{V(a,b)D_{on}} - D_{on}$$

$$D'_{off} = 1 - D_{on}$$

$$D_{off} \le 1 - D_{on}$$



The combined DCM / CCM mode



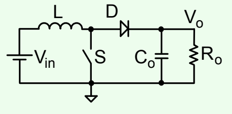
$$G_a \equiv \bar{I}_L$$

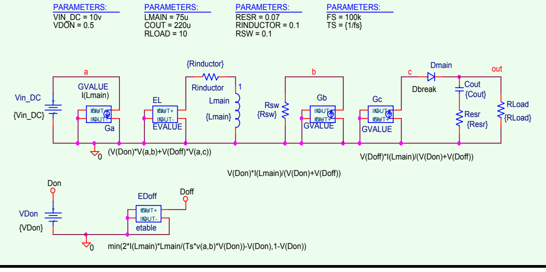
$$G_b \equiv \frac{\bar{I}_L D_{on}}{D_{on}+D_{off}} \qquad G_c \equiv \frac{\bar{I}_L D_{off}}{D_{on}+D_{off}}$$

$$E_L = V(a,b)\cdot D_{on} + V(a,c)\cdot D_{off}$$

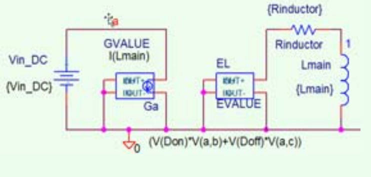
$$D_{off} = \min\left\{(1-D_{on}),\ \left(\frac{2\bar{I}_L L f_s}{V(a,b) D_{on}} - D_{on}\right)\right\}$$

Example: Boost average model simulation





Example: Boost average model simulation



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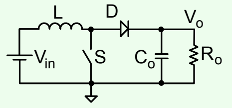
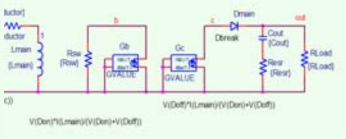
Example: Boost average model simulation





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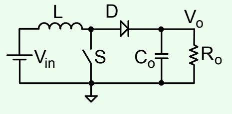
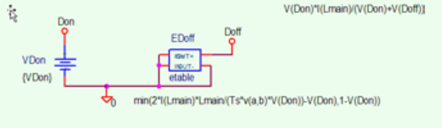
Example: Boost average model simulation





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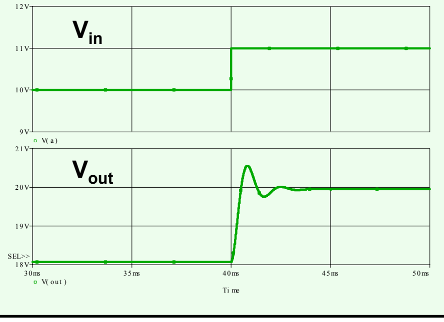
Boost: Response to step of input voltage
(average model simulation)



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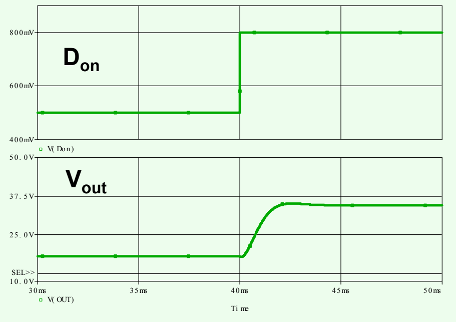
Boost: Response to step of duty cycle



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Boost transfer function (CCM)

DC Sweep simulation