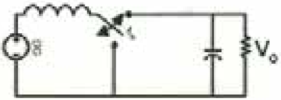
B. BOOST TOPOLOGY:

Inductor is attached to crude dc (rectified mains): again note that L is preventing kvl violations during switching as well as storing energy.



- V_{out} NEVER REACHES ZERO. v_{out}(minimum) = v_{dc} and can exceed v_{dc}

Why

- V_{out} IS UNIPOLAR but can achieve $v_o > v_{in}$
- $V_o/V_{in} = 1 / (1-D)$. non-linear dependence on d will be shown in later lectures
- Note that the input and the output are NOT electrically isolated from each other as we have a common terminal to both the input and the output. How to easily fix this??. Finally, we consider one special case for the duty cycle- D=1/2

S

Consider the switch duty cycle of ½ and consider the power in the inductor for each switch position.

$p_{in}(av) = v_{dc}i/2$ while $p_{out}(av) = (v_{out} - v_{dc})i/2 = p(\text{inductor})$

if no losses occur in switching, wires or in reactive elements: $p_{in} = p_{out}$ which implies $v_o = 2v_{dc}$

$S_{in} = S_{out}$

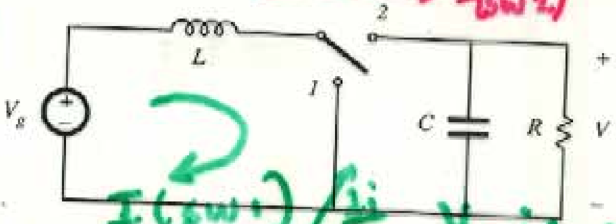
On the next page we give a qualitative summary of the boost topology for the conditions of the bipolar transistor switch on and off. Note the very different current paths for the two circuit conditions. Of special note is the inductive kick fron the series inductor which makes the switch voltage exceed V(in) when the transistor is switched off. **Why does this occur??**

The boost converter

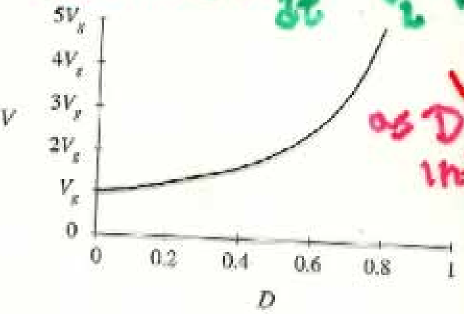
Suprising Role of L ?

di/dt V_L is - → + Boost

→ I(sw 2)

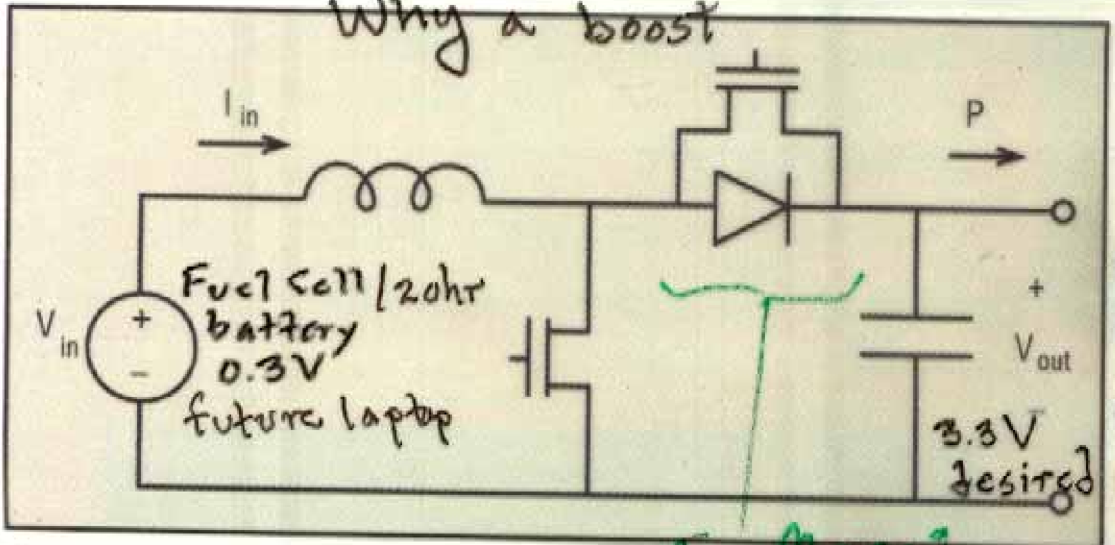


I(sw 1) / di/dt V_L is + → -



why $V_0 > V_g$? as D increases intuitively

Why a boost



Fuel cell / 20hr battery 0.3V future laptop

3.3V desired

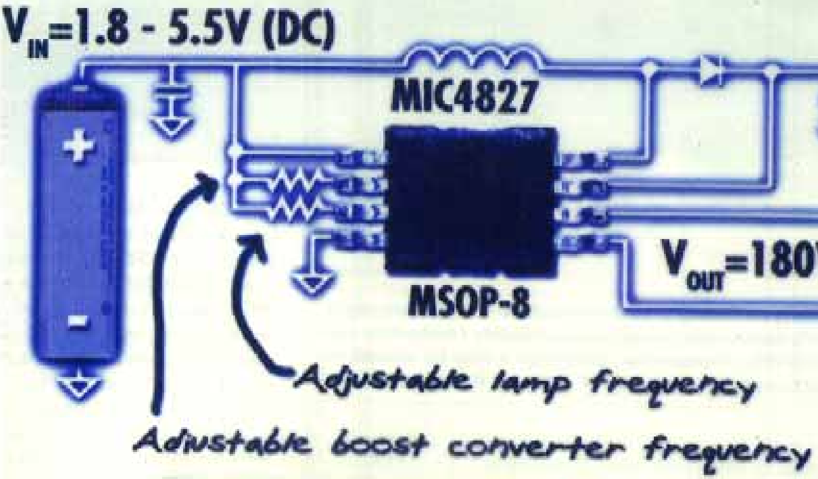
For $\eta = 90\%$ $R_{ON} \sim 4m\Omega$

Fig. 1. *Synchronous boost converter.*

(during analog operation of a dual

1" long 50mil 2oz Cu pcb trace

Camera flash voltage >> $V_{battery}$



The Good Stuff

- 1.8V to 5.5V DC input — V_{IN}
- 160V_{pp} AC output (MIC4826)
- 180V_{pp} AC output (MIC4827)

} Vout for lamp

- Independently adjustable boost converter frequency
- Independently adjustable EL lamp frequency
- <0.1µA shutdown current
- Small MSOP-8 package

Subinterval 1: switch in position 1

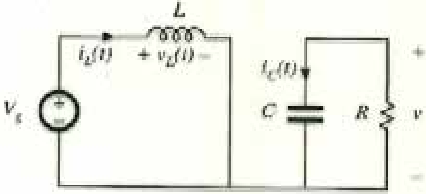
Inductor voltage and capacitor current

$$v_L = V_g$$
$$i_C = -v / R$$

Small ripple approximation:

$$v_L = V_g$$
$$i_C = -V / R$$

filling up with i_L



Subinterval 2: switch in position 2

di/dt is $\ominus$

$\Rightarrow$

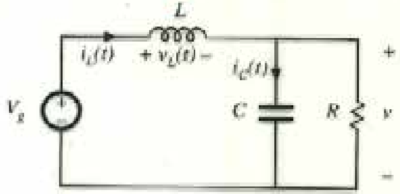
V_L is

$- \rightarrow$

Boost

Inductor voltage and capacitor current

$$v_L = V_g - v$$
$$i_C = i_L - v / R$$



Small ripple approximation:

$$v_L = V_g - V$$
$$i_C = I - V / R$$

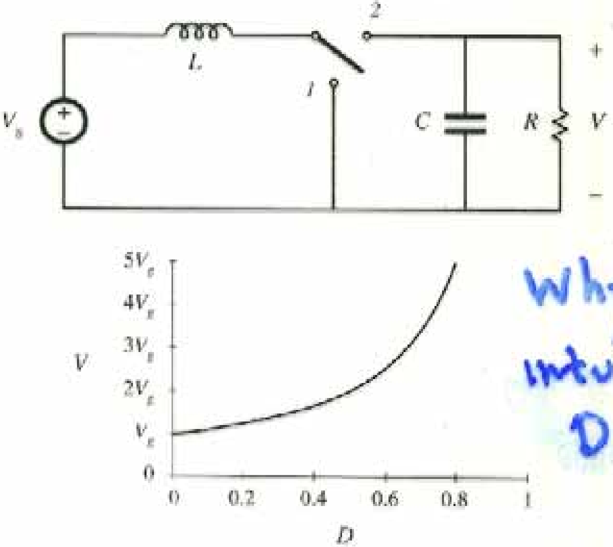
↑

dc inductor current

$$V_0 = \frac{V_g}{D'} = \frac{V_g}{1-D}$$

$D = \frac{1}{2}$ $V_0 = ?$

The boost converter



Why $V_0^{DC} > V_{IN}^{DC}$?
intuitively as
D↑

Switch Realization

Pg22 2.3 Boost converter example

implies V_{out} vs V_{IN}

Boost converter with ideal switch

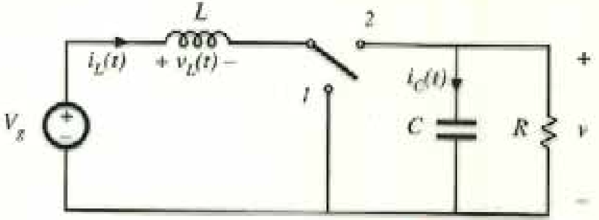
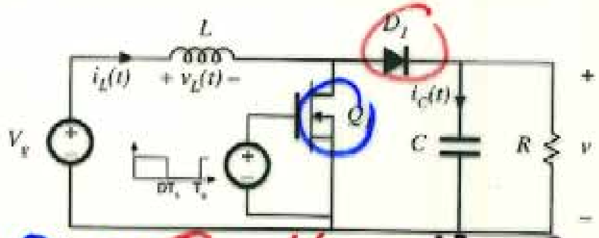


Fig 2.13 pg 22

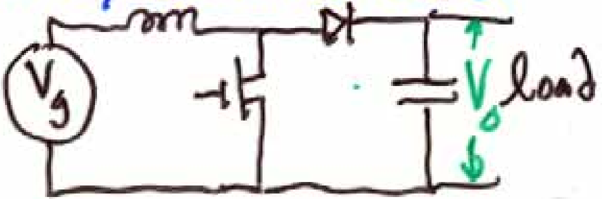
Realization using power MOSFET and diode



Q_1 ON D_1 off Why?

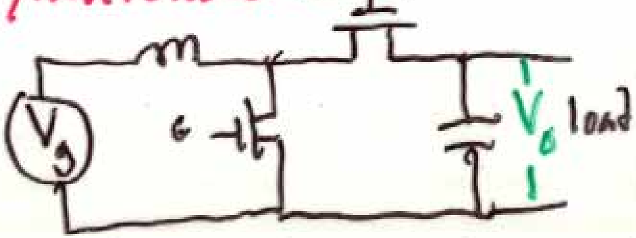
Use solid state switches

Non-synchronous Boost



$V_o >> V_g$ diode ok but...

Synchronous Boost



Eliminates diode loss due to :
Q_{rr}, V_D^{ON}

Details Ch3

I of FET

Determination of inductor current ripple

Δi spec easy

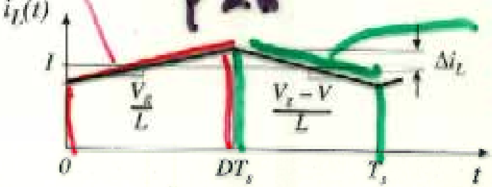
Fig 2.78 p 26

Inductor current slope during subinterval 1:

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

Inductor current slope during subinterval 2:

$$\frac{di_L(t)}{dt} = \frac{v_L(t)}{L} = \frac{V_g - V}{L}$$ down $\frac{di}{dt}$



I of diode

$\Delta i_{\text{peak peak}} = 2\Delta i$

Change in inductor current during subinterval 1 is *(slope) (length of subinterval)*:

$$2\Delta i_L = \frac{V_g}{L} DT_s$$

Δi spec from $e = L\,\Delta i/\Delta t$

Solve for peak ripple:

$$\Delta i_L = \frac{V_g}{2L} DT_s$$

- Choose L such that desired ripple magnitude is obtained

$L \sim D$

L sets Δi

Determination of capacitor voltage ripple

ΔV spec easy

Fig 2.14 p26

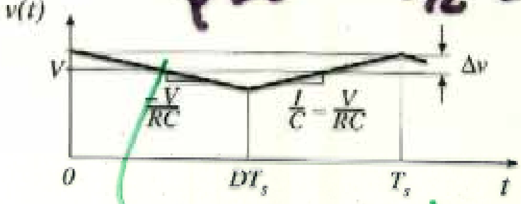
$I/C = \frac{\Delta V}{\Delta t}$

Capacitor voltage slope during subinterval 1:

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

Capacitor voltage slope during subinterval 2:

$$\frac{dv_C(t)}{dt} = \frac{i_C(t)}{C} = \frac{I}{C} - \frac{V}{RC}$$



small ripple

Change in capacitor voltage during subinterval 1 is *(slope) (length of subinterval)*:

$$-2\Delta v = \frac{-V}{RC} DT_s$$

Solve for peak ripple:

$$\Delta v = \frac{V}{2RC} DT_s$$

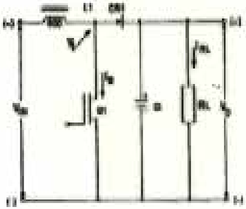
C ~ D

- Choose *C* such that desired voltage ripple magnitude is obtained
- In practice, capacitor *equivalent series resistance* (esr) leads to increased voltage ripple

$\Delta i \cdot R_{ESR}$ ✱

☺

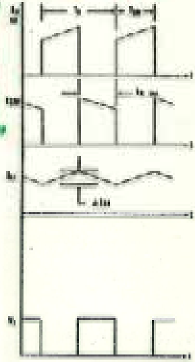
C sets ΔV

TYPE OF CONVERTER	Boost (Step Up)
CIRCUIT CONFIGURATION	
IDEAL TRANSFER FUNCTION	$\frac{V_O}{V_{IN}} = \frac{T_S}{T_S - t_{on}} = \frac{1}{(1-D)}$
PEAK DRAIN CURRENT	$I_{DMAX} = I_{RL}\left(\frac{1}{1-D}\right) + \frac{\Delta I_{L1}}{2}$
PEAK DRAIN VOLTAGE	$V_{DS} = V_O + \underline{V_D}$ ← diode
AVERAGE DIODE CURRENTS	$I_{CR1} = I_{RL}$
DIODE VOLTAGES (VRM)	$V_{RM} = V_O$

#2 of 11

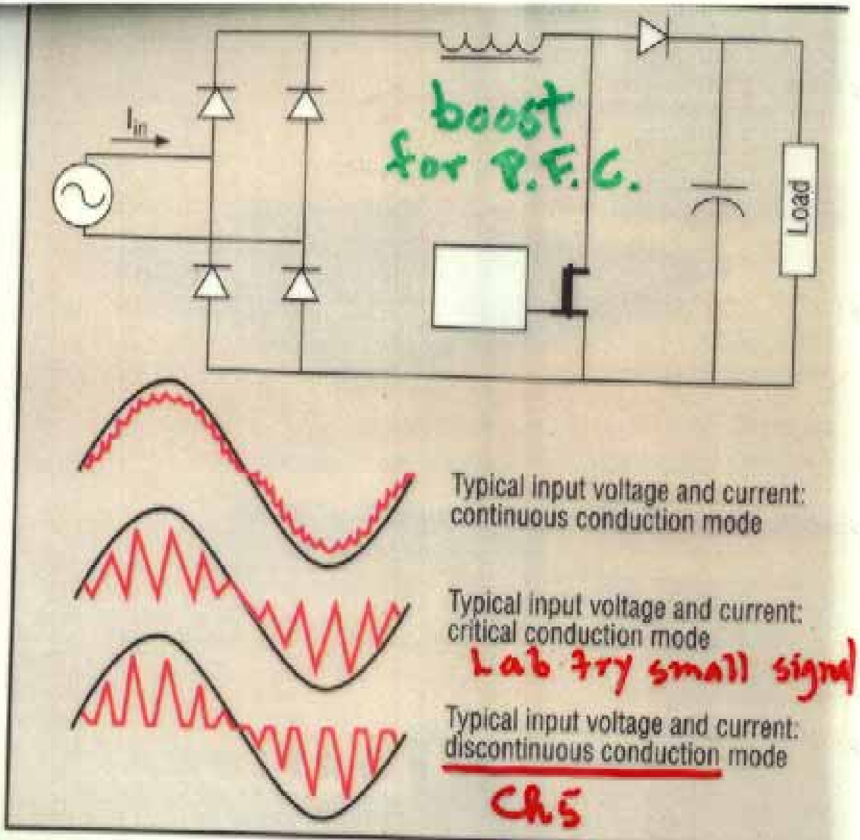
Careful

Not small ripple

VOLTAGE AND CURRENT WAVEFORMS	

$i_L = i_D + i_Q$ is small ripple

ADVANTAGES	High efficiency, simple, no transformer. Low input ripple current.
DISADVANTAGES	No isolation between input and output. High peak collector current. Only one output is possible. Regulator loop hard to stabilize. High output ripple. Unable to control short-circuit current.
TYPICAL APPLICATIONS	Power-factor correction. Battery up-converters.
APPLICABLE HARRIS PRODUCTS	HIP5061, ICL7667, HV400



boost for P.F.C.

Lab try small signal

Ch.5

Fig. 1. *Comparison of conduction modes for a boost converter.*

In just four simple steps, you can go from component

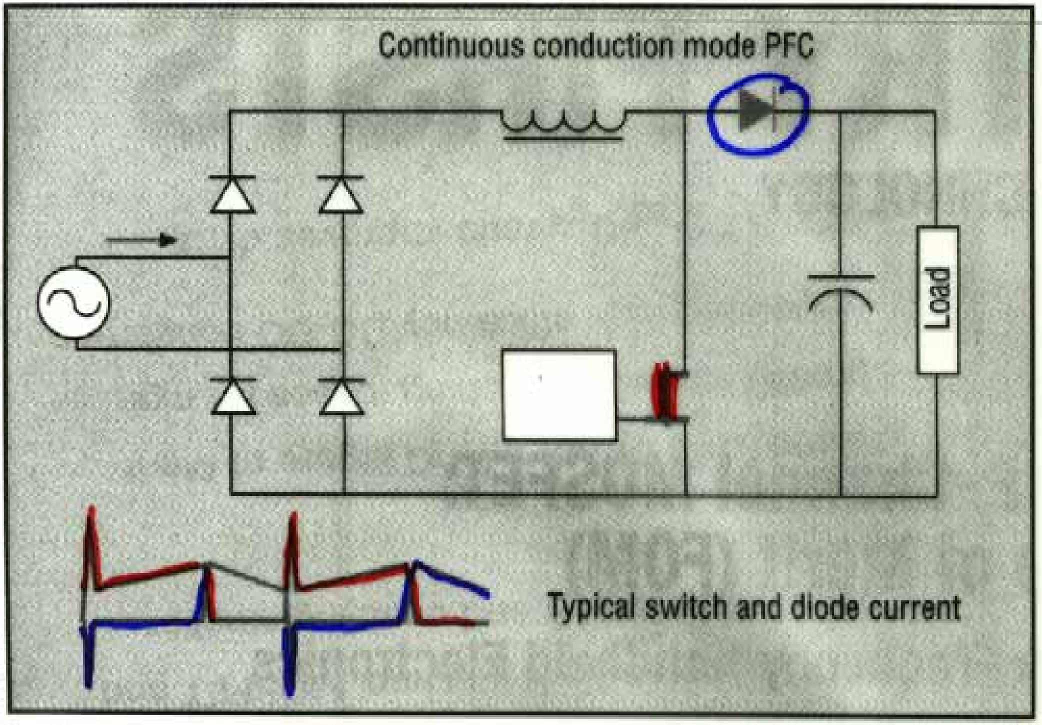


Fig. 2. *Typical MOSFET and diode current waveforms.*

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E
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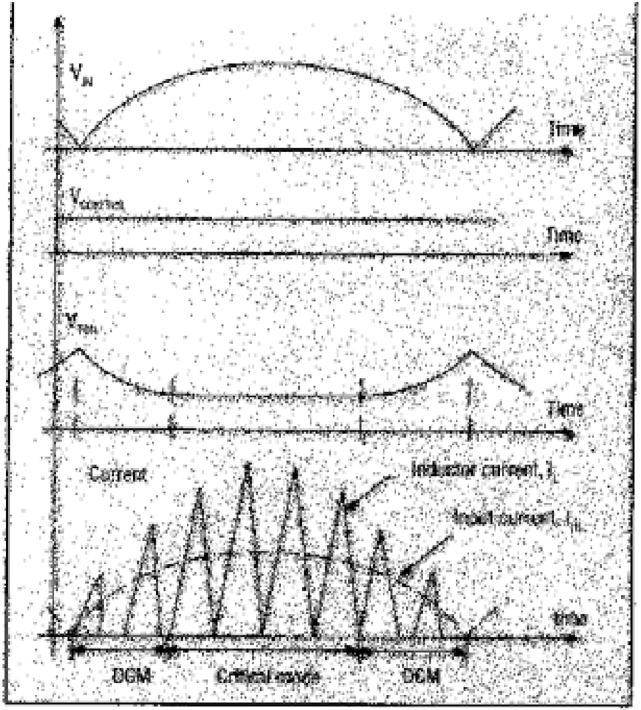
are a
desi



The timing diagram of the PFC stage reveals key voltage and current parameters as the controller transitions between discontinous conduction mode and critical conduction modes.

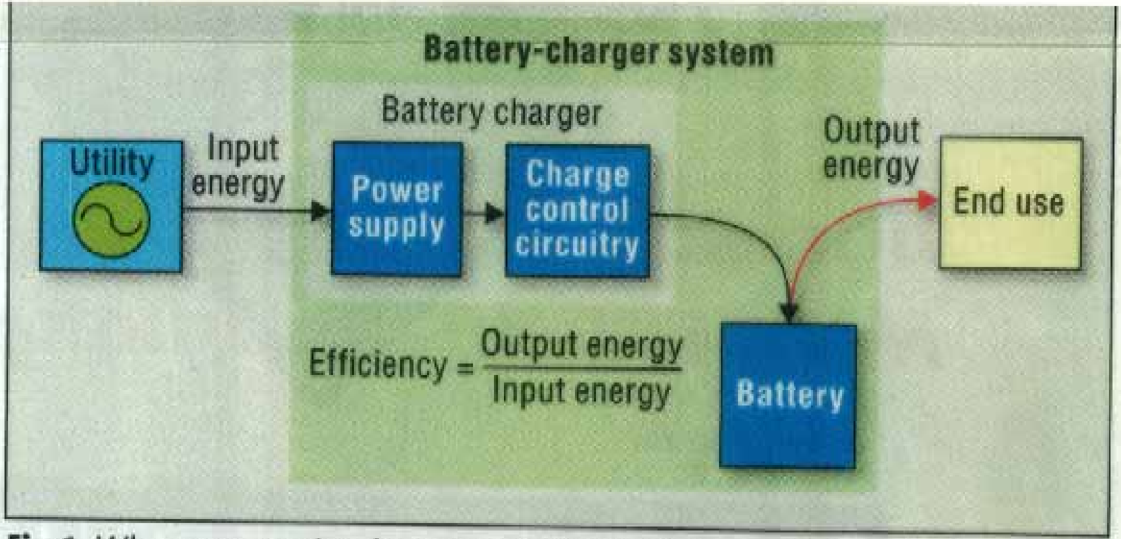
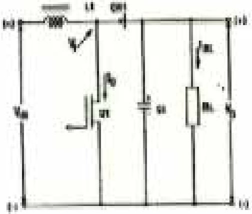


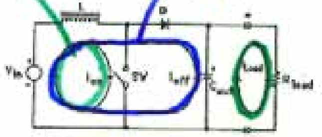
Fig. 1. *When measuring battery-charger efficiency, the ac-dc power supply, the charge control circuitry, and the battery should all be counted as parts of the battery-charger system.*

TYPE OF CONVERTER	Boost (Step Up)
CIRCUIT CONFIGURATION	
IDEAL TRANSFER FUNCTION	$\frac{V_O}{V_{IN}} = \frac{T_S}{T_S - t_{on}} = \frac{1}{(1-D)}$
PEAK DRAIN CURRENT	$I_{DMAX} = I_{RL}\left(\frac{1}{1-D}\right) + \frac{\Delta I_{L1}}{2}$
PEAK DRAIN VOLTAGE	$V_{DS} = V_O + V_D$
AVERAGE DIODE CURRENTS	$I_{CR1} = I_{RL}$
DIODE VOLTAGES (VRM)	$V_{RM} = V_O$
VOLTAGE AND CURRENT WAVEFORMS	 Iout EMC IIN EMC?
ADVANTAGES	High efficiency, simple, no transformer. Low input ripple current.
DISADVANTAGES	No isolation between input and output. High peak collector current. Only one output is possible. Regulator loop hard to stabilize. High output ripple. Unable to control short-circuit current.
TYPICAL APPLICATIONS	Power-factor correction. Battery up-converters.
APPLICABLE HARRIS PRODUCTS	HIP5061, ICL7667, HV400

I_{ON}

I_{off}

DCM
Ch 5
Spice Lab
$i_2 \to 0$



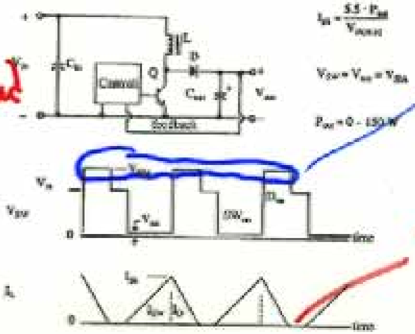
A basic flyback-mode converter (boost converter shown)

V_{off}
Spec on
FET

look ahead

Ch5
$i_2=0$

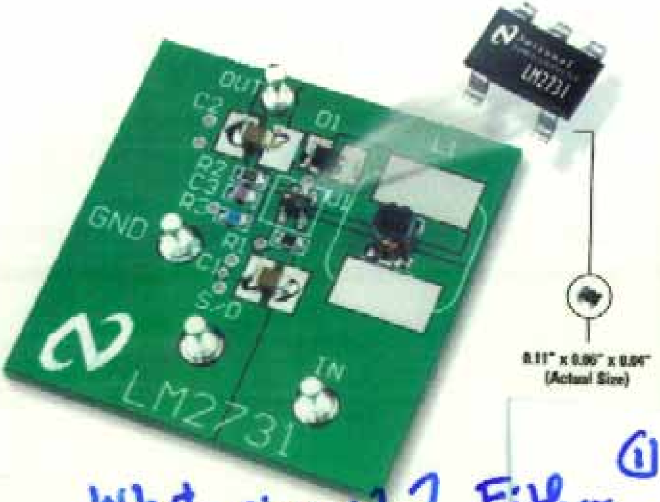
? $i_2=0$
$\Rightarrow$



The boost regulator topology

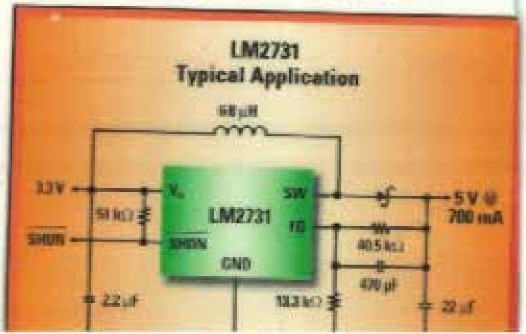
For now realize that the boost circuit while delivering an output voltage above V(in) does have to ask the solid state switch to handle a **peak current 6 times the nominal** average current when the switch is on. When the switch is off the solid state switch must withstand across itself a voltage up to the full output value.

Another unemployed English major.



0.11" x 0.06" x 0.04"
(Actual Size)

What circuit? Either ① ?
②

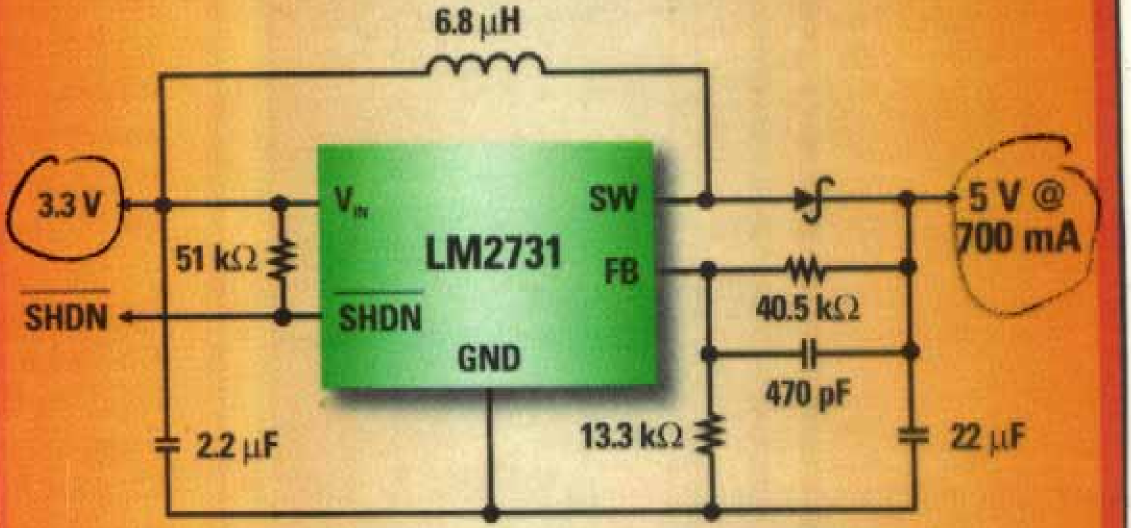


LM2731
Typical Application

National Semi Boost

Talk #1

LM2731
Typical Application

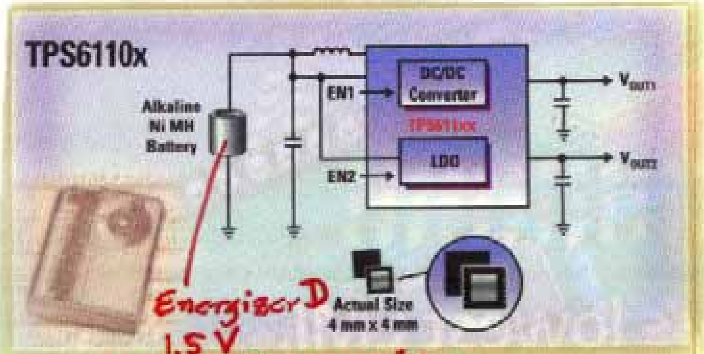


LM2731/33: SOT-23 Switchers Establish New Standards In Power Density, Efficiency, And Performance

- 1.6 MHz-(X), 0.6 MHz-(Y) Switching Frequency Options
- Up to 90% Conversion Efficiency
- Low $r_{DS(ON)}$ DMOS Power Switch
- 1A, 40 V Switch (LM2733)
- 1.8A, 22 V Switch (LM2731)
- Wide Input Voltage Range (2.7 V to 14 V)
- Low Shutdown Current (<1 µA)
- Current-Mode Control for Superior Performance Over Wide Input Voltage Range

diode
why

Ideal for Use in USB/xDSL Modems, Digital Cameras, and Cellular Handsets (esp. White-LED Backlights and Flash)



Energizer D
1.5 V
and sinking vs time

▶ **95% efficient dual output boost converter with integrated LDO for 1-cell/2-cell alkaline/NiMH applications**

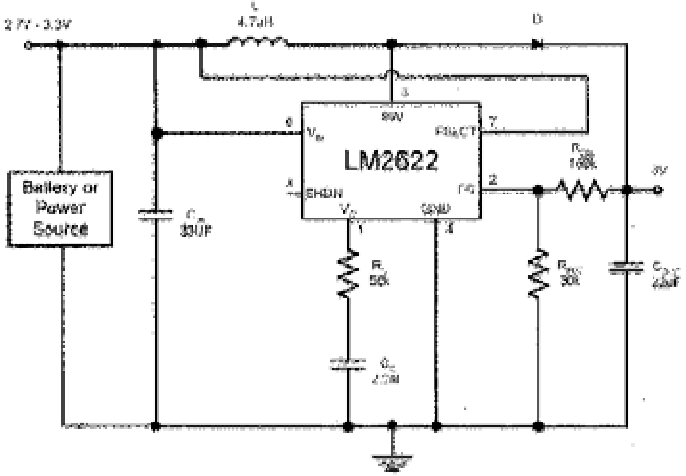
Applications

- All 1-cell or 2-cell alkaline/NiMH battery-operated products like:
  - Digital still camera
  - Internet audio player
  - PDA
  - Portable meter

Features

- Synchronous 95% efficient boost with 200-mA output current from 0.9-V supply
- Input: 0.8 V to 3.3 V, output: up to 5.5 V
- 120-mA LDO for second output voltage
- 4x4 mm² QFN/MLP package
- 65-μA quiescent current
- Pricing starts at $1.75 in quantities of 1,000

High-Frequency Boost: Integrated Regulator



Boost @ 1.3MHz – tiny external components

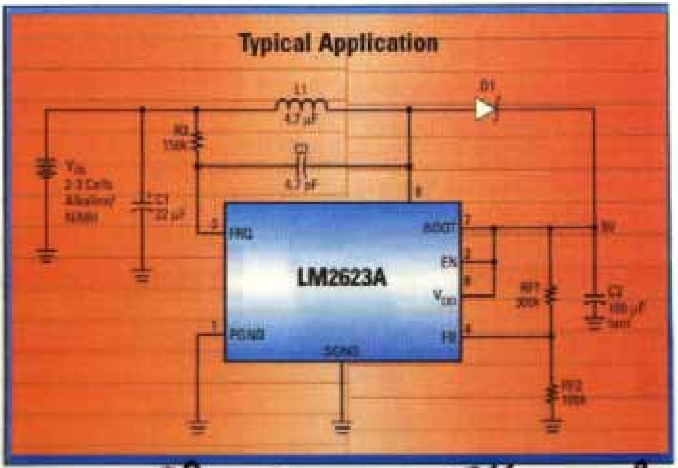
National Semiconductor

▼Features

- High Efficiency: Up to 95%
- 4-Phase, 8MHz Operation
- 5A Rated Switch Current
- Ultralow Output Ripple
- Output Disconnect and Inrush Current Limiting
- Only 12μA Quiescent Current
- 5mm x 5mm QFN Package
- Footprint < 3cm^2, ≤ 2mm Profile

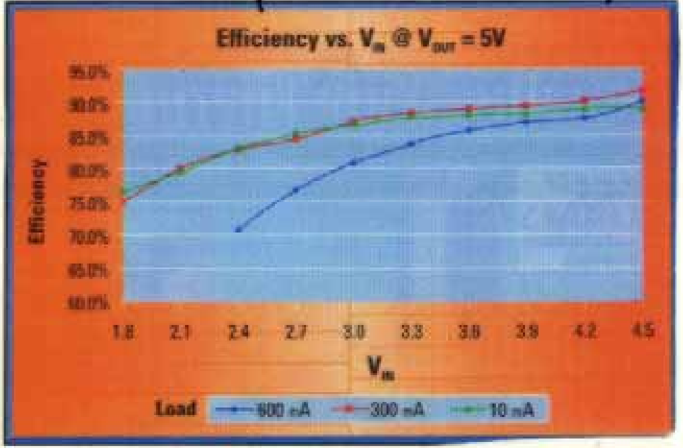
Fig. 2. *Photograph of sample boost converter.*

efficiency is greater than 85%. For an [illegible] load, efficiency is only 67%. Re



Typical Application

Chapter 3 Efficiency / Losses



Efficiency vs. V_{in} @ V_{OUT} = 5V

COMPARE

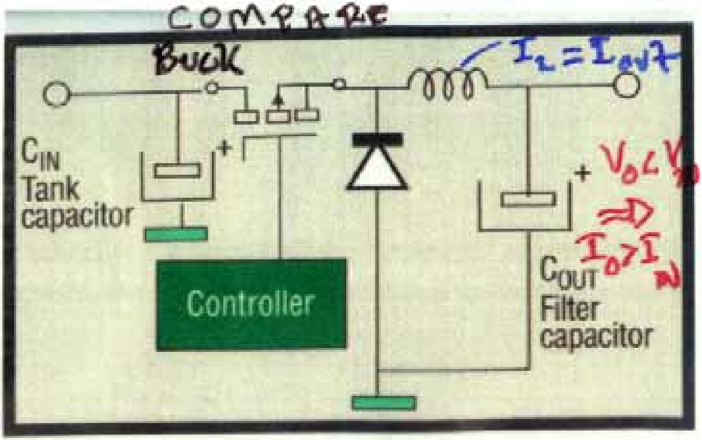


Fig. 1. *Basic schematic for a buck converter.*

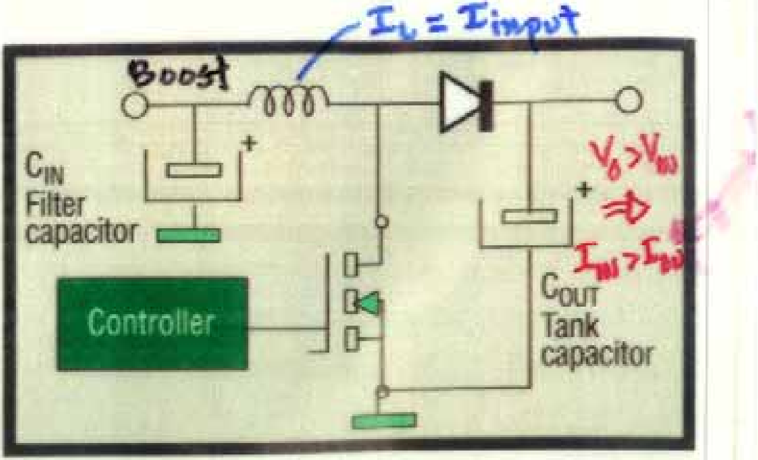
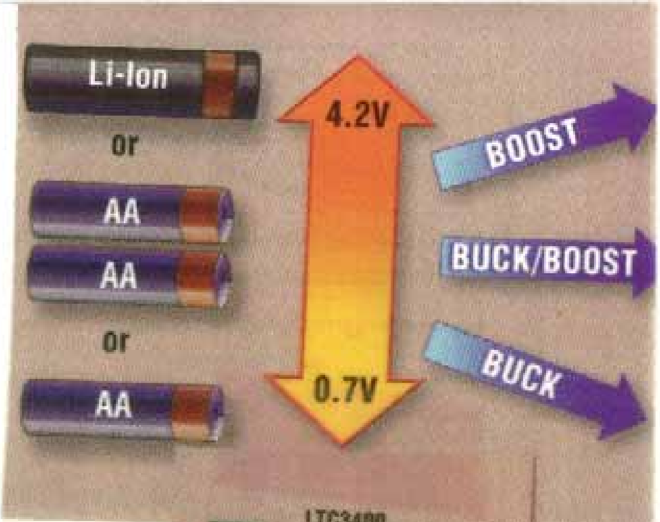


Fig. 2. *Basic schematic for a boost converter.*



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

Chapter 2
Principles of Steady-State Converter Analysis

2.1. Introduction

2.2. Inductor volt-second balance, capacitor charge balance, and the small ripple approximation

2.3. Boost converter example ← Today pg 22 - 27

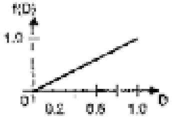
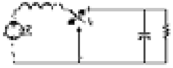
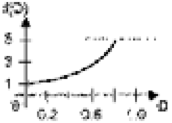
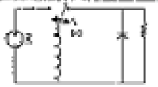
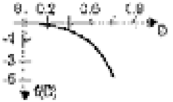
2.4. Cuk converter example

2.5. Estimating the ripple in converters containing two-pole low-pass filters

2.6. Summary of key points

L 2

SIMPLE SWITCH MODE CONVERTERS

 **BUCK** The buck is limited in that $V_{out} < V_{in}$ only		$V_L=V_s$ 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

for Single Cell Li-Ion USB Applications

Total Power Solutions

AC

5 V USB

bqTINY™II (bq24022) Charger

bqJUNIOR™ (bq270x0) Battery Fuel Gauge

Li-Ion battery

5 V USB

3.3 to 4.2 V

TPS2110 Power Switch

TPS78833 LDO – USB Circuit Supply

TPS61045 Boost – LCD Bias Voltage

TPS62050 Buck – 1.5, 1.8, 3.3 V fixed or adjustable output down to 0.7 V

TPS61030 Boost – Adjustable output up to 5.5 V, 1 A

2.6 Summary of Key Points

1. The dc component of a converter waveform is given by its average value, or the integral over one switching period, divided by the switching period. Solution of a dc-dc converter to find its dc, or steady-state, voltages and currents therefore involves averaging the waveforms.

$V_o(\text{buck}) = ?\ V_{IN}$

Δi_L I_{DC}

2. The linear ripple approximation greatly simplifies the analysis. In a well-designed converter, the switching ripples in the inductor currents and capacitor voltages are small compared to the respective dc components, and can be neglected.
3. The principle of inductor volt-second balance allows determination of the dc voltage components in any switching converter. In steady-state, the average voltage applied to an inductor must be zero.

$I_{DC} = \text{Constant}$

Summary of Chapter 2

4. The principle of capacitor charge balance allows determination of the dc components of the inductor currents in a switching converter. In steady-state, the average current applied to a capacitor must be zero.
5. By knowledge of the slopes of the inductor current and capacitor voltage waveforms, the ac switching ripple magnitudes may be computed. Inductance and capacitance values can then be chosen to obtain desired ripple magnitudes.
6. In converters containing multiple-pole filters, continuous (nonpulsating) voltages and currents are applied to one or more of the inductors or capacitors. Computation of the ac switching ripple in these elements can be done using capacitor charge and/or inductor flux-linkage arguments, without use of the small-ripple approximation.
7. Converters capable of increasing (boost), decreasing (buck), and inverting the voltage polarity (buck-boost and Cuk) have been described. Converter circuits are explored more fully in a later chapter.

$V_c \approx$ Constant

Double Pole Case

Entry Level Engineer Expectations

		Proficiency
✓ Switching power supply technology		4
✓ Analog circuit design and analysis techniques		3
✓ Understanding of magnetics		3
✓ Simulation skills SPICE		3
• Basic understanding		
✓ Communication skills	Group Project Oral Talks Written Papers	5
• Written ← Word		
• Oral ← Powerpoint		
✓ Teamwork experience and skills		5

Experienced Engineer Expectations

	Proficiency
✓ Power supply design experience	5
✓ Analog circuit design and analysis	5
✓ Magnetic component design and implementation	5
✓ Analog simulation	5
✓ Digital design	4
✓ Digital simulation	3
✓ Verbal communication	5
✓ Written communication	5
✓ Teamwork experience and skills	5

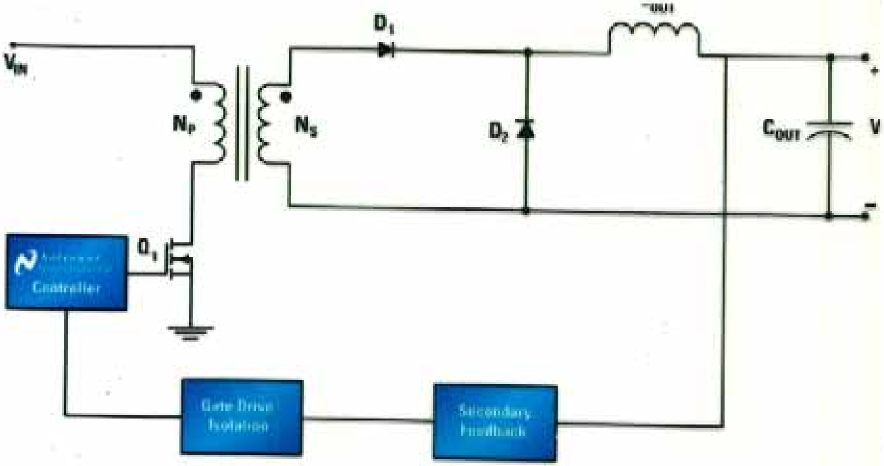


Figure 2. Isolated power converter with output synchronous rectification

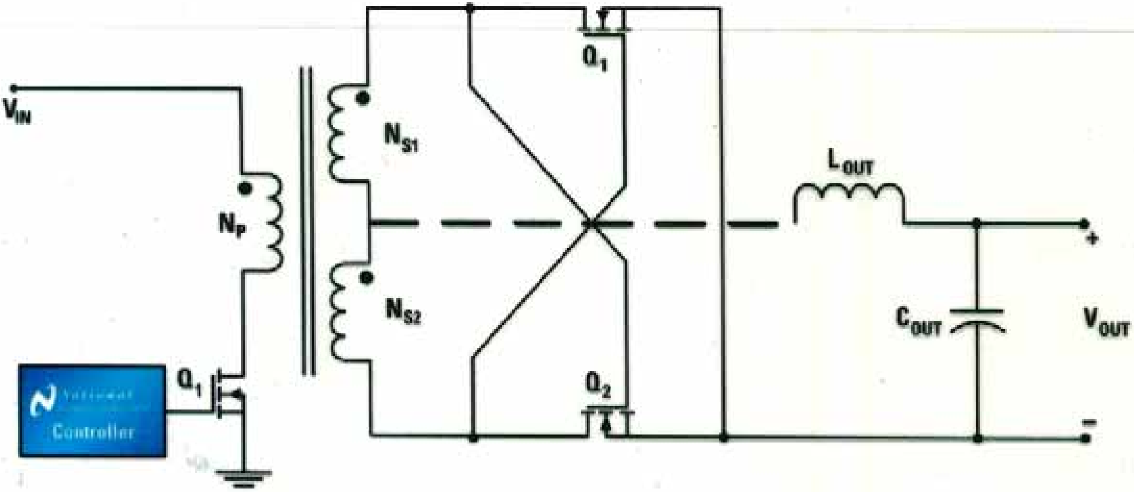


Figure 3. Self-driven synchronous rectification output stage

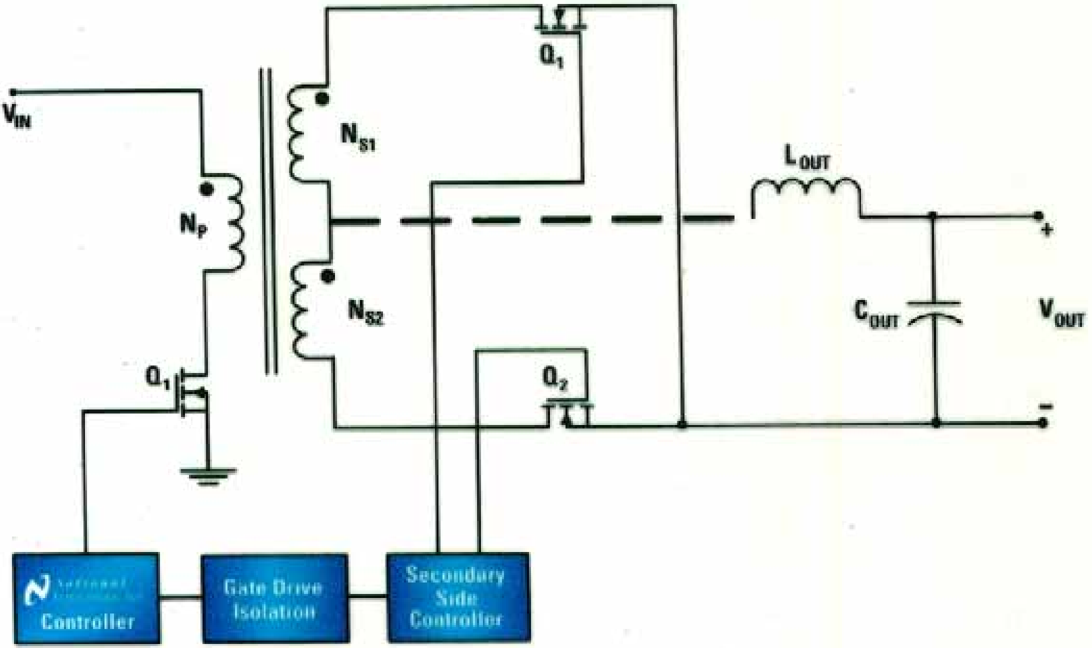
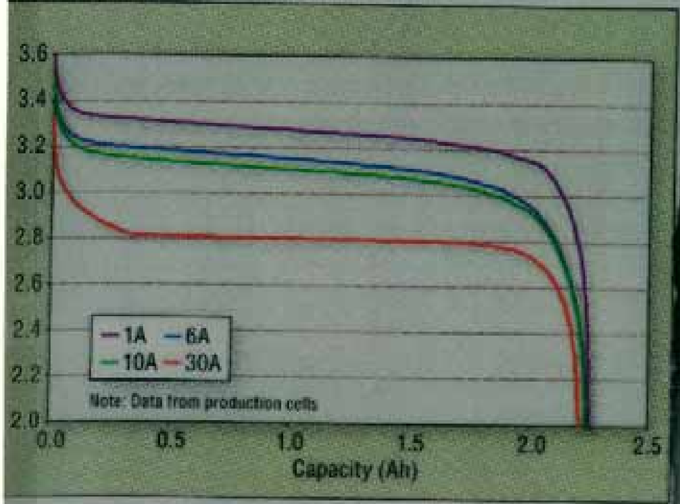


Figure 4. Control-driven synchronous rectification output stage



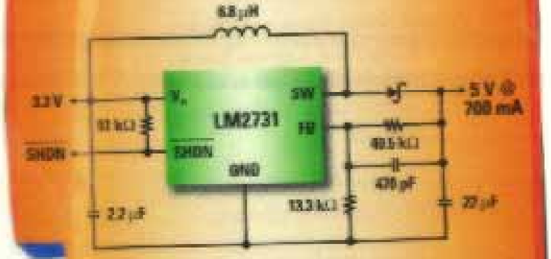
Note: Data from production cells

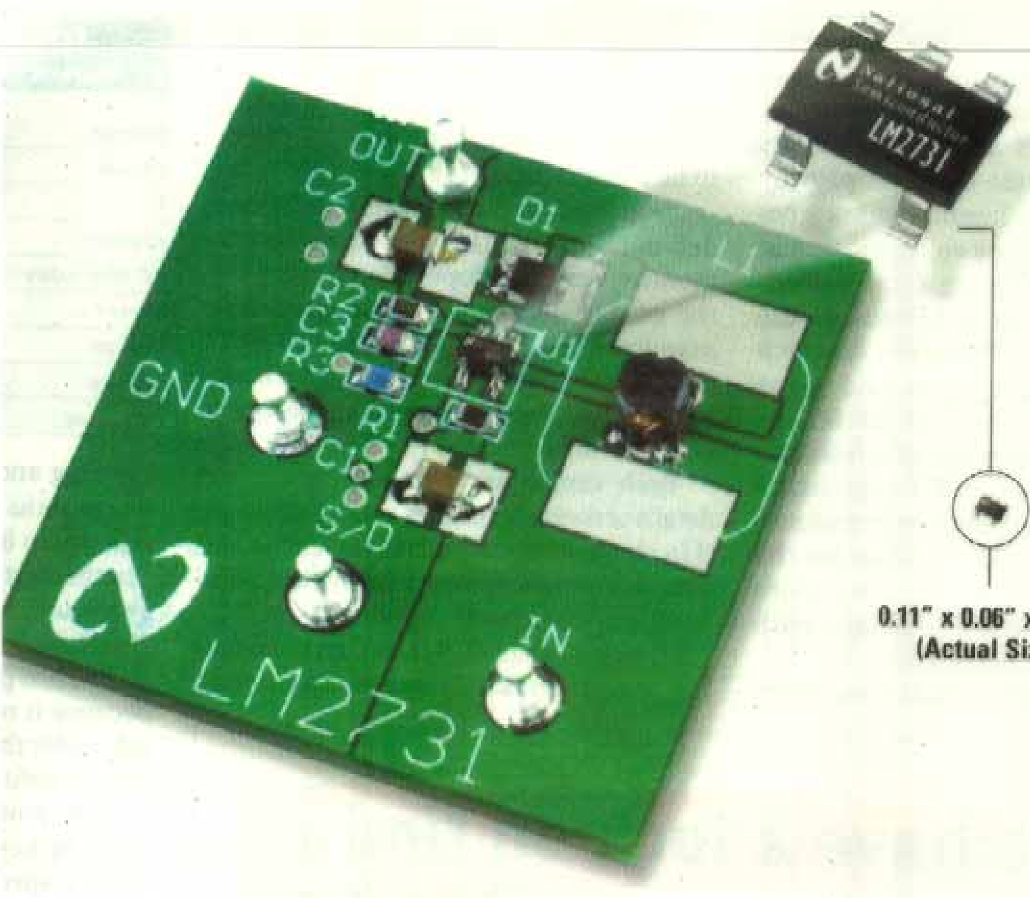
. Based on a lithium-iron-phosphate cathode, a Li-ion cell from supports high-drain rates, but has a lower operating voltage cells using more conventional cathode materials.

LM2731/33: SOT-23 Switchers Establish New Standards In Power Density, Efficiency, And Performance

- 1.6 MHz-(X), 0.6 MHz-(Y) Switching Frequency Options
- Up to 90% Conversion Efficiency
- Low $r_{DS(ON)}$ DMOS Power Switch
- 1A, 40 V Switch (LM2733)
- 1.8A, 22 V Switch (LM2731)
- Wide Input Voltage Range (2.7 V to 14 V)
- Low Shutdown Current (<1 μA)
- Current-Mode Control for Superior Performance Over Wide Input Voltage Range

LM2731
Typical Application





0.11" x 0.06" x 0.04"
(Actual Size)

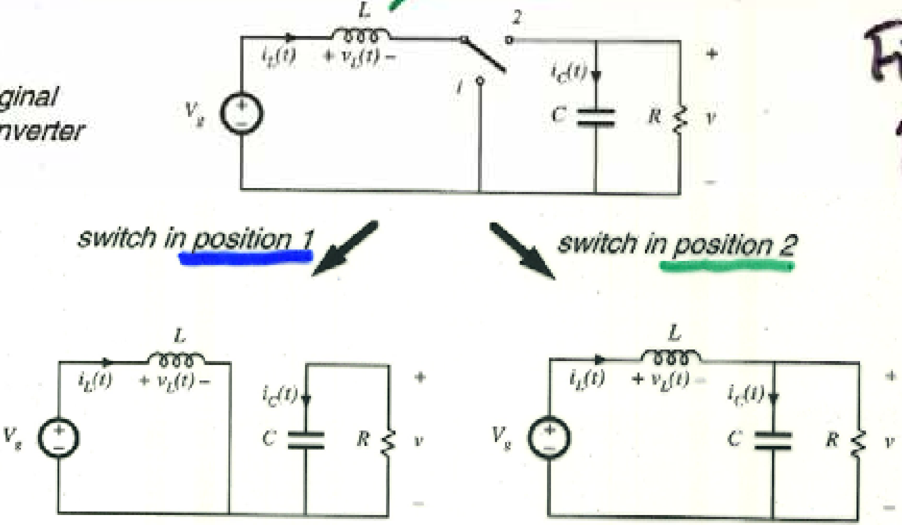
2.6 Summary of Key Points

1. The dc component of a converter waveform is given by its average value, or the integral over one switching period, divided by the switching period. Solution of a dc-dc converter to find its dc, or steady-state, voltages and currents therefore involves averaging the waveforms.
2. The linear ripple approximation greatly simplifies the analysis. In a well-designed converter, the switching ripples in the inductor currents and capacitor voltages are small compared to the respective dc components, and can be neglected.
3. The principle of inductor volt-second balance allows determination of the dc voltage components in any switching converter. In steady-state, the average voltage applied to an inductor must be zero.

Boost converter analysis

$I_L^{DC} + \Delta i_L$ (ac)

Fig 2.14
pg 23



original converter

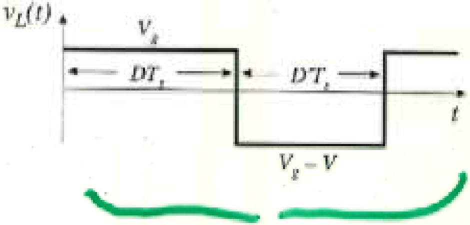
switch in position 1

switch in position 2

Inductor volt-second balance

Net volt-seconds applied to inductor over one switching period:

$$\int_0^{T_s} v_L(t)\,dt = (V_g)\,DT_s + (V_g - V)\,D'T_s$$



Sets $\frac{V_o}{V_{IN}}$

Equate to zero and collect terms:

$$V_g\,(D + D') - V\,D' = 0$$

Solve for V:

$$V = \frac{V_g}{D'}$$

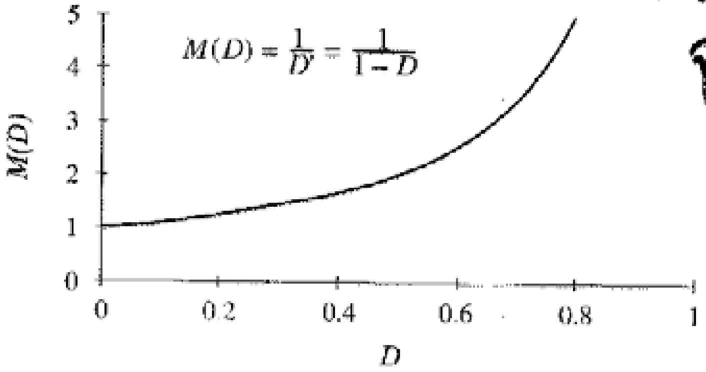
The voltage conversion ratio is therefore

$$M(D) = \frac{V}{V_g} = \frac{1}{D'} = \frac{1}{1-D}$$

OK? $D \rightarrow 1$ $V_{out} = ?$

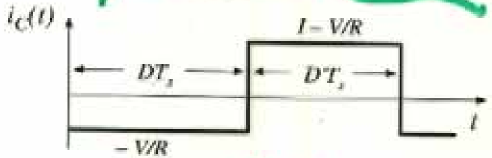
Conversion ratio *M(D)* of the boost converter

Fig 2.16
Pg 24



Determination of inductor current dc component

sets I_L (DC)



Capacitor charge balance:

$$\int_0^{T_s} i_C(t)\,dt = \left(-\frac{V}{R}\right) DT_s + \left(I - \frac{V}{R}\right) D'T_s$$

Collect terms and equate to zero:

$$-\frac{V}{R}(D + D') + I\,D' = 0$$

Solve for I:

$$I = \frac{V}{D'\,R}$$

Eliminate V to express in terms of V_g:

$$I = \frac{V_g}{D'^2\,R}$$

effective dc value

$I_o = V_g/R$ no switching

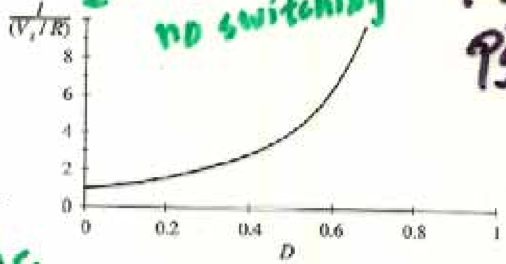
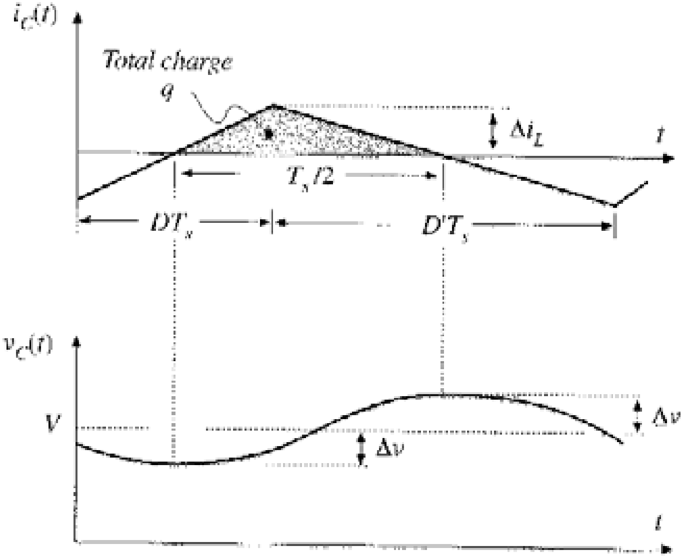


Fig 2.17 pg 25

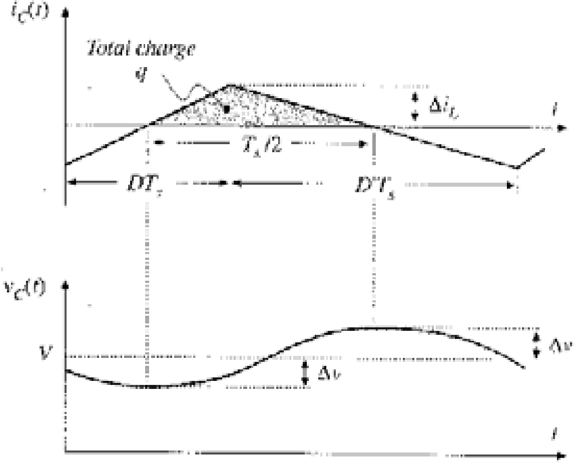
Capacitor current and voltage, buck example

Must not neglect inductor current ripple!

If the capacitor voltage ripple is small, then essentially all of the ac component of inductor current flows through the capacitor.



Estimating capacitor voltage ripple Δv

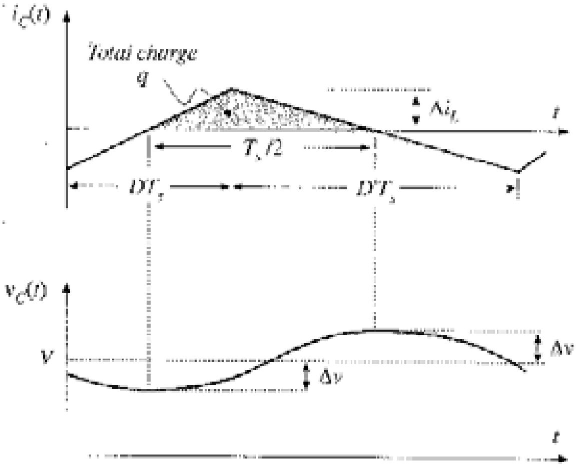


Current $i_C(t)$ is positive for half of the switching period. This positive current causes the capacitor voltage $v_C(t)$ to increase between its minimum and maximum extrema. During this time, the total charge q is deposited on the capacitor plates, where

$$q = C\,(2\Delta v)$$

(change in charge) =
C (change in voltage)

Estimating capacitor voltage ripple Δv



The total charge q is the area of the triangle, as shown:

$$q = \frac{1}{2}\Delta i_L \frac{T_s}{2}$$

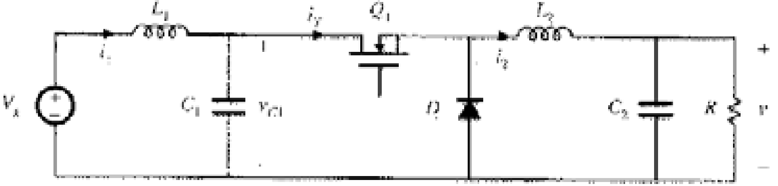
Eliminate q and solve for Δv:

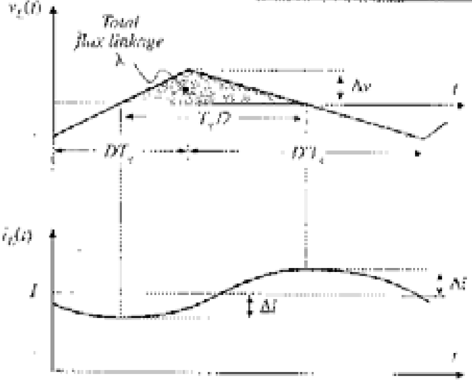
$$\Delta v = \frac{\Delta i_L T_s}{8\,C}$$

Note: in practice, capacitor equivalent series resistance (esr) further increases Δv.

Inductor current ripple in two-pole filters

Example:
problem 2.9





can use similar arguments, with

$$\lambda = L\,(2\Delta i)$$

λ = inductor flux linkages

= inductor volt-seconds

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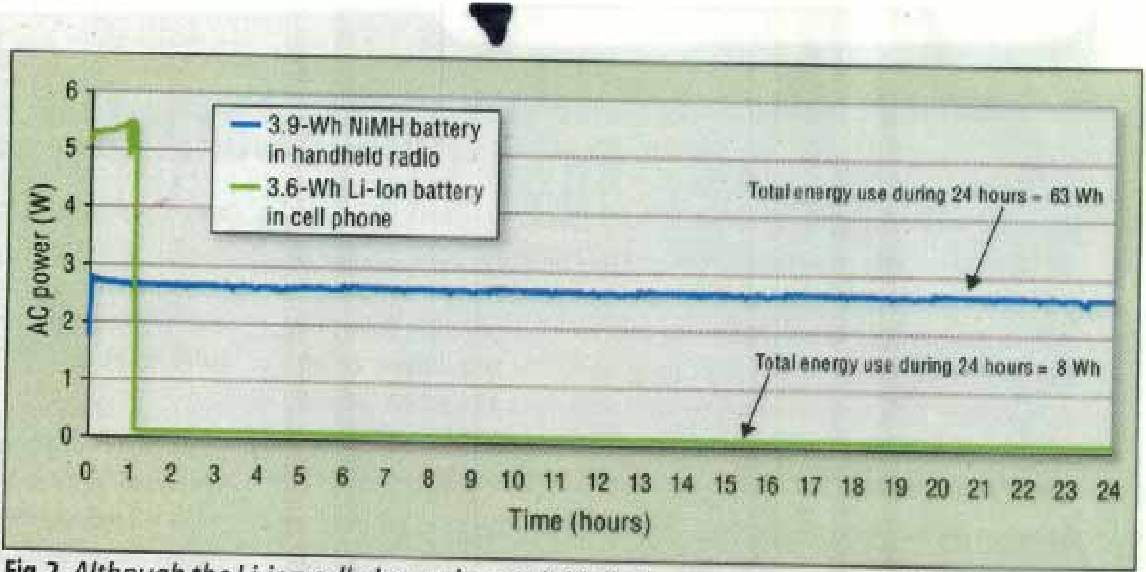

Fig. 2. *Although the Li-ion cell phone charger initially draws more ac power than the NiMH-powered radio when charging, the Li-ion charger completes the charging process more rapidly, so its total energy consumption is less than the NiMH charger.*