ECE 562

Week 5 Lecture 2

Fall 2008

Week 5 Lecture 2
Summary

- Section notes
  - Slides 3-9 – Power consumption in switches
  - Slides 10-14 – Current losses
  - Slides 15-21 – Managing heat
  - Slides 22-34 – Problem 3.8 homework
  - Slides 35-39 – Problem 3.9 homework
  - Slides 40-43 – Problem 3.9 homework
  - Slides 44-51 – Buck converters

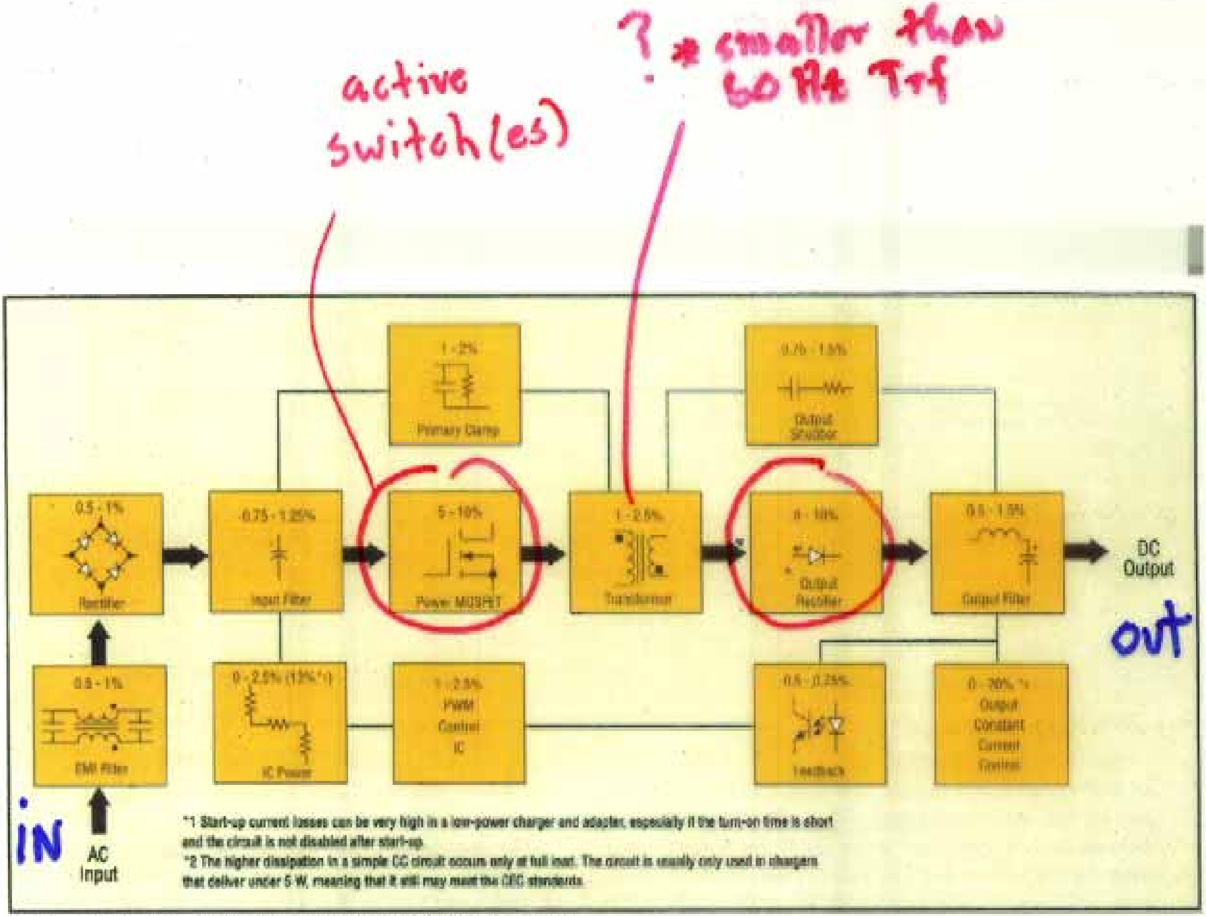
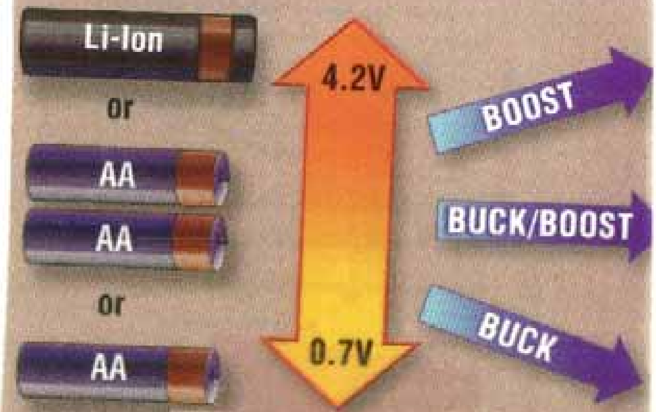


Fig. 2. Block diagram of the power-consuming circuits within a SMPS.



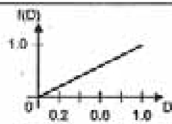
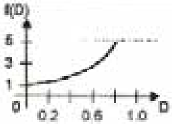
LTC3400
95% Efficient ThinSOT
Synchronous Boost
V_{OUT} = 5V @ 300mA

LTC3440
96% Efficient MSOP
Buck/Boost
V_{OUT} = 3.3V @ 600mA

LTC3405
96% Efficient ThinSOT
Synchronous Buck
V_{OUT} = 1.8V @ 300mA

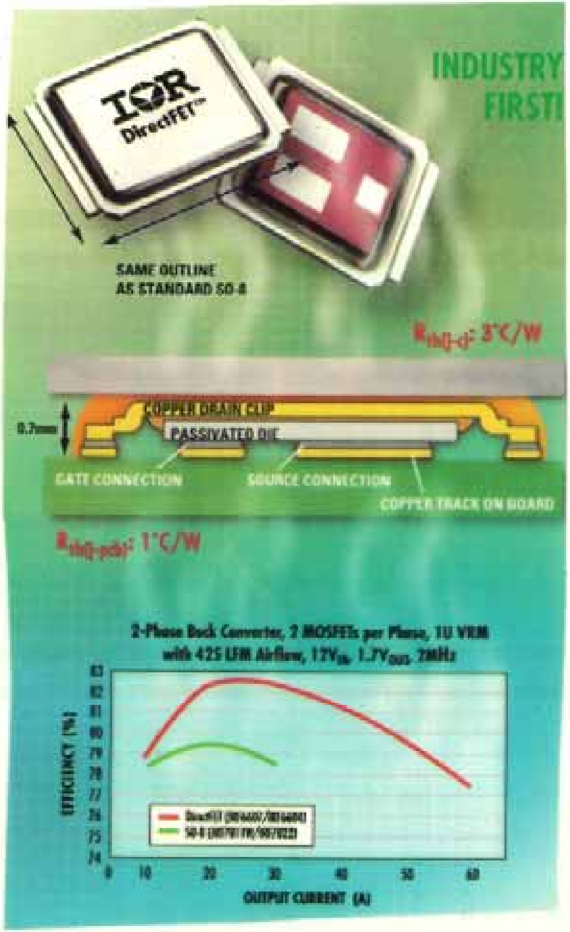
L2

SIMPLE SWITCH MODE CONVERTERS

 BUCK The buck is limited in that $V_{out} < V_{in}$ only		$V_L=V_o$ or $V_{DC}-V_o$ •$f(D)=D$ •Never get negative output •$V_o(min) = 0$
 BOOST The boost is limited in that $V_{out} > V_{in}$ only		•$f(D)=1/(1-D)$ •Never get zero output: $V_o(min) \neq 0$ $V_L=V_{DC}-V_o$ or V_o
 BUCK-BOOST The buck-boost is limited to negative voltages		•$f(D)=-D/(1-D)$ •Inverting output w.r.t. V_s $V_L = V_o = -V_{DC}$ for $D = ½$

4. UNSYMMETRIC i_L AND v_C WAVEFORMS OF EQUAL INTEGRATED AREA IN THE ABOVE THREE CONVERTERS

ideal no Losses
no heat


INDUSTRY FIRST!
IOR
DirectFET
SAME OUTLINE AS STANDARD SO-8
$R_{th(j-c)}$: 3°C/W
COPPER DRAIN CLIP
0.7mm
PASSIVATED DIE
GATE CONNECTION
SOURCE CONNECTION
COPPER TRACK ON BOARD
$R_{th(j-pcb)}$: 1°C/W
2-Phase Buck Converter, 2 MOSFETs per Phase, 1U VRM with 425 LFM Airflow, $12V_{IN}$, $1.7V_{OUT}$, 2MHz
EFFICIENCY (%)
OUTPUT CURRENT (A)
0 10 20 30 40 50 60

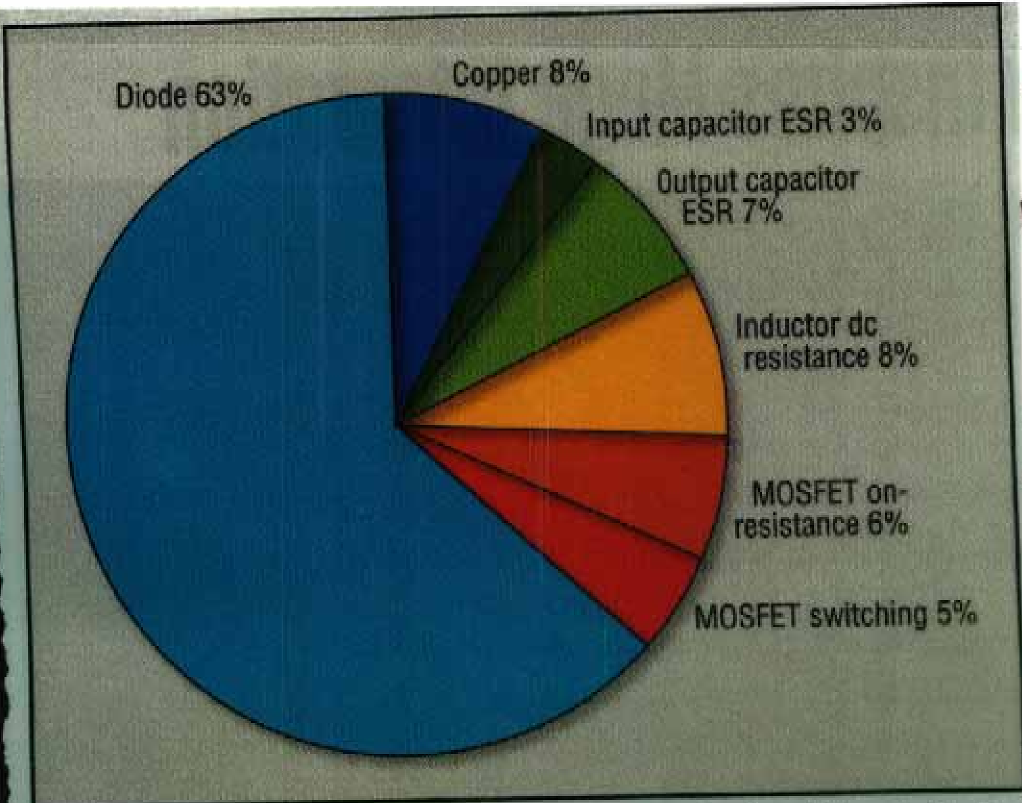
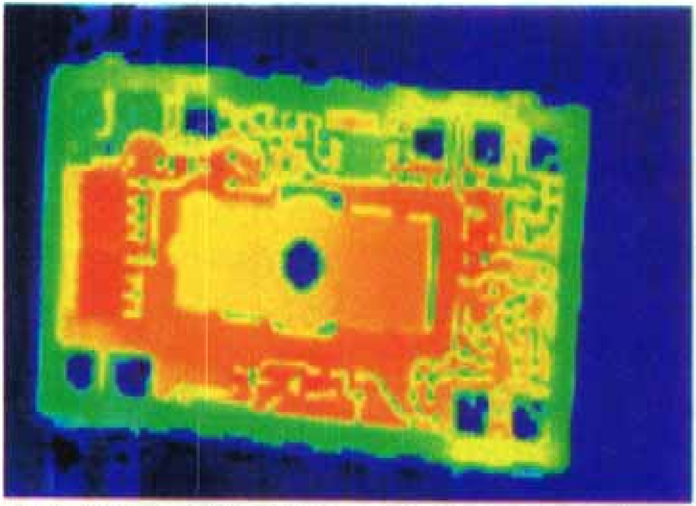


Fig. 6. *Power loss caused by the freewheeling diode should be eliminated to increase the converter's efficiency.*

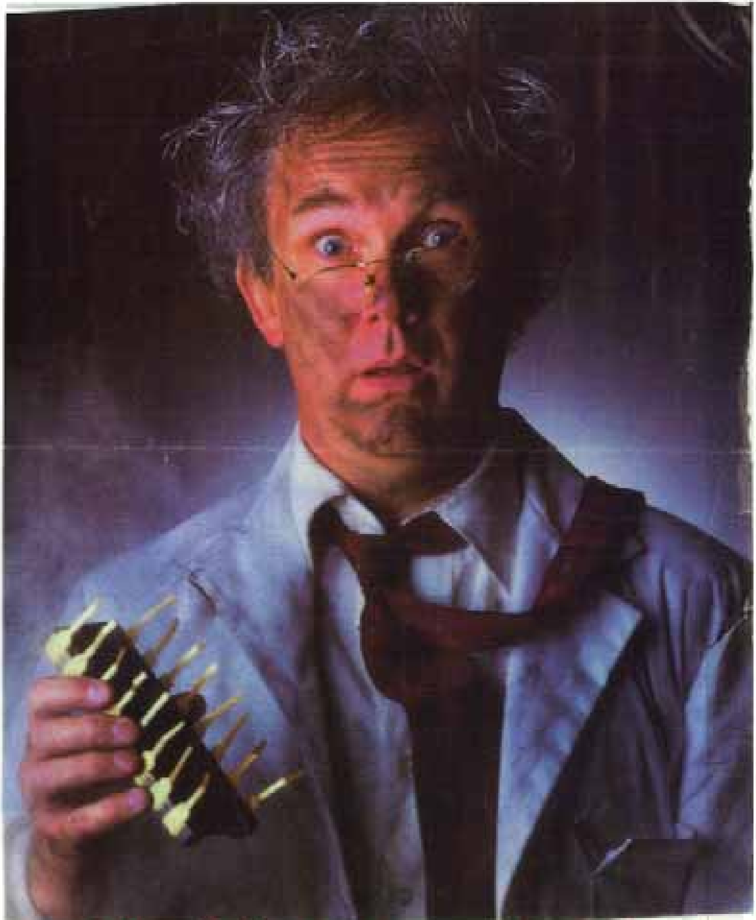
Diode is biggest source losses

- hot spot to cool
- max fsw limit
- ignores magnetic core loss



I.R Camera!

Fig. 4. *Thermal photograph of a dc-dc converter with uniform heat distribution.*

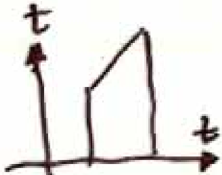


Ch3/Ch4 Address Sw 1065

Simple $I_{RMS}^2 R$ heating

- $I_{rms}^2 R_{ON}$ (FET)

↑ not so simple
see $i(t)$ various shapes
Calculate I_{Rms} from
say I(peak)



Diodes/Transistors

R_L in inductor

Rms Sine → $V_{pk}/\sqrt{2}$

□-wave RMS → $\sqrt{D}\,V_{pk}$

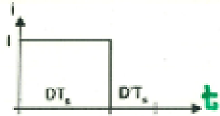
M(D) lossless itself will change only when we include lossy L and C inside the converter itself. See section III below.

C. RMS Values for Converter Waveforms

1. Square and Ramp Waveforms

I waveforms

Typical Transistor Waveform

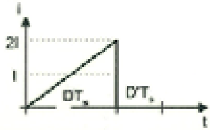


Erickson Appendix 1

$$I_{rms} = \sqrt{\frac{1}{T_s}\int_0^{T_s} i_s^2\,dt}$$

$$I_{rms} = I\sqrt{D}$$

Typical Diode Waveform



$$I_{rms} = 1.15I\sqrt{D}$$

easiest case

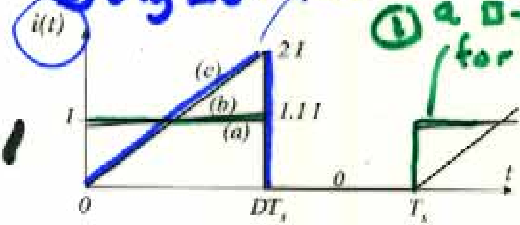
The two above are among the simplest cases. Recall that in the big three circuits we have even more complex AC wave forms as those shown below from Lecture 4. We repeat only one BOOST circuit waveforms from lecture 4 below but the point is made that each waveform has a unique RMS value that I_{rms} is a function of the duty cycle D.

On the next pages we also review the converter topologies as well as the current flows in each switch position so that the full waveform is developed. It is left to the student to match waveforms to RMS calculations using Appendix 1 of Erickson.

Accuracy of the averaged equivalent circuit in prediction of losses

- Model uses average currents and voltages
- To correctly predict power loss in a resistor, use rms values
- Result is the same, provided ripple is small

MOSFET current waveforms, for various ripple magnitudes:



Inductor current ripple	*MOSFET rms current*	*Average power loss in* R_{on}
(a) $\Delta i = 0$	$I\sqrt{D}$	$D\,I^2 R_{on}$
(b) $\Delta i = 0.1\,I$	$(1.00167)\,I\sqrt{D}$	$(1.0033)\,D\,I^2 R_{on}$
(c) $\Delta i = I$	$(1.155)\,I\sqrt{D}$	$(1.3333)\,D\,I^2 R_{on}$

Losses – Two Types

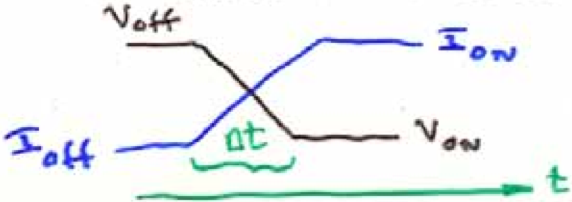
DC losses in electronics

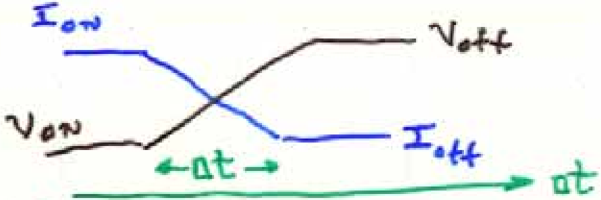
$I_{DC}^2 R$

$I_{DC}(on) V_{ON}$ (diode)

$I_{DC}^2(on) R_{DS}$ (FET)

AC losses in electronics





Other two device losses

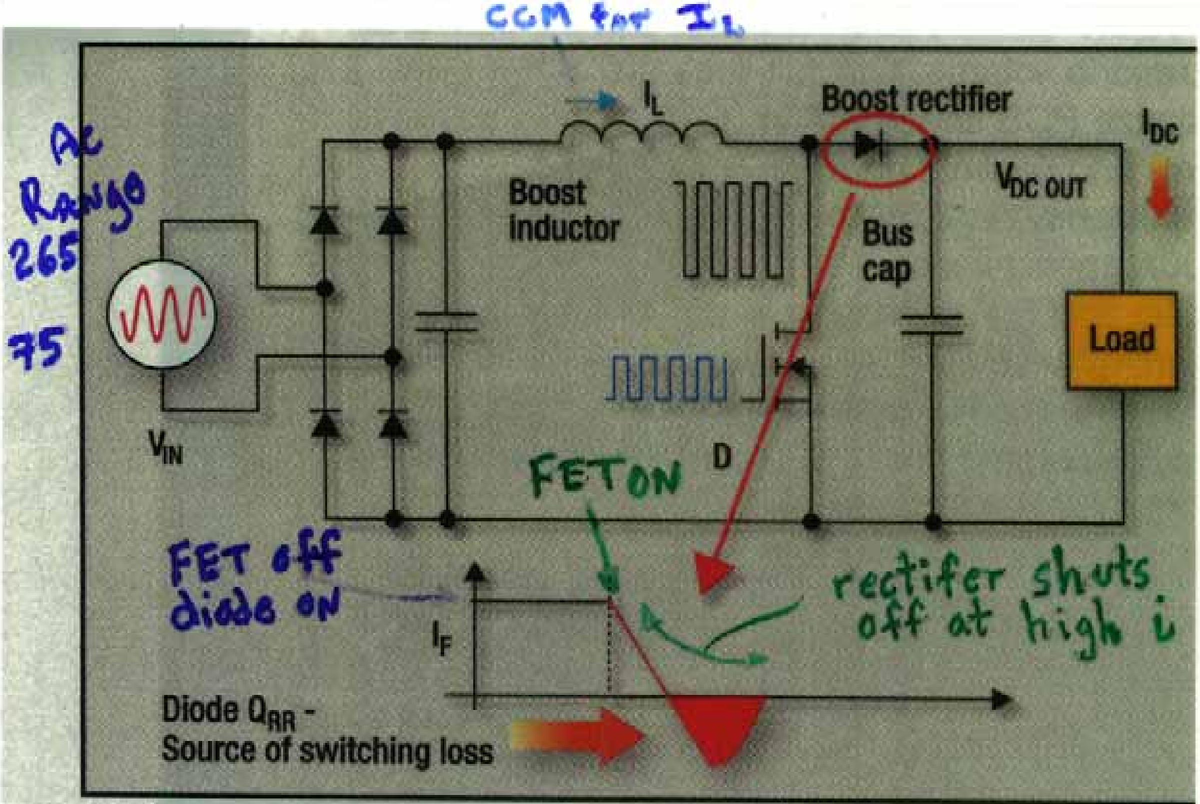


Fig. 1. *In the basic single-phase boost PFC converter, the boost rectifier's Q_{RR} produces significant switching losses.*

HW 3.8 You choose Heatsinks Boardlevel for power semiconductors

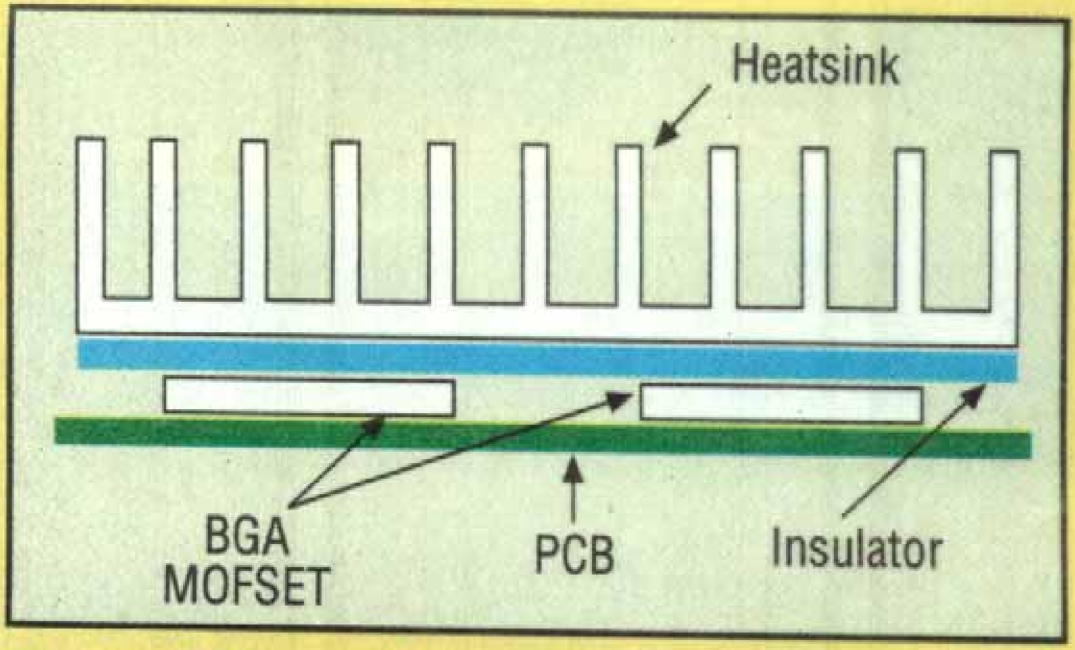


Fig. 1. *BGA heatsinking arrangement.*

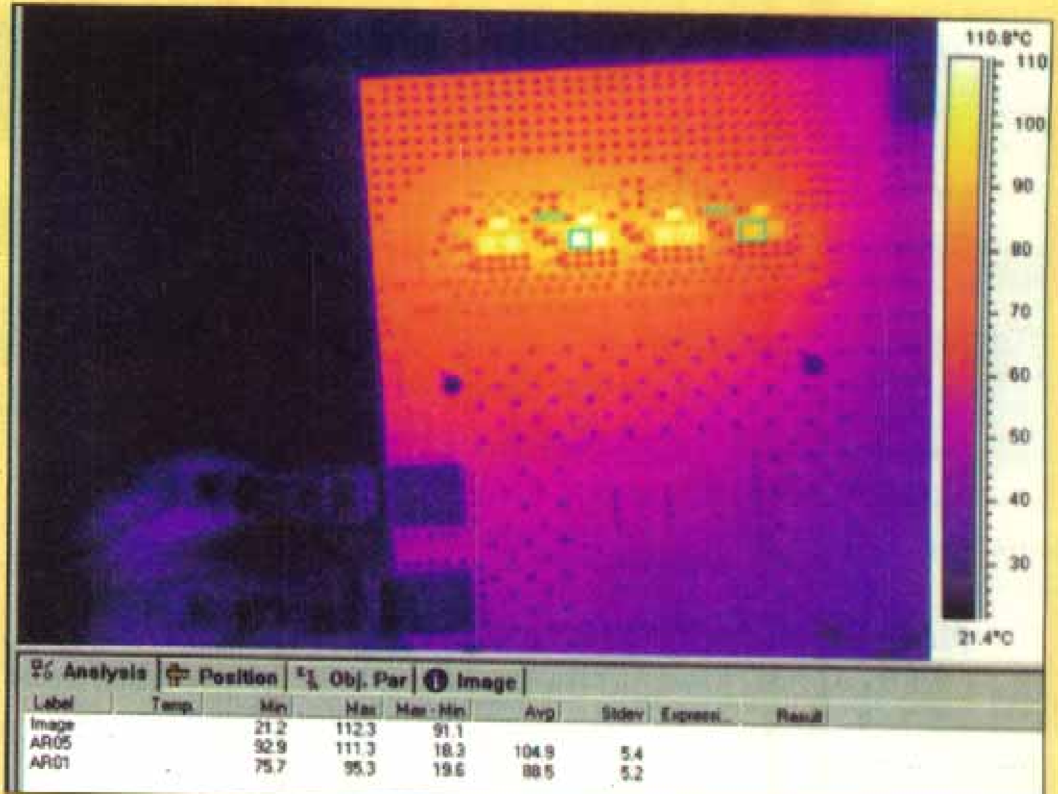


Fig. 4. *IR image of the notebook board running at output current of 90 A.*

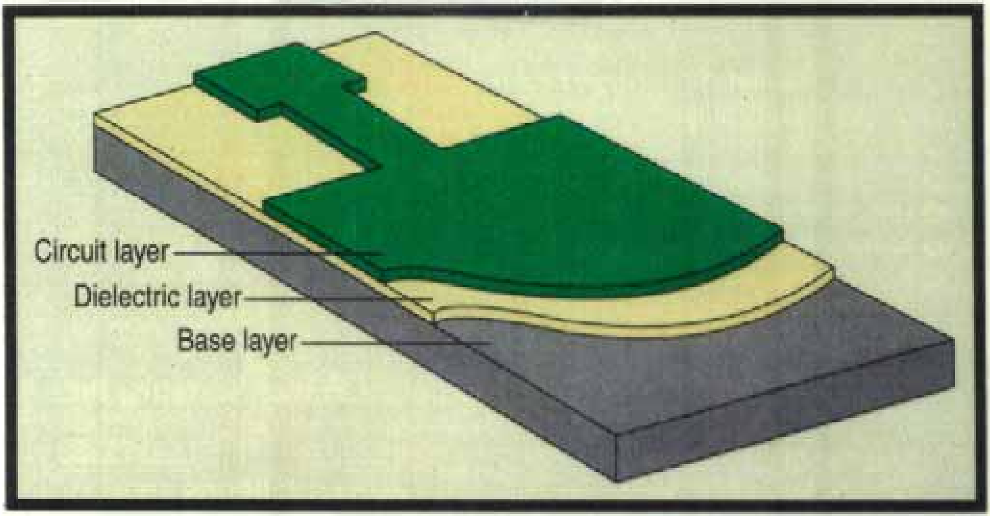


Fig. 1. *Insulated metal substrate construction.*

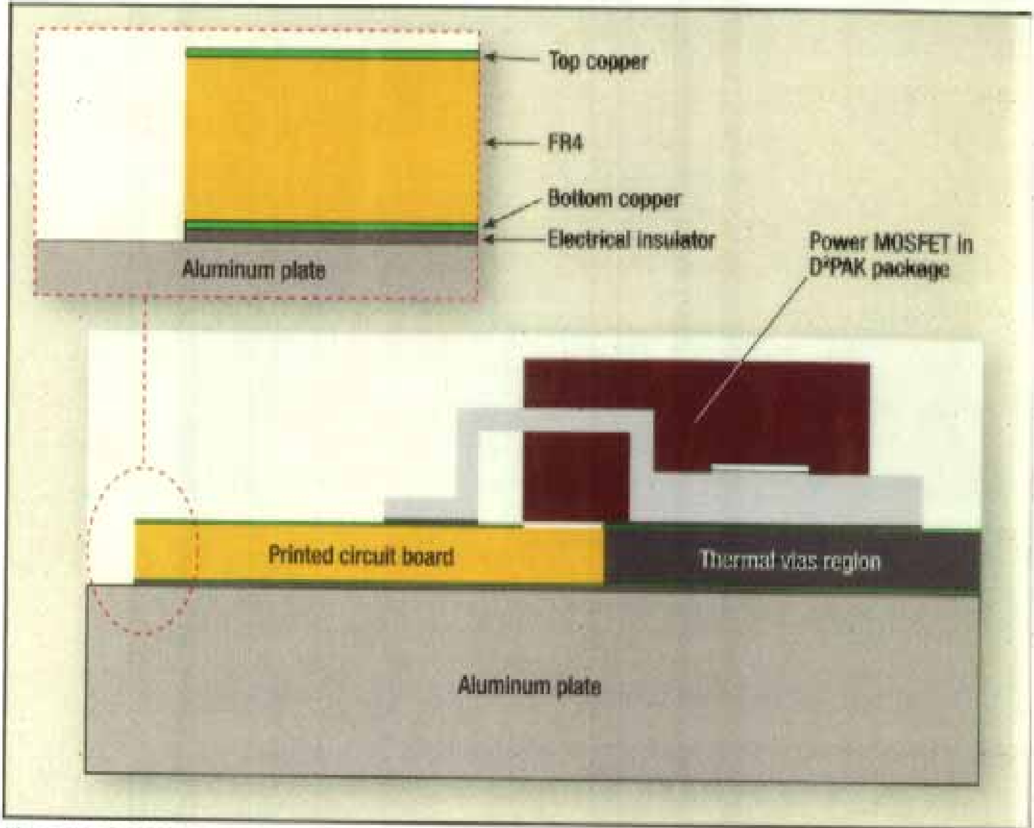


Fig. 1. *A D^2PAK MOSFET mounted on a pc board employing bottom-side cooling transfers heat to the aluminum plate heatsink through the thermal vias region.*

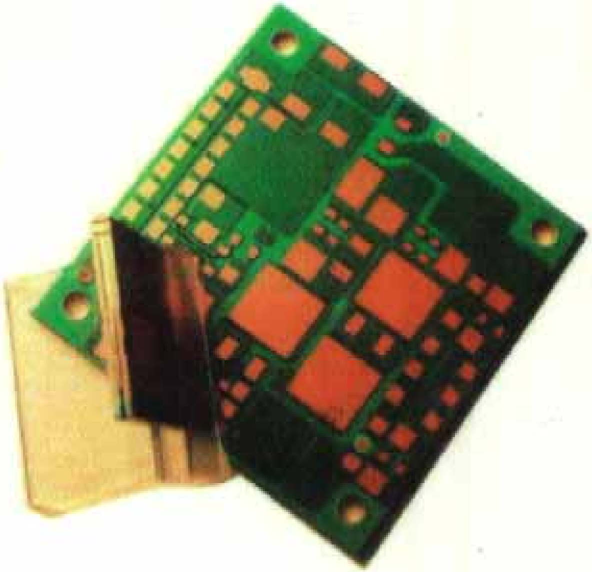


Fig. 2. *The copper core board spreads heat, eliminating hot spots and reducing thermal resistance for higher reliability. The copper core adds a 10°C edge to converter performance.*

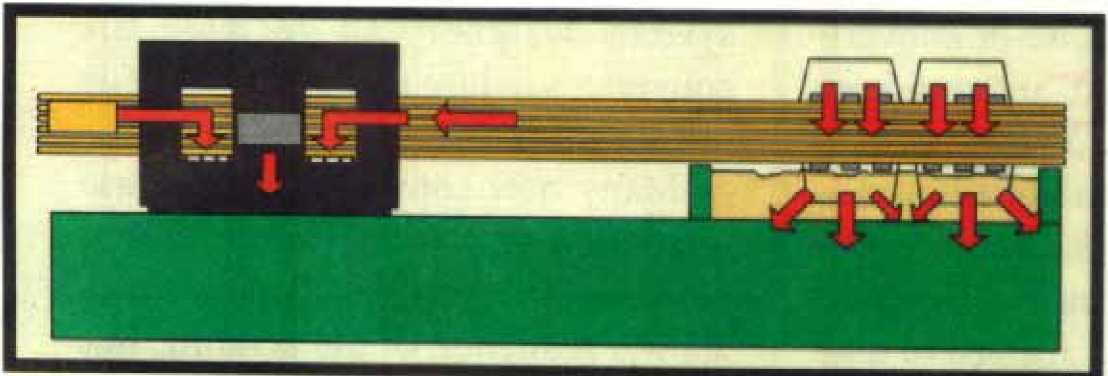


Fig. 3a. *The Cast Carrier is shown in green, with direct contact to a ferrite core, and an encapsulant bath for semiconductors.*

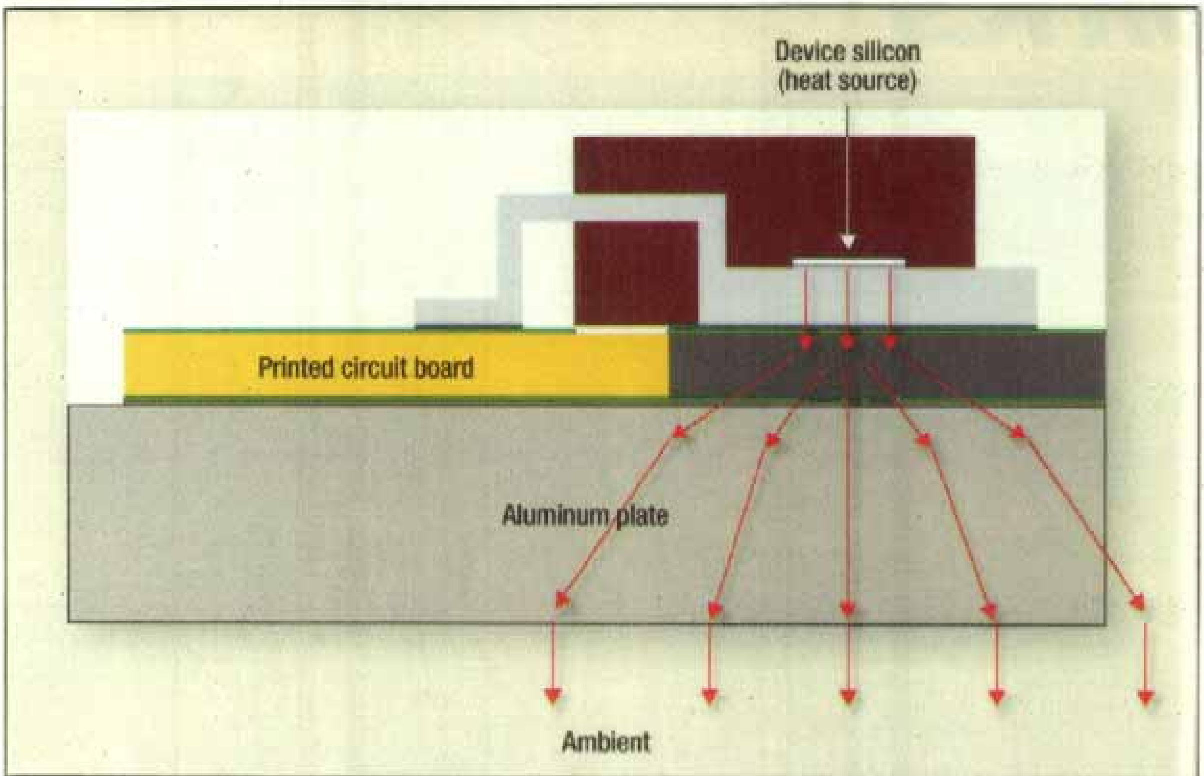


Fig. 2. *The primary heat path from device silicon to ambient for a D^2PAK MOSFET in a bottom-side cooling scheme diverts the majority of heat directly to ambient via the pc board and heatsink.*

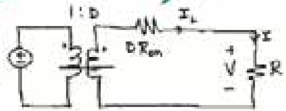
L3 Copy

<u>Problem 3.8</u> Note paragraph above problem 3.8

(a) Buck converter model

FET $R_{DS(ON)}$

500 V_g



I_L = inductor current

I = load current

$R = \frac{400V}{10A} = 40\,\text{ohm}$

Buck-boost converter model

FET $R_{DS(ON)}$

(b) (c) <u>Buck converter analysis</u>

$$V = DV_g \frac{R}{R + DR_{on}} = \frac{DV_g}{1 + D\frac{R_{on}}{R}}$$

$$\eta = \frac{1}{1 + D\frac{R_{on}}{R}}$$

Solve for D:

$$V + DV\frac{R_{on}}{R} = DV_g$$

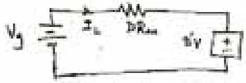
$$\Rightarrow D\left(V_g - V\frac{R_{on}}{R}\right) = V$$

$$D = \frac{V}{V_g - V\frac{R_{on}}{R}} = \frac{400}{500 - 400\frac{0.5}{40}} = 0.808$$

No loss 0.8

Construct equivalent circuit

inductor – loop equation $\langle v_L \rangle = 0 = V_g - D R_{on} I_L - D' V$



capacitor – node equation

Combine circuits, replace dependent sources with $D':1$ transformer

Solution:

$$V = \frac{1}{D'} V_g \frac{1}{1 + \frac{D}{(D')^2}\frac{R_{on}}{R}} \qquad I_L = \frac{V}{D'R}$$

$$\eta = \frac{1}{1 + \frac{D}{(D')^2}\frac{R_{on}}{R}} \qquad P_{loss} = I_L^2 D R_{on}$$

For the values $V_g = 300$, $V = 400$, $R = 40$, $R_{on} = 0.5$

find D and η (and also I_L and P_{loss})

Solve quadratic equation for D (arises from $\frac{V}{V_g} = \frac{1}{1-D} \frac{1}{1 + \frac{D}{(1-D)^2}\frac{R_{on}}{R}}$)

$\Rightarrow D = 0.2543$ (note $D \to 0.2500$ for $R_{on} \to 0$)

You! "Pick real R – web I rating on R ?

$$\eta = \frac{1}{1+(0.909)\frac{0.5}{40}} = 0.990$$

$$\text{loss} = (400)(10)\left(\frac{1}{0.990} - 1\right) \qquad \text{from Eq. (1.2)}$$

$$= 40.4\ \text{W} \qquad \text{Mosfet conduction loss}$$

Find a Heat Sink

Buck-boost converter analysis 500 → 400

$$V = \frac{D}{D'} V_g \frac{R}{R + \frac{D R_{on}}{(D')^2}} = \frac{D}{D'} \frac{1}{1 + \frac{D R_{on}}{D'^2 R}} V_g$$

$$\eta = \frac{1}{1 + \frac{D R_{on}}{D'^2 R}}$$

Solve for D:

$$D' V + \frac{D}{D'} \frac{R_{on}}{R} V = D V_g$$

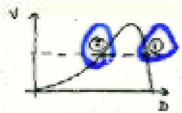
$$(1 - 2D + D^2) V + D \frac{R_{on}}{R} V = (D - D^2) V_g$$

$$D^2 (V + V_g) + D\left(\frac{R_{on}}{R} V - 2V - V_g\right) + V = 0$$

$$D = \frac{-\left(\frac{R_{on}}{R} V - 2V - V_g\right) \pm \sqrt{\left(\frac{R_{on}}{R} V - 2V - V_g\right)^2 - 4V(V+V_g)}}{2(V+V_g)}$$

Two roots:

	D	η
(1)	0.9999	0.005
(2)	0.4989	0.982



We would always choose to operate at root (2) because of higher efficiency

MOSFET conduction loss at $D = 0.4483$ is

$$P_{loss} = P_{out}\left(\frac{1}{\eta} - 1\right) = (400)(10)\left(\frac{1}{0.982} - 1\right)$$

$$= 73.9\ W$$

Find a Heatsink

This is nearly twice as large as in the buck converter.

⇒ The buck-boost approach would require a heatsink that is nearly twice as large.

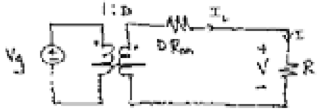
⇒ Buck is better approach.

L3 Copy

Problem 3.8 — Note paragraph above problem 3.8

(a)

Buck converter model

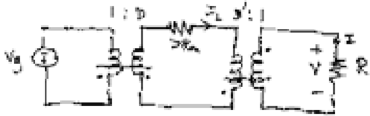


I_L = inductor current

I = load current

$R = \frac{400V}{10A} = 40\Omega$

Buck-boost converter model



(b)
(c)

Buck converter analysis

$$V = DV_g \frac{R}{R + DR_{on}} = \frac{DV_g}{1 + D\frac{R_{on}}{R}}$$

$$\eta = \frac{1}{1 + D\frac{R_{on}}{R}}$$

Solve for D:

$$V + DV\frac{R_{on}}{R} = DV_g$$

$$\Rightarrow D\left(V_g - V\frac{R_{on}}{R}\right) = V$$

$$D = \frac{V}{V_g - V\frac{R_{on}}{R}} = \frac{400}{500 - 400\frac{0.5}{40}} = 0.808$$

— [illegible]

$$\eta = \frac{1}{1 + (5.909)\frac{0.5}{40}} = 0.990$$

$$\text{loss} = (400)(10)\left(\frac{1}{0.990} - 1\right) \qquad \text{from Eq. (1.2)}$$

$$= 40.4\ W \qquad \text{Mosfet conduction loss}$$

<u>Buck-boost converter analysis</u>

$$V = \frac{D}{D'} V_g \frac{R}{R + \frac{D R_{on}}{(D')^2}} = \frac{D}{D'} \frac{1}{1 + \frac{D R_{on}}{D'^2 R}} V_g$$

$$\eta = \frac{1}{1 + \frac{D R_{on}}{D'^2 R}}$$

Solve for D:

$$D'V + \frac{D}{D'}\frac{R_{on}}{R} V = D V_g$$

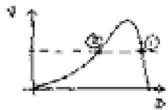
$$(1 - 2D + D^2) V + D \frac{R_{on}}{R} V = (D - D^2) V_g$$

$$D^2 (V + V_g) + D\left(\frac{R_{on}}{R} V - 2V - V_g\right) + V = 0$$

$$D = \frac{-\left(\frac{R_{on}}{R} V - 2V - V_g\right) \pm \sqrt{\left(\frac{R_{on}}{R} V - 2V - V_g\right)^2 - 4V(V + V_g)}}{2(V + V_g)}$$

Two roots:

	D	η
①	0.9999	0.005
②	0.8889	0.992



We would always choose to operate at root ② because of higher efficiency

MOSFET conduction loss at $D = 0.4489$ is

$$P_{loss} = P_{out}\left(\frac{1}{\eta} - 1\right) = (400)(10)\left(\frac{1}{0.982} - 1\right)$$

$$= 73.9\ W$$

This is nearly twice as large as in the buck converter.

⇒ The buck-boost approach would require a heatsink that is nearly twice as large.

⇒ Buck is better approach.

500 → 400 How to

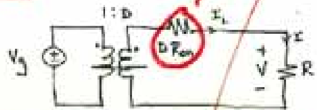
Choices - - - -

Problem 3.8 Note paragraph above problem 3.8

FET R_{on} → .1Ω even 10mΩ

(a)

Buck converter model



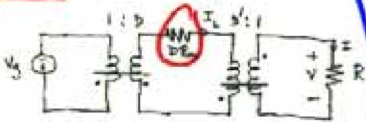
I_L = inductor current

I = load current

$R = \frac{400V}{10A} = 40\Omega$

Pbm 2.1 handout

Buck-boost converter model



Both can provide $V_{out} = 400$ which is better? and why? as an engineer

(b)
(c)

Buck converter analysis

$$V = DV_g \frac{R}{R + DR_{on}} = \frac{DV_g}{1 + D\frac{R_{on}}{R}}$$

$$\eta = \frac{1}{1 + D\frac{R_{on}}{R}}$$

Solve for D:

$$V + DV\frac{R_{on}}{R} = DV_g$$

$$\Rightarrow D\left(V_g - V\frac{R_{on}}{R}\right) = V$$

$$D = \frac{V}{V_g - V\frac{R_{on}}{R}} = \frac{400}{500 - 400\frac{0.5}{40}} = 0.808$$

D to achieve 500 → 400

$$\eta = \frac{1}{1 + (0.907)\frac{0.5}{40}} = 0.990$$

$$\text{loss} = (400)(10)\left(\frac{1}{0.990} - 1\right) \qquad \text{from Eq. (1.2)}$$

$$= 40.4\ \text{W} \qquad \text{MOSFET conduction loss}$$

Choose Q, D Heatsink required? Fan?

Buck-boost converter analysis

$$V = \frac{D}{D'} V_g \frac{R}{R + \frac{D R_{on}}{(D')^2}} = \frac{D}{D'} \frac{1}{1 + \frac{D R_{on}}{D'^2 R}} V_g$$

$$\eta = \frac{1}{1 + \frac{D R_{on}}{D'^2 R}}$$

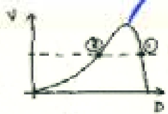
Solve for D:

$$D'V + \frac{D}{D'}\frac{R_{on}}{R} V = D V_g$$

$$(1 - 2D + D^2) V + D \frac{R_{on}}{R} V = (D - D^2) V_g$$

$$D^2 (V + V_g) + D\left(\frac{R_{on}}{R} V - 2V - V_g\right) + V = 0$$

$$D = \frac{-\left(\frac{R_{on}}{R} V - 2V - V_g\right) \pm \sqrt{\left(\frac{R_{on}}{R} V - 2V - V_g\right)^2 - 4V(V + V_g)}}{2(V + V_g)}$$



Same V_{out}

Two roots:

	D	η
①	0.9999	0.0008
②	0.4989	0.982

We would always choose to operate at root ② because of higher efficiency

But for f.b. stability?

MOSFET conduction loss at $D = 0.4487$ is

$$P_{loss} = P_{OUT}\left(\frac{1}{\eta} - 1\right) = (400)(10)\left(\frac{1}{0.982} - 1\right)$$

$$= 73.9 \text{ W}$$

Choose Q, D

Heat sink?

This is nearly twice as large as in the buck converter.

⇒ The buck-boost approach would require a heatsink that is nearly twice as large.

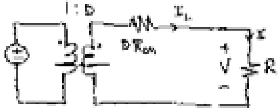
⇒ Buck is better approach.

Problem 3.8

Note paragraph above problem 3.8

(a)

Buck converter model

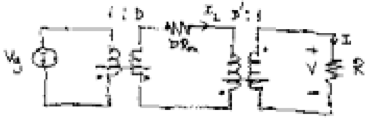


I_L = inductor current

I = load current

$R = \frac{400V}{10A} = 40\Omega$

Buck-boost converter model



(b)
(c)

Buck converter analysis

$$V = D V_g \frac{R}{R + DR_{on}} = \frac{D V_g}{1 + D\frac{R_{on}}{R}}$$

$$\eta = \frac{1}{1 + D\frac{R_{on}}{R}}$$

Solve for D:

$$V + D V \frac{R_{on}}{R} = D V_g$$

$$\Rightarrow D\left(V_g - V\frac{R_{on}}{R}\right) = V$$

$$D = \frac{V}{V_g - V\frac{R_{on}}{R}} = \frac{400}{500 - 400\frac{0.5}{40}} = 0.808$$

$$\eta = \frac{1}{1 + (0.909)\frac{0.5}{400}} = 0.990$$

$$\text{loss} = (400)(10)\left(\frac{1}{0.990} - 1\right) \qquad \text{from Eq. (1.2)}$$

$$= 40.4\ \text{W} \qquad \text{Mosfet conduction loss}$$

<u>Buck-boost converter analysis</u>

$$V = \frac{D}{D'} V_g \frac{R}{R + \frac{D R_{on}}{(D')^2}} = \frac{D}{D'} \frac{1}{1 + \frac{D R_{on}}{D'^2 R}} V_g$$

$$\eta = \frac{1}{1 + \frac{D R_{on}}{D'^2 R}}$$

Solve for D

$$D' V + \frac{D}{D'} \frac{R_{on}}{R} V = D V_g$$

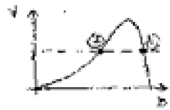
$$(1 - 2D + D^2) V + D \frac{R_{on}}{R} V = (D - D^2) V_g$$

$$D^2 (V + V_g) + D\left(\frac{R_{on}}{R} V - 2V - V_g\right) + V = 0$$

$$D = \frac{-\left(\frac{R_{on}}{R} V - 2V - V_g\right) \pm \sqrt{\left(\frac{R_{on}}{R} V - 2V - V_g\right)^2 - 4V(V + V_g)}}{2(V + V_g)}$$

Two roots:

	D	η
(1)	0.9989	0.008
(2)	0.4409	0.962



We would always choose to operate at root (2) because of higher efficiency

MOSFET conduction loss at $D = 0.9989$ is

$$P_{loss} = P_{out}\left(\frac{1}{\eta} - 1\right) = (400)(10)\left(\frac{1}{0.982} - 1\right)$$

$$= 73.9\ W$$

This is nearly twice as large as in the buck converter.

⇒ The buck-boost approach would require a heatsink that is nearly twice as large.

⇒ Buck is better approach.

Choices
...

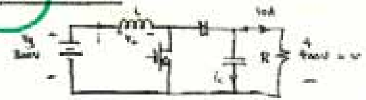
Tutorial

Solution to Problem 3.7

Note paragraph above Problem 3.8

Interface a 300V battery to a 400V, 10A load.
Investigate boost and buck-boost converters: which has better efficiency?
MOSFET has 0.5Ω on-resistance. All other losses can be ignored.

Boost converter



$R = \frac{400V}{10A} = 40\Omega$

transistor on   diode off

small ripple approximation

$v_L(t) = V_g - i_L(t)R_{on} \approx V_g - I_L R_{on}$

$i_C(t) = -v(t)/R \approx -\frac{V}{R}$

transistor off   diode on

$v_L(t) = V_g - v(t) \approx V_g - V$

$i_C(t) = i_L(t) - \frac{v(t)}{R} \approx I_L - \frac{V}{R}$

volt-second balance

$\langle v_L(t)\rangle = 0 = D(V_g - I_L R_{on}) + D'(V_g - V) = V_g - DR_{on}I_L - D'V$

charge balance

$\langle i_C(t)\rangle = 0 = D\left(-\frac{V}{R}\right) + D'\left(I_L - \frac{V}{R}\right) = D'I_L - \frac{V}{R}$

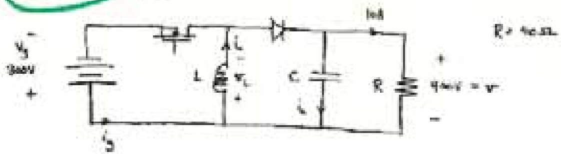
Then $\eta = 0.9943$ 99.43%

$I_L = 13.4A$

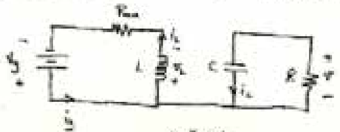
$P_{loss} = 22.7\ W$ ← **Heat sink**

Pick a

Buck-boost converter



transistor on $0 < t < DT_s$ diode off



Since the converter input current $i_g(t)$ is pulsating, we must write equations for $i_g(t)$ during each subinterval, then average to find the dc component

small ripple approximation

$$v_L(t) = V_g - i_L R_{on} \approx V_g - I_L R_{on}$$

$$i_C(t) = -v(t)/R \approx -V/R$$

$$i_g(t) = i_L(t) \approx I_L$$

transistor off $DT_s < t < T_s$ diode on

$v_L(t) = -v(t) \approx -V$

$i_C(t) = i_L(t) - v(t)/R \approx I_L - V/R$

$i_g(t) = 0$

volt-second balance

$\langle v_L(t) \rangle = 0 = D(V_g - I_L R_{on}) + D'(-V)$

charge balance

$\langle i_C(t) \rangle = 0 = D(-V/R) + D'(I_L - V/R)$

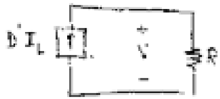
average input current

$\langle i_g \rangle = I_g = D(I_L) + D'(0)$

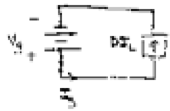
Construct equivalent circuit

inductor loop equation: $DV_g - I_L DR_{on} - D'V = \langle v_L \rangle = 0$

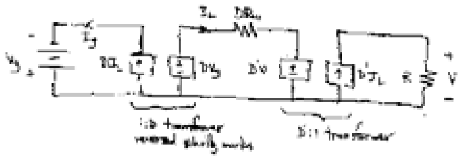
Capacitor node equation: $D' I_L - \frac{V}{R} = \langle i_C \rangle = 0$



Input current (node) equation: $I_g = D I_L$



Draw circuit models together:



Model including ideal dc transformers:

Solution of model:

$$V = \frac{D}{D'} V_g \frac{R}{R + \frac{D}{(D')^2} R_{on}} \Rightarrow \frac{V}{V_g} = \frac{D}{D'} \frac{1}{1 + \frac{D}{(D')^2} \frac{R_{on}}{R}}$$

$$\eta = \frac{1}{1 + \frac{D}{(D')^2} \frac{R_{on}}{R}}$$

$$I_L = \frac{V}{D' R}$$

$$P_{loss} = I_L^2 D R_{on}$$

Note that, with the exception of the extra factor of D in the $\frac{V}{V_g}$ equation, all of the above equations are identical to the respective boost converter equations on page 2. Because of the extra factor of D, the buck-boost converter must operate at a larger duty cycle. This leads to increased inductor current, increased transistor conduction time, and increased power loss.

Solution

$D = 0.5813$

$\eta = 0.7602$ 76.02%

$I_L = 23.89$ A

$P_{loss} = 165.8$ W — more than 7 times larger than boost; heatsink must be 7 times larger; boost is much better than buck-boost in this application

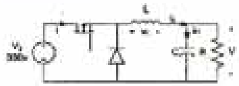
Pick a heatsink!

End of problem

10

Prob 3.

Buck Converter



Known: $V_g = 325 + 20\%$
$V = 240$ VDC
$10A \le I \le 1A$
Mosfet loss: $R_{on} = 0.8\Omega$
Diode loss: $V_{Diode} = 0.7V$
$R_{Diode} = 0.2\Omega$

Pick:
① Heat Sinks
② FET
③ Diode

Position 1: Mosfet on and Diode off

$v_L(t) = Vg - I\,Ron - V$; $i_c(t) = I - V/R$; $i_g(t) = I$

Position 2: Mosfet off and Diode on

$v_L(t) = -V_D - I\,R_D - V$; $i_c(t) = I - V/R$; $i_g(t) = 0$

(a) For the equivalent circuit all we need is to set the average inductor voltage equal to zero and model the equation.

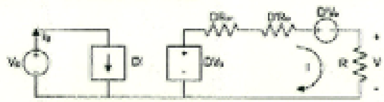
$\langle v_L \rangle = D(Vg - I\,Ron - V) + D'(-V_D - IR_D - V) = 0$

Thus $\Rightarrow DVg - DI\,Ron - D'V_D - D'IR_D - V = 0$

Now we need to get the Primary for the DC transformer model.

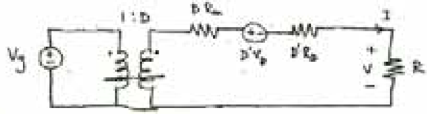
The DC component of $\langle i_g(t) \rangle = \frac{1}{Ts}\int_0^{Ts} i_g(t)dt = DI$.

Now we can model the circuit.



Solution to Problem 3.10 — Buck converter with regulated output voltage

a)



$$V = \left(DV_g - D'V_D\right)\frac{R}{R + DR_{on} + D'R_D}$$

$$\frac{V}{V_g} = D\,\frac{\left(1 - \frac{D'V_D}{DV_g}\right)}{\left(1 + D\frac{R_{on}}{R} + D'\frac{R_D}{R}\right)}$$

$$\eta = \frac{\left(1 - \frac{D'V_D}{DV_g}\right)}{\left(1 + D\frac{R_{on}}{R} + D'\frac{R_D}{R}\right)}$$

b) solve for D:

$$V\left(1 + D\frac{R_{on}}{R} + (1-D)\frac{R_D}{R}\right) = DV_g - (1-D)V_D$$

$$D\left[V\frac{R_{on}}{R} - V\frac{R_D}{R} - V_g - V_D\right] = -V_D - V - V\frac{R_D}{R}$$

$$D = \frac{V_D + V\left(1 + \frac{R_D}{R}\right)}{V_g + V_D + V\left(\frac{R_D - R_{on}}{R}\right)}$$

Results tabulated on next page

c) we expect the worst-case η to occur at min V_g and max I.
Results given on next page.

We notice that the turns ratio is 1:D. The final transformer model is:

Note: The transformer model is completed when you have the input voltage Vg alone as the input and the output voltage V alone as the output. If you have VgD or Vg times some other function then you must create a *DC* transformer to get Vg alone as the input. The same holds for the output voltage V.

(b) $DV_g - DI\,R_{on} - D'V_D - D'IR_D - V = 0 \Rightarrow$ Solve for D

$DV_g - DI\,R_{on} - V_D + DV_D - IR_D - DIR_D - V = 0$

$D(V_g - I\,R_{on} + V_D + IR_D) = V + V_D + IR_D$

$D = (V + V_D + IR_D)/(V_g - I\,R_{on} + IR_D + V_D)$

Thus: we find D_{max} when Vg = 260volts and I = 10A: D_{max} = 0.953

we find D_{min} when Vg = 390volts and I = 1A: D_{min} = 0.62

$0.62 \leq D \leq 0.953$

(c) Power(out) = VI $\Rightarrow$ 2400 watts and 240 watts at I = 10A and 1A

Power(in) = DVgI $\Rightarrow$ 2478 watts and 242 watts at D = 0.953 and 0.62

P_{loss}(max) = 2478 - 2400 = 78 watts which is at **Vg = 260v and I = 10A**

$\eta = P_{out}/P_{in}$ = 2400/2478 * 100% = 96.85%

High I

Buck converter with variable input voltage and load current

	nominal	H	L	H	L
Vg	325	390	260	390	260
I	10	10	10	1	1
V ← fixed out	240	240	240	240	240
VD	0.7	0.7	0.7	0.7	0.7
Ron	0.8	0.8	0.8	0.8	0.8
RD	0.2	0.2	0.2	0.2	0.2
D	0.7592	0.6309	0.9529	0.6175	0.9262
Dideal	0.7385	0.6154	0.9231	0.6154	0.9231
efficiency	97.27%	97.54%	96.87%	99.65%	99.66%
Ploss	67.28 W	60.50 W	77.51 W	0.84 W	0.81 W

low I

D varies between
0.6175 and
0.9529

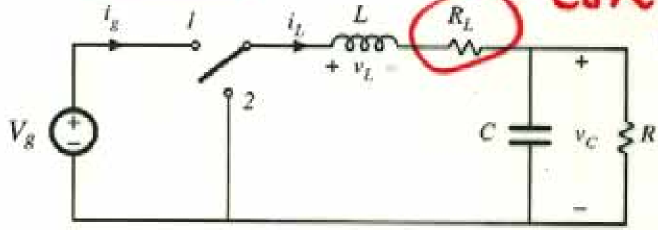
Worst-case effcy is
96.87%
which occurs at min Vg and max I
Power loss at this point is
77.51 W

← Pg 50

3.4. How to obtain the "input port" of the model

Real Buck Model

Buck converter example —use procedure of previous section to derive equivalent circuit



Average inductor voltage and capacitor current:

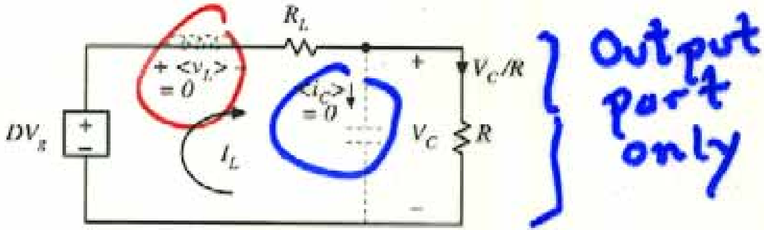
$$\langle v_L \rangle = 0 = DV_g - I_L R_L - V_C \qquad \langle i_C \rangle = 0 = I_L - V_C/R$$

Togeather same ckt loop
is it input or output?

Construct equivalent circuit as usual

$\langle v_L \rangle = 0 = DV_g - I_L R_L - V_C$ $\langle i_C \rangle = 0 = I_L - V_C / R$

Fig 3.?? p 50



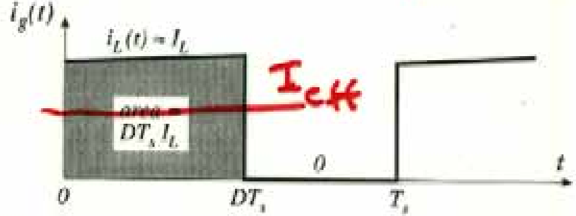
What happened to the transformer?
- Need another equation

Whats an equation for Trf?

Modeling the converter input port

Input current waveform $i_g(t)$: ← *Good choice for input port*

Fig 3.18 p 51



Dc component (average value) of $i_g(t)$ is

$$I_g = \frac{1}{T_s} \int_0^{T_s} i_g(t)\, dt = DI_L \quad = I_{eff}$$

Input port equivalent circuit

$$I_g = \frac{1}{T_s}\int_0^{T_s} i_g(t)\,dt = DI_L$$

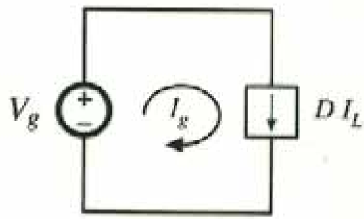


Fig 3.19
pg 51

Complete equivalent circuit, buck converter

Now combine both and simplify

Input and output port equivalent circuits, drawn together:

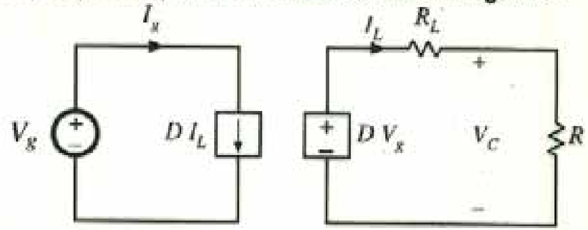
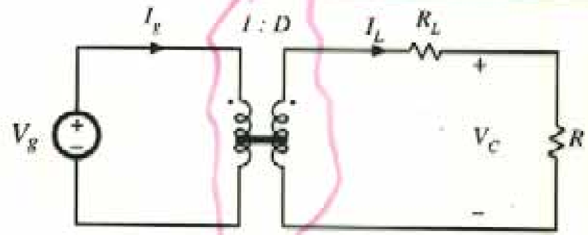


Fig 3.20
3.21
Pg 51

Replace dependent sources with equivalent dc transformer:

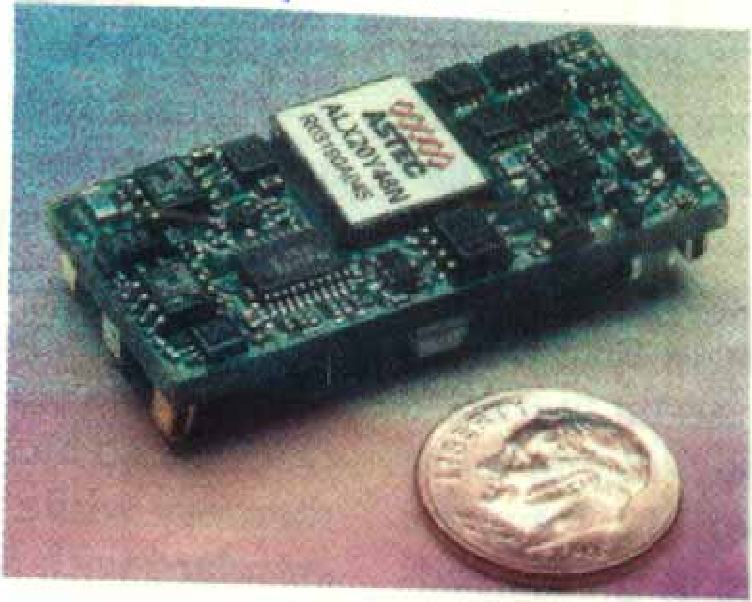


Move all to input port. How?

Talk #1

"Computer chips . . . computer chips . . ."

Paper #1 Astec



ALX series provides up to 20 A and 50 W for datacom and wireless apps.

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