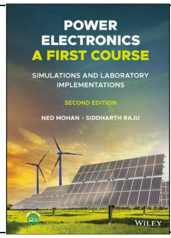
ECEN 438/738 Power Electronics



Power Electronics
A First Course: 2nd Edition

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Chapter 1
Power Electronics: An Enabling Technology

1

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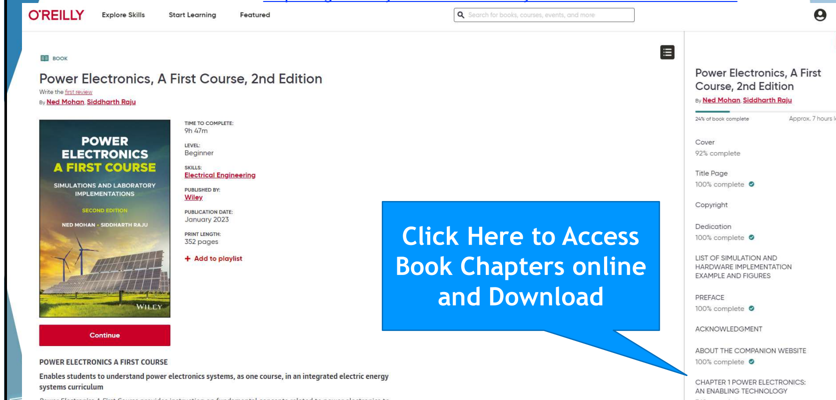

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2

DC-DC Buck Converter - DC-DC Boost Converter

1 $V_o = D V_{in}$

2 $\Delta I_L = \frac{V_o (1-D) T}{L}$

3 $L_{min} = \frac{(1-D)R}{2f}$

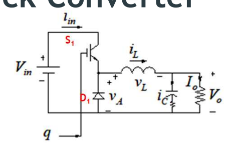
4 $I_L = I_o = \frac{V_o}{R}$

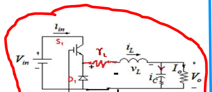
$T = \frac{1}{f}$

5 (Input Power) $V_{in} I_{in} = V_o I_o$ (output power)

$I_{in} = \frac{V_o}{V_{in}} \cdot I_o = D \cdot I_o = D I_L$

6 $C = \frac{(1-D)}{\left(\frac{\Delta V_o}{V_o}\right) * 8 * L * f^2}$





$$V_o = \frac{V_{in} * D}{1 + \frac{r_L}{R}}$$

$$\eta = \frac{1}{1 + \frac{r_L}{R}}$$

$$V_o = \frac{V_{in}}{1-D}$$

$$\Delta I_L = \frac{V_{in} * DT}{L}; \quad L = \frac{V_{in} * DT}{\Delta I_L} = \frac{V_{in} * D}{f * \Delta I_L}$$

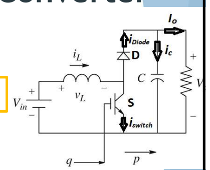
$$L_{min} = \frac{D * (1-D)^2 * R}{2 * f}$$

$$V_{in} * I_L = V_o * I_o$$

$$I_{Diode} = I_o = \frac{V_o}{R}$$

$$I_{switch} = I_L * D$$

$$C = \frac{I_o * DT}{\Delta V_o} = \frac{D}{R * \left(\frac{\Delta V_o}{V_o}\right) * f}$$



$$C = \frac{I_0 * DT}{\Delta V_0} = \frac{D}{R * \left(\frac{\Delta V_0}{V_0}\right) * f}$$

$$\frac{V_o}{V_{in}} = \left(\frac{1}{1-D}\right)\left(\frac{1}{1 + \frac{r_L}{R(1-D)^2}}\right)$$

$$\eta = \frac{1}{1 + \frac{r_L}{R(1-D)^2}}$$

3

DC - DC Buck-Boost Converter Summary

1 $$\frac{V_o}{V_{in}} = \frac{D}{1-D}$$

2 $$\Delta I_L = \frac{V_{in} * DT}{L}; \quad L = \frac{V_{in} * DT}{\Delta I_L} = \frac{V_{in} * D}{f * \Delta I_L}$$

$L = \frac{N^2}{R_e}$

$R = \frac{\rho l}{A}$

$v_L = L \frac{di}{dt}$

Follow the same procedure as detailed in buck & boost converter analysis to show the following

3 $$L_{min} = \frac{R * (1-D)^2}{2 * f}$$

4 $$C = \frac{I_o * DT}{\Delta V_o} = \frac{D}{R * \left(\frac{\Delta V_o}{V_o}\right) * f}$$

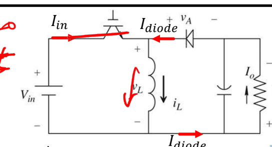
$$V_{in} * I_{in} = V_o * I_o$$

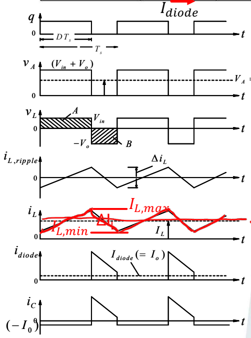
$$I_{in} = \frac{V_o}{V_{in}} I_o = \frac{D}{1-D} I_o$$

$$I_L = I_{in} + I_o$$

$$I_L = I_{in} + I_o = \frac{1}{1-D} I_o = \frac{1}{1-D} \frac{V_o}{R}$$

$$I_{Diode} = I_o = \frac{V_o}{R}$$





4

DC - DC Converters - Discontinuous Conduction

Section 3.19 (page 69/99)

5

DC - DC Converters - Discontinuous Conduction — Buck Converter

Border of CCM and DCM:

- *As we decrease the inductance L or the output load decreased (i.e. R increased the inductor current starts to shift downwards and hits the critical boundary.*
- *Any further decrease in load for a low value of L we enter into discontinuous conduction.*

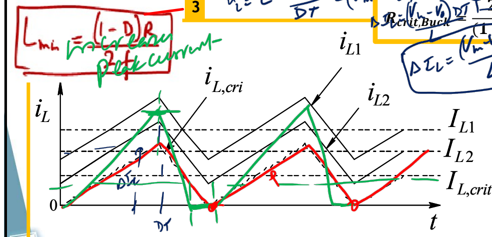
$v_L = L\frac{\Delta I_L}{DT} = (V_{in} - V_o)$

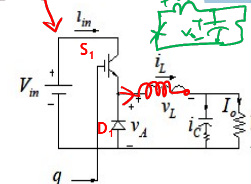
$\Delta I_L = \frac{(V_{in} - V_o)D}{L \cdot f}$

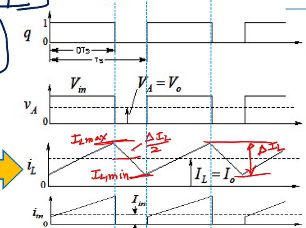
$L_{min} = \frac{(1-D)R}{2f}$ — increase peak current

3

$$R_{crit,Buck} = \frac{2Lf}{(1-D)}$$







6

DC - DC Converters - Discontinuous Conduction — Buck Converter

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

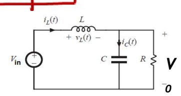
3

$$R_{crit,Buck} = \frac{2Lf}{(1-D)}$$

for continuous conduction

$V_o = DV_{in}$

Switch - ON



$$v_L = L\frac{di_L}{dt} = V_{in} - V_o$$

the solution is:

$$i_L = \frac{(V_{in} - V_o)}{L}t$$

The average input current:

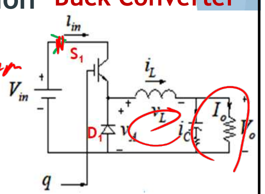
$$I_{in} = \frac{1}{T}\int_0^{DT}\frac{(V_{in} - V_o)}{L}t\,.dt$$

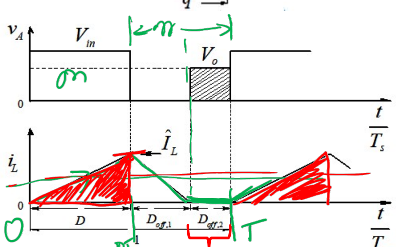
$$I_{in} = \frac{(V_{in} - V_o) * D^2}{2 * L * f}$$

Now: $V_{in} * I_{in} = \frac{V_o^2}{R}$

$$V_{in} * \frac{(V_{in} - V_o) * D^2}{2 * L * f} = \frac{V_o^2}{R}$$

Simplifying this further and solving the quadratic equation for V_o yields:





Note: $D_{off,1} + D_{off,2} = (1-D)$ Current is zero

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DC - DC Converters - Discontinuous Conduction — Buck Converter

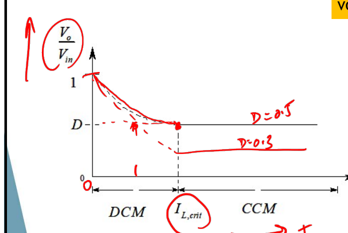
$V_o = DV_{in}$

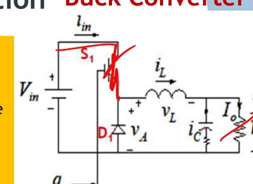
$$V_o = \frac{V_{in}}{2}\left(\sqrt{M * (M + 4)} - M\right)$$

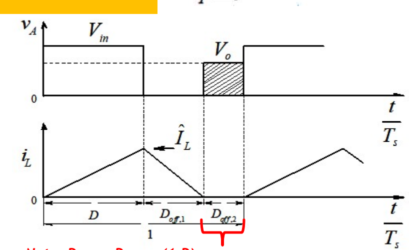
Where:

$$M = \left(\frac{R}{2 * L * f}\right) * D^2$$

For light loads i.e. $R > R_{crit,Buck}$ causes the output voltage to rise towards the input voltage under discontinuous conduction. Note: the feedback controller will adjust the duty-ratio in order to regulate the output voltage







Note: $D_{off,1} + D_{off,2} = (1-D)$ Current is zero

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DC - DC Converters - Discontinuous Conduction — Buck Converter

Input voltage V_{in} = 36V

Output voltage V_o = 3.3V ; voltage ripple not to exceed 2%

Output power P_o = 5 watts

Switching Frequency f = 300kHz

Design the buck converter in discontinuous mode to have small inductance value, hence the size.

$V_o = D V_{in}$

Design at the boundary

$$D = \frac{3.3}{36} = 0.0917$$

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

$$R = \frac{V_o^2}{P_o} = \frac{3.3*3.3}{5} = 2.2\ ohms$$

$$L_{min} = \frac{(1-0.0917)*2.2}{2*300khz} = 3.33\ uH$$

$$I_{L,avg} = \frac{3.3}{2.2} = 1.5\ A$$

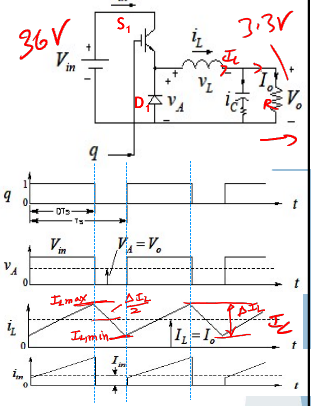
$$\Delta I_L = \frac{V_o(1-D)T}{L} = 0.27$$

$P_o = V_o \cdot I_o$, $R = \frac{V_o}{I_o}$, 36V, 3.3V, $I_L = 1.5A$

$I_{L,max} = I_L + \frac{\Delta I_L}{2}$

$I_{L,max} = 1.635\ A$

$\frac{I_{L,max}}{I_{L,av}} = \frac{1.635}{1.5} = 1.09$



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DC - DC Converters - Discontinuous Conduction — Buck Converter

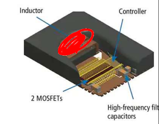
Input voltage V_{in} = 36V

Output voltage V_o = 3.3V ; voltage ripple not to exceed 2%

Output power P_o = 5 watts

Switching Frequency f = 300kHz

$V_o = D V_{in}$ not valid



Design the buck converter in discontinuous mode to have small inductance value, hence the size.

Let us choose the inductance $L = 0.5*L_{min}$

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

$$R = \frac{V_o^2}{P_o} = \frac{3.3*3.3}{5} = 2.2\ ohms$$

$$L_{min} = \frac{(1-0.0917)*2.2}{2*300khz} = 3.33\ uH$$

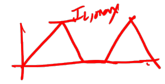
$M = \frac{R\,D^2}{2Lf}$

$$Now\ V_o = \frac{V_{in}}{2}\left(\sqrt{M*(M+4)} - M\right)$$

$Solve\ M = 0.00925$

$$Since\ M = \left(\frac{R}{2*L*f}\right)*D^2\ ;\ \text{Find D for L} = 1.7\text{uH}$$

D = 0.0655



Let us choose the inductance $L = 0.5*L_{min}$

$L = 1.7\ uH$

This design has a small inductor that can be integrated into a chip

Calculate $I_{L,peak}$ and $\frac{I_{L,peak}}{I_{L,avg}}$

$$I_{L,peak} = \frac{V_{in}*D}{L*f} = 4.62A \qquad \frac{I_{L,peak}}{I_{L,avg}} = \frac{\cancel{4.62}}{1.5} = \cancel{3.05}$$

4.12, 2.8

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DC - DC Converters - Discontinuous Conduction — Buck Converter

Input voltage V_{in} = 36V

Output voltage V_o = 3.3V ; voltage ripple not to exceed 2%

Output power P_o = 5 watts

Switching Frequency f = 300kHz

Design the buck converter in discontinuous mode to have small inductance value, hence the size.

result in peak current for the MOSFET

$L = 0.83\ uH$

Repeat this by choosing $L = 0.25*L_{min}$

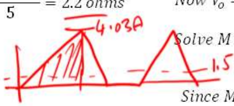
$$L_{min} = \frac{(1-D)R}{2f}$$

$$R = \frac{V_o^2}{P_o} = \frac{3.3*3.3}{5} = 2.2\ ohms$$

$$Now\ V_o = \frac{V_{in}}{2}\left(\sqrt{M*(M+4)} - M\right)$$

$Solve\ M = 0.00925$

$$L_{min} = \frac{(1-0.0917)*2.2}{2*300khz} = 3.33\ uH$$



$$Since\ M = \left(\frac{R}{2*L*f}\right)*D^2\ ;\ \text{Find D for L} = 0.83\text{uH}$$

D = 0.046

Let us choose the inductance $L = 0.25*L_{min}$

$L = 0.83\ uH$

This design has a small inductor that can be integrated into a chip

Calculate $I_{L,peak}$ and $\frac{I_{L,peak}}{I_{L,avg}}$

$$I_{L,peak} = \frac{V_{in}*D}{L*f} = 6.65A \qquad \frac{I_{L,peak}}{I_{L,avg}} = \frac{6.65}{1.5} = 4.4$$

$(V_i - V_o)$, 6.04, 6.04, 4.03

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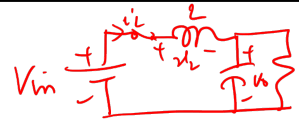

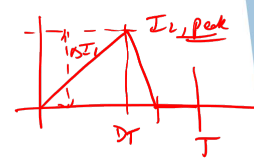

$L\frac{di_L}{dt} = V_{in} - V_o$

$L \cdot \frac{\Delta I_L}{DT} = V_{in} - V_o$

$\Delta I_L = I_{peak} = \frac{(V_{in} - V_o)DT}{L}$

$$\boxed{I_{L,peak} = \frac{(V_{in} - V_o)D}{L \cdot f}}$$

$I_{peak} = \frac{(36 - 3.3)(0.0655)}{1.7\mu H \times 300\,kHz}$

$= 4.2\ A$

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DC - DC Converters - Discontinuous Conduction — Buck Converter

Input voltage V_{in} = 36V
Output voltage V_o = 3.3V ; voltage ripple not to exceed 2%
Output power P_o = 5 watts
Switching Frequency f = 300kHz
Inductance L = 40 micro-H

a) Specify the output power at which the boundary between continuous and discontinuous occur?
b) If the output load resistance R = 30 ohms, is the converter is discontinuous conduction? If yes calculate the duty cycle D required to regulate the output voltage.

$R = \frac{V_o^2}{P_o} = \frac{3.3 * 3.3}{5} = 2.2\ ohms$

$V_o = DV_{in}$

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

3

$D = \frac{3.3}{36} = 0.0917$

@ 0.412 watts

$R_{crit,Buck} = 26.42\ ohms$

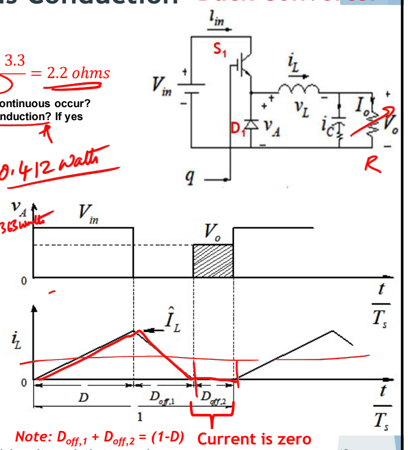
$R \approx 30\Omega \rightarrow P_o = \frac{3.3^2}{30} = 0.363\ watts$

$R_{crit,Buck} = \frac{2Lf}{(1-D)}$

The output Power P_o at the boundary $= \frac{V_o^2}{R_{crit}} = 0.412\ W$

a) Now for an output load resistance R = 30 ohms > $R_{crit,Buck}$= 26.42 ohms the buck converter will be in discontinuous conduction

$P_o = 0.363$ watts



Note: $D_{off,1} + D_{off,2}$ = (1-D) Current is zero

DC - DC Converters - Discontinuous Conduction — Buck Converter

Input voltage V_{in} = 36V
Output voltage V_o = 3.3V ; voltage ripple not to exceed 2%
Output power P_o = 5 watts
Switching Frequency f = 300kHz
Inductance L = 40 micro-H
a) Specify the output power at which the boundary between continuous and discontinuous occur?
b) If the output load resistance R = 30 ohms, is the converter is discontinuous conduction? If yes calculate the duty cycle D required to regulate the output voltage.

a) Now for an output load resistance R = 30 ohms the buck converter will be in discontinuous conduction

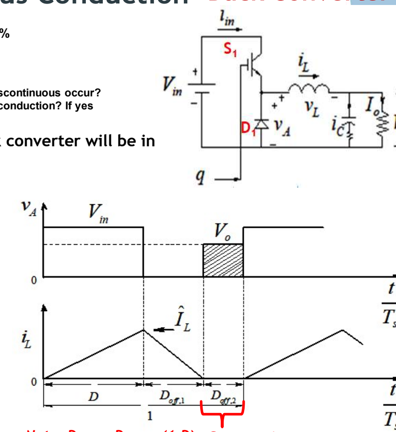
$V_o = \frac{V_{in}}{2}\left(\sqrt{M*(M+4)} - M\right)$ → $M = 0.00925$

Where:

$M = \left(\frac{R}{2*L*f}\right) * D^2$ → $D = 0.086$

30, 40μH, 300kHz

Calculate $I_{L,peak}$ and $\frac{I_{L,peak}}{I_{L,avg}}$



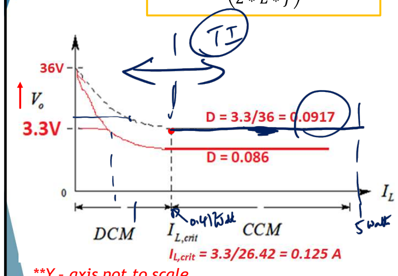
Note: $D_{off,1} + D_{off,2}$ = (1-D) Current is zero

DC - DC Converters - Discontinuous Conduction — Buck Converter

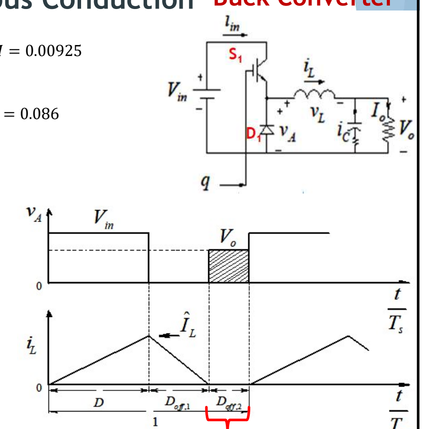
$V_o = \frac{V_{in}}{2}\left(\sqrt{M*(M+4)} - M\right)$ → $M = 0.00925$

Where:

$M = \left(\frac{R}{2*L*f}\right) * D^2$ → $D = 0.086$

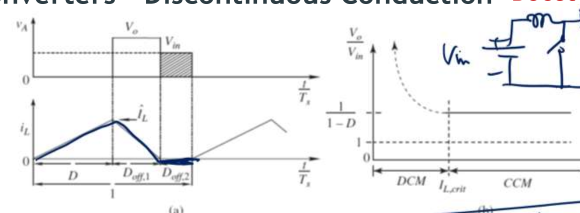


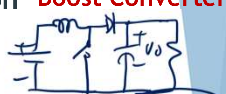
**Y - axis not to scale



Note: $D_{off,1} + D_{off,2}$ = (1-D) Current is zero

DC - DC Converters - Discontinuous Conduction — Boost Converter





$\frac{V_o}{V_{in}} = \frac{1}{1-D}$

FIGURE 3.26 Boost converter in DCM.

$D = f(R, L, f_s)$

$V_o = \frac{V_{in}}{2}(1 + \sqrt{1+4M})$ in DCM (3.53a)

Solve for m

$M = \left(\frac{R}{2Lf_s}\right)D^2$ (3.53b)

Solve for $D = f(R, L, f_s)$

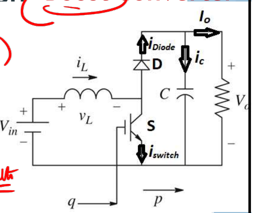
DC - DC Converters - Discontinuous Conduction — Boost Converter

Input voltage V_{in} = 4.2V
Output voltage V_o = 8V ; voltage ripple not to exceed 2%
Output current I_o = 1A
Switching frequency f = 200kHz
Inductor L = *15 micro-H*

a) Is the converter operating is continuous conduction mode?
b) At what output power does discontinuous conduction begins to occur (i.e. the boundary)
c) Find the required D to regulate the output voltage at 8V when P_o drops to 1 watt

$P_o = 8$ watt (8×1)

$\frac{V_o}{V_{in}} = \frac{8}{4.2} = \frac{1}{1-D}$
$D = 0.475$



$$\boxed{L_{min} = \frac{D*(1-D)^2*R}{2*f}}$$ 3

$D = 0.475$

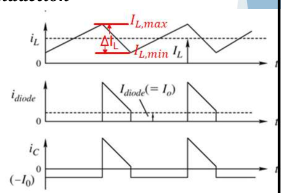
$R_{crit} = \frac{2*f*L}{D*(1-D)^2}$ = 45.8 ohms $\rightarrow P_{o\,crit} = 1.4$ watt

a) $V_o = 8V, I_o = 1A$ $R = \frac{8}{1} = 8\ ohm$ $< 45.8\ ohm$ ***Therefore Continious conduction***

b) At what output power does discontinuous conduction begins to occur (i.e. the boundary)

Therefore $P_o = \frac{V_o^2}{R_{crit}} =$ 1.4 watts

for $P = 1$ Watt Discontinuous



Therefore P_o = 1.4 W to 8 W continuous conduction will occur

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DC - DC Converters - Discontinuous Conduction — Boost Converter

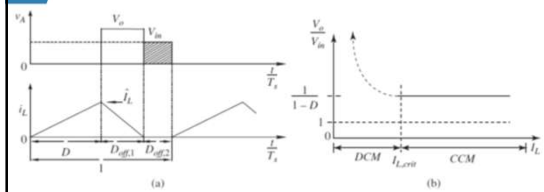

FIGURE 3.26 Boost converter in DCM.

Find the required D to regulate the output voltage at 8V when P_o drops to 1 watt

- Find the output resistance R at 1 watt

$P_o = \frac{V_o^2}{R}$; $R = \frac{V_o^2}{P_o} = 64\ ohms$

8V, 4.2V

$V_o = \frac{V_{in}}{2}(1 + \sqrt{1 + 4M})$ in DCM (3.53a) ➡ $M = 1.723$

1.723, 64

$M = \left(\frac{R}{2Lf_s}\right)D^2$ (3.53b) ➡ $D = 0.4$

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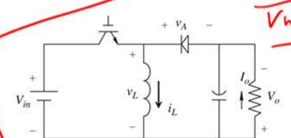
DC - DC Converters - Discontinuous Conduction — Buck Boost Converter

$\frac{V_o}{V_{in}} = \frac{D}{1-D}$ for Continuous



$V_o = DV_{in}\sqrt{\frac{R}{2Lf_s}}$ in DCM (3.57)

$$\boxed{\frac{V_o}{V_{in}} = D\sqrt{\frac{R}{2Lf_s}}} \Rightarrow f(D, R, L, f_s)$$

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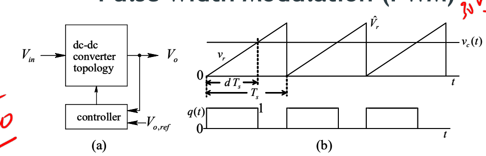
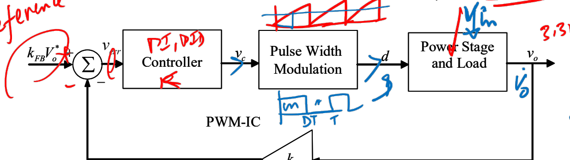
Regulation of DC-DC Converter by Pulse width Modulation (PWM)



$v_c(t)$ — $\frac{1}{\hat{V}_r}$ — $d(t) = \frac{v_c(t)}{\hat{V}_r}$

DC-DC

AC-DC



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