Lecture # 5

ECEN 438/738 Power Electronics

Spring 2025 Semester

Dr. Prasad Enjeti,
Electrical & Computer Engineering
Texas A&M University
http://enjeti.tamu.edu

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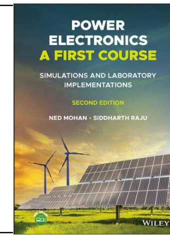

Power Electronics
A First Course: 2nd Edition

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Chapter 1
Power Electronics: An Enabling Technology

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DC - DC Buck Converter → $0 \le D \le 1$

$\boxed{V_o = D V_{in}}$ — 1 Where the duty cycle is 0<D<1

$\boxed{\Delta I_L = \frac{V_o (1-D) T}{L}}$ — 2 Where ΔI_L is inductor current ripple (peak to peak)

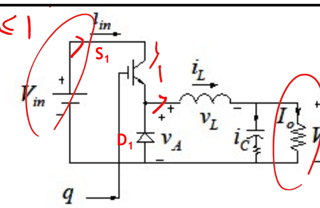
$\boxed{L_{min} = \frac{(1-D)R}{2f}}$ — 3 Where L_{min} is the minimum (critical) inductance required to maintain continuous conduction

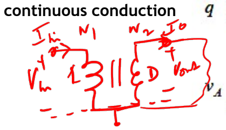
4 $I_L = I_o = \frac{V_o}{R}$

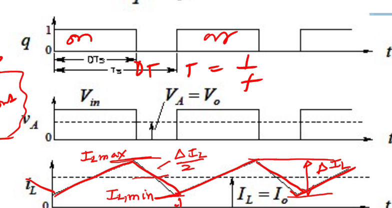
$T = \frac{1}{f}$

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

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







$\frac{V_{out}}{V_{in}} = D$

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

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

6 $\frac{I_{in}}{I_o} = \frac{V_{out}}{V_{in}} = D$

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DC - DC Buck Converter -Design Example # 2

Input voltage V_{in} = 7.5V to 36V

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

Output current I_o = 0.5A ← Full load 100%

Switching Frequency f = 300kHz

a) Specify the inductor value such that continuous conduction is achieved from 25% load to 100% load

b) Find the capacitor value C that meets the specification.

c) Also determine the required rms current ratings of the MOSFET and the Diode

$V_o = DV_{in}$ 1

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

Solution: # 1 Input voltage = 7.5V

$D = \frac{3.3}{7.5} = 0.44$ 25% load, I_o = 0.5*5 = 0.125A

Load resistance $R_{25\%} = \frac{3.3}{0.125} = 26.5\ ohms$

$L_{min-@25\%-load} = \frac{(1-0.44)*26.5}{2*300{,}000} = 24.6\ micro-H$

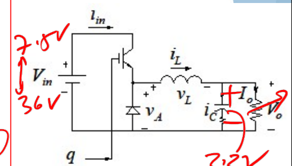
Input voltage = 36V

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

$L_{min-@25\%-loa} = \frac{(1-0.0917)*26.5}{2*300{,}000} = 40\ micro-H$

Pick the largest $L = 40\ micro-H$

7.5V – 36V



Smallest 3.3V

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

Use the smallest D to get the larger C to meet the spec.

$C = \frac{(1-0.0917)}{(0.02)*8*L*f^2} = 1.58$ micro-f

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DC - DC Buck Converter -Design Example # 2

Input voltage V_{in} = 7.5V to 36V

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

Output current I_o = 0.5A → I_o

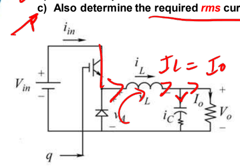
Switching Frequency f = 300kHz

a) Specify the inductor value such that continuous conduction is achieved from 25% load to 100% load

b) Find the capacitor value C that meets the specification

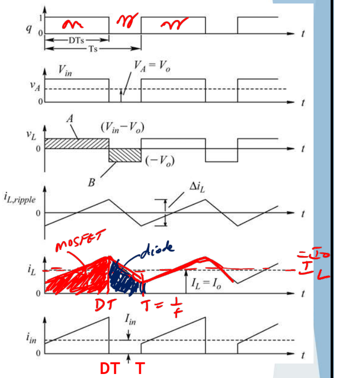
c) Also determine the required rms current ratings of the MOSFET and the Diode

Find $I_{L,rms}$.



$I_L = I_o$

$(\sqrt{D}\cdot I)$ DT T



rms current ratings of the MOSFET = $I_{in,rms} = \sqrt{D} * I_{L,rms}$

Note: $I_{L,rms} = I_o = 0.5A$; Use larger value of D (larger)

Therefore ratings of the MOSFET = $I_{in,rms} = \sqrt{0.44} *).5 = 0.33A$

rms current ratings of the Diode = $I_{D,rms} = \sqrt{1-D} * I_{L,rms}$

Use smaller value of D for this (smaller)

Therefore ratings of the Diode = $I_{d,rms} = \sqrt{1-0.0917} * 5 = 0.476A$

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DC - DC Buck Converter

19V

Input voltage V_{in} = 19V

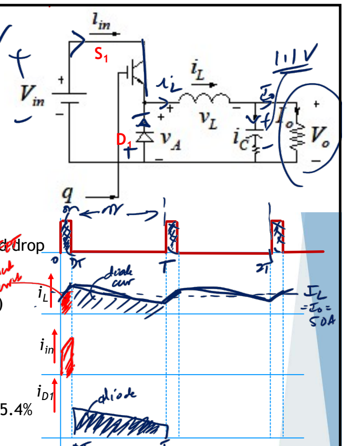
Output voltage V_o = 1.1V; voltage ripple not to exceed 2%

Output current I_o = 50A

Switching Frequency f = 500kHz

$V_o = DV_{in}$ 1   D = 1.1/19 = 0.058

Let us only consider diode conduction losses



Silicon diode = 0.7 V forward drop

Conduction loss = 0.7*50*(1-D)
= 33 watts

Output power Po = 1.1*50 = 55 watts

Efficiency = 55/(55+33) = 62.5%

$\eta = \frac{P_{out}}{P_{out}+P_{loss}}$

Schottky diode = 0.2 V forward drop

Conduction loss = 0.2*50*(1-D)
= 9.42 watts

Efficiency = 55/(55+9.42) = 85.4%

What we need is the efficiency to be in 90% range. How can we achieve this?

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DC - DC Buck Converter

Input voltage V_{in} = 19V

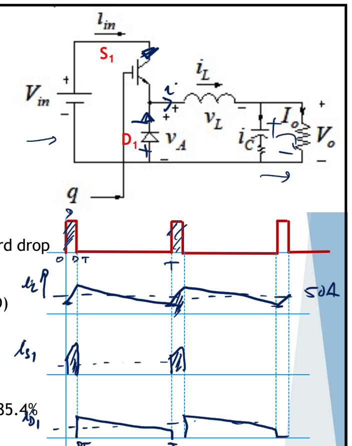
Output voltage V_o = 1.1V; voltage ripple not to exceed 2%

Output current I_o = 50A

Switching Frequency f = 500kHz

$V_o = DV_{in}$ 1   D = 1.1/19 = 0.058

Let us only consider diode conduction losses



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What we need is the efficiency to be in 90% range. How can we achieve this?

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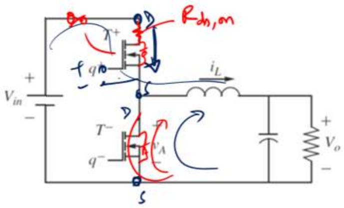
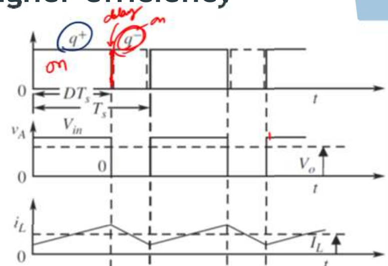
DC - DC Buck Converter - Synchronous Rectifier for Low output voltage and higher efficiency





- Diode is replaced by a MOSFET
- The MOSFETs are driven by complimentary gating signals with sight delay to avoid shoot through
- When the upper MOSFET is off, the inductor current flows through the channel, from the source to the drain, of the lower MOSFET
- This configuration is suitable for low output voltages - say 1V and also yields higher efficiency

Reverse conduction of GaN MOSFETS https://www.youtube.com/watch?v=QNHzaiWCUeE
Gan System FAQ: https://gansystems.com/gan-transistors/faq/#toggle-id-39

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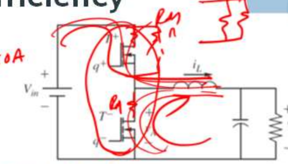
DC - DC Buck Converter - Synchronous Rectifier for Low output voltage and higher efficiency

Input voltage V_{in} = 19V
Output voltage V_o = 1.1V ; voltage ripple not to exceed 2%
Output current I_o = 50A
Switching Frequency f = 500kHz

$$Conduction\ Loss = I_L^2 * R_{DS(on)}$$

$$= 50^2 * 1.45 * 10^{-3} = 3.625\ watts$$

$$Efficiency \sim \frac{55}{55 + 3.625} * 100 = 93.8\%$$



EPC2023 - Enhancement Mode Power Transistor

Now we are in the ball park of 90% efficiency once we add switching losses, losses in the inductor/capacitor etc.

https://epc-co.com/epc/Products/eGaNFETsandICs/EPC2023.aspx

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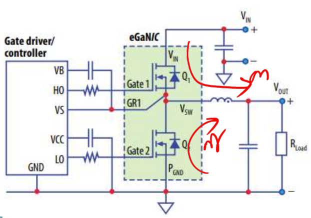
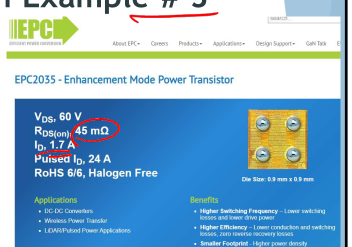
DC - DC Buck Converter -Design Example # 3

Input voltage V_{in} = 35V
Output voltage V_o = 5V voltage ripple not to exceed 2%
Output current I_o = 1A
Switching Frequency f = 500kHz

a) Specify the inductor value such that the peak-to-peak variation in inductor current ΔI_L does not exceed 40% of the average value (I_L).
b) Find the capacitor value C that meets the specification.
c) Also determine the required *rms* current rating of the inductor and the capacitor.





https://epc-co.com/epc/Products/eGaNFETsandICs/EPC2035.aspx

$$\boxed{\text{Conduction loss} = I^2 * R_{DS(on)} = 1 * 1 * 0.045 = 45mW}$$

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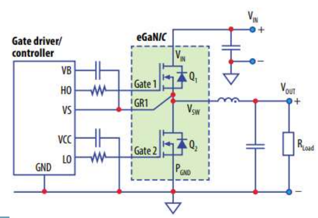
DC - DC Buck Converter -Design Example # 3

Input voltage V_{in} = 35V
Output voltage V_o = 5V ; voltage ripple not to exceed 2%
Output current I_o = 1A
Switching Frequency f = 500kHz

a) Specify the inductor value such that the peak-to-peak variation in inductor current ΔI_L does not exceed 40% of the average value (I_L).
b) Find the capacitor value C that meets the specification.
c) Also determine the required *rms* current rating of the inductor and the capacitor.



https://epc-co.com/epc/Products/eGaNFETsandICs/EPC2035.aspx

From the data sheet

$$t_r = 1.3\ ns$$
$$t_f = 1.8\ ns$$

Switching Losses:

$$P_{sw} = \frac{1}{2} V_{in} I_o (t_{c,on} + t_{c,off}) f_s$$

$$t_{c,on} = t_{ri} + t_{fv} = 1.3 + 1.8 = 3.1\ ns$$

$$t_{c,off} = t_{rv} + t_{fi} = 1.3 + 1.8 = 3.1\ ns$$

$$\boxed{P_{sw} = \frac{1}{2} V_{in} I_o (t_{c,on} + t_{c,off}) f_s} \boxed{= 0.5 * 35 * 1 * 6.2ns * 500kHz = 54.25\ mW}$$

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DC - DC Buck Converter -Design Example # 3

Input voltage V_{in} = 35V
Output voltage V_o = 5V ; voltage ripple not to exceed 2%
Output current I_o = 1A
Switching Frequency f = 500kHz

a) Specify the inductor value such that the peak-to-peak variation in inductor current Δi_L does not exceed 40% of the average value (I_L).
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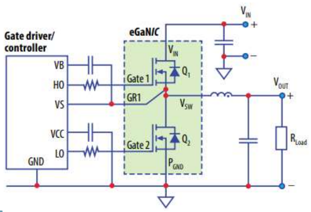

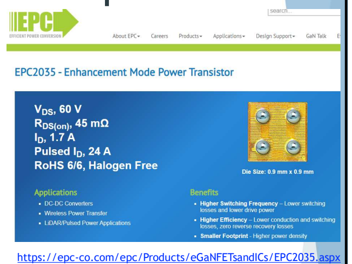

Switching Losses $= 0.5 * 35 * 1 * 6.2ns * 500kHz = 54.25\ mW$

Conduction loss $= I^2 * R_{DS(on)} = 1 * 1 * 0.045 = 45mW$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{5*1}{5+0.09925} * 100 = 98.05\%$$

Compared to 14.3% efficiency with linear regulator

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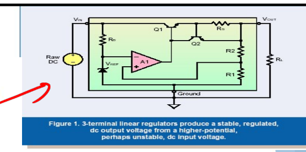
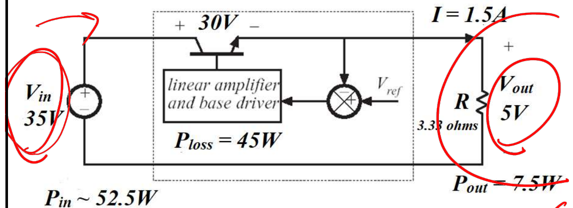
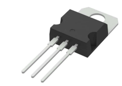
Linear Regulator

Dissipative realization



Series pass regulator: transistor operates in active region





L 7805 - \$0.77 - Qty = 1 or \$0.34 - Qty = 1000

Input voltage (max) = 35 V
Output voltage (fixed) = 5 V
Output current (max) = 1.5 A

$$\eta = \frac{P_{out}}{P_{in}} = \frac{7.5}{52.5} * 100 = 14.3\%$$

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Suggested Problems - for you to solve

DC - DC Buck Converter -Problems in the book

1. Problem 3.6, Assume a switching frequency f = 400kHz
2. Problem 3.7

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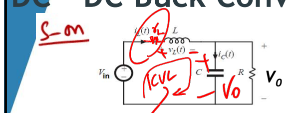
DC - DC Buck Converter Effect of Inductor Resistance r_L

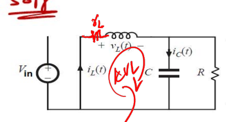
S-on



$-V_{in} + r_L * i_L + L\frac{di_L}{dt} + V_o = 0$

$v_L = L\frac{di_L}{dt} = V_{in} - V_o - i_L * r_L$ — 1

S-off

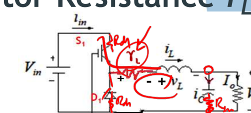


$r_L * i_L + L\frac{di_L}{dt} + V_o = 0$

$v_L = L\frac{di_L}{dt} = -V_o - i_L * r_L$ — 2

Inductor Quality factor : Q = $\frac{2*\pi*f*L}{r_L}$

Q - Factor



Inductor Vol-second-balance
$(V_{in} - V_o - i_L * r_L) * D + (-V_o - i_L * r_L)*(1\text{-}D) = 0$

Solve the above equation to obtain V_o

$$V_o = \frac{V_{in} * D}{1 + \frac{r_L}{R}} \quad \text{— 3}$$

Repeat the analysis if MOSFT on-resistance and diode forward drop need to be considered

Efficiency $\eta = \frac{V_o * I_o}{V_o * I_o + I_L^2 * r_L}$ since $I_L = I_o$ we have

Simplify the above equation to obtain η

$$\eta = \frac{1}{1 + \frac{r_L}{R}} \quad \text{— 4}$$

$\frac{r_L}{R}$	$\frac{V_o}{V_{in}}$	η
0.01	0.99D	99%
0.1	0.91D	90.9%

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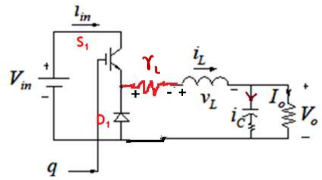
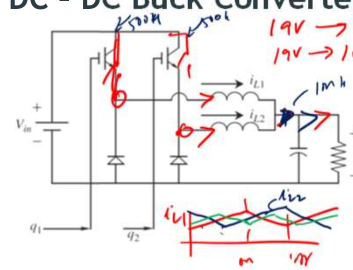
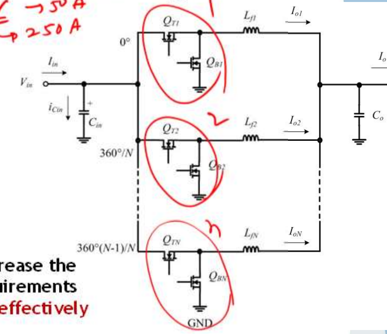


ECEN 738 Section Course Project

DC – DC Buck Converter Analysis - effect of inductor resistance r_L ; Mosfet $R_{ds(on)}$; capacitor *ESR* on converter performance – steady state and transient – design a feedback loop

DC - DC Buck Converter - Interleaving





- Parallel operation / Multiphase operation - to increase the current output. Used in high output current requirements
- Phase shift can be employed between phases to effectively multiply the ripple frequency at the output
- Also power dissipation is spread to multiple phases over a wider area
- Offers improved reliability and redundancy against failures

* Possible course project for 738-section
TI-article: Benefits of a multiphase buck converter
& https://www.eetimes.com/benefits-of-multiphasing-buck-converters-part-1/

Multiphase Buck Converter - link

Course Project for ECEN 738 section - design a 6 phase converter & simulate its performance

2 Multiphase Buck Regulator Overview

A multiphase buck regulator is a parallel set of buck power stages as shown in Figure 2-1 and Figure 2-2, each with its own inductor and set of power MOSFETs. Collectively, these components are called a phase. These phases are connected in parallel and share both input and output capacitors. During steady-state operation, individual phases are active at spaced intervals equal to 360° / n throughout the switching period where n is the total number of phases. Figure 2-2 shows a TPS53679 multiphase controller demonstration board and TI power stages for a six-phase design.

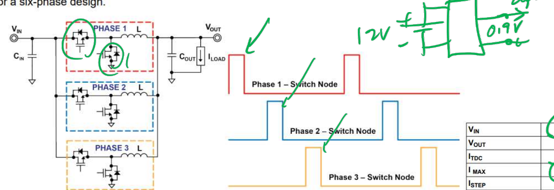


Figure 2-1. Multiphase Regulator Example

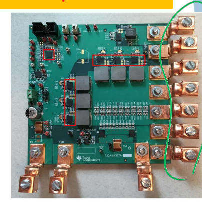


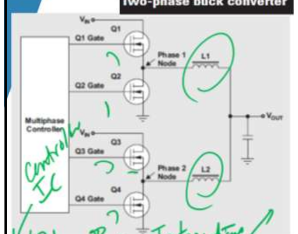
Figure 2-2. TPS53679 Demo Board With Controller and Power Stage ICs Highlighted

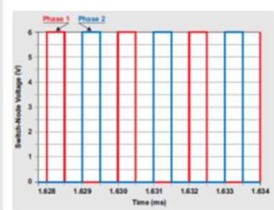
Table 5-1. Multiphase Design Targets

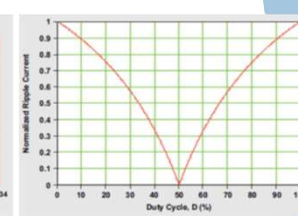
V_{IN}	12 V	Input Voltage
V_{OUT}	0.9 V	Nominal Output Voltage
I_{TDC}	200 A	Thermal Design Current
I_{MAX}	240 A	Max Current
I_{STEP}	150 A	Max Load Step
DCLL	0.5 mΩ	DC Load Line
$\Delta V_{OUT(DC)}$	±1%	V_{OUT} DC Ripple
$\Delta V_{OUT(AC)}$	±5%	V_{OUT} Transient Specifications
$\Delta V_{IN(DC)}$	240 mVpp	V_{IN} DC Ripple
$\Delta V_{IN(AC)}$	±360 mV	V_{IN} Overshoot and Undershoot
PMBus with Telemetry	Yes	Requires PMBus interface with V_{IN}, I_{IN}, V_{OUT}, I_{OUT}, and Temp readings

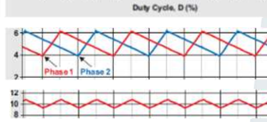
DC - DC Buck Converter - Interleaving

Two-phase buck converter







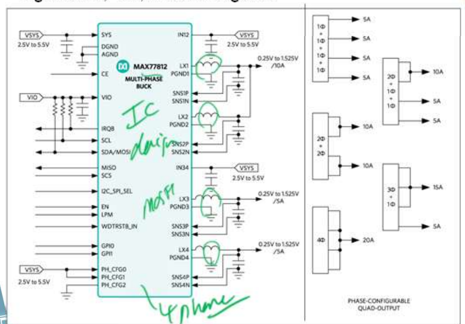


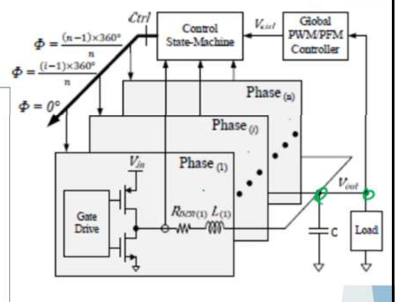
- Parallel operation / Multiphase operation - to increase the current output. Used in high output current requirements
- Phase shift can be employed between phases to effectively multiply the ripple frequency at the output
- Also power dissipation is spread to multiple phases over a wider area on a PCB
- Offers improved reliability and redundancy against failures

TI-article: Benefits of a multiphase buck converter
& https://www.eetimes.com/benefits-of-multiphasing-buck-converters-part-1/

DC – DC Buck Converter – Interleaving - multiphase

- Each phase is driven by gate drive signals of the same switching frequency f_s but adjacent phases are phase shift by 360°C/N .
- For example, a three-phase converter is driven by gate signals at 0, 120, and 240 degrees.





The MAX77812 is a quad-phase high-efficiency stepdown (buck) converter capable of delivering up to 20A of maximum current

Additional Design Problems for you to solve

DC – DC Buck Converter –Problems in the book

1. Problem 3.4

3.4. Calculate the critical value of the inductance L such that this Buck converter remains in the continuous conduction mode at and above $P_o = 5$ W under all values of the input voltage V_{in} in a range from 24 V to 50 V. Assume Vo=15V and f = 400kHz

Answer: 39.4 uH

2. Problem 3.7

3.7. A Buck dc-dc converter is to be designed for $V_{in} = 20$ V, $V_o = 12$ V, and the maximum output power $P_o = 72$ W. The switching frequency is selected to be $f_s = 400$ kHz. Assume ideal components. Estimate the value of the filter inductance that should be used if the converter is to remain in CCM at one-third the maximum output power.

Answer: 3 uH

3. Problem

For the Buck dc-dc converter in problem 3.4 above, if the resistance of the inductor r_L = 2.25 ohms, calculate the required duty cycle D for V_{in} = 24V and 50V. Also calculate the efficiency