ECE 562

Week 1 Lecture 2

Week 1 Lecture 2 Summary

- Section 2
  - Slides 3-8 – Power conversion tasks
  - Slides 9-17 – Efficiency characteristics
  - Slides 18-40 – Buck converters and filtering
  - Slides 41-45 – Circuit elements
  - Slides 46-48 – PSpice setup
  - Slides 49-67 – Commercial power supply characteristics

1972:
Odyssey [above], the first home video game, and *Pong*, the first commercial video game, are released.

1979:
Sony debuts the Walkman.

1981:
IBM introduces its first personal computer—the IBM PC.

1982:
The Commodore 64, the best-selling single personal computer model of all time, debuts, featuring 64-bit graphics.

CONSUMER

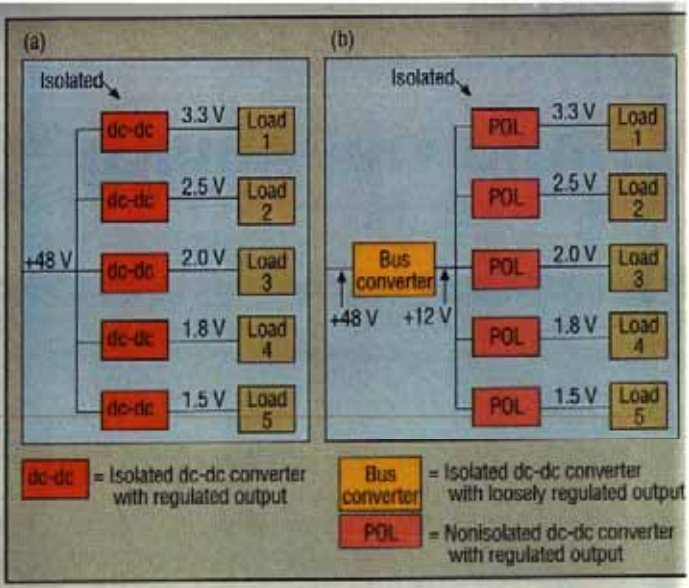
1971:
Intel invents the first microprocessor.

1973:
Xerox introduces the Alto—the first computer with a graphical user interface.

1978:
Philips announces the first CD.

1982:
Silicon Graphics Inc. (SGI) is launched, sparking an era of high-end 3-D graphics workstations.

1988:
Deep Thought becomes the first computer to beat a human chess master. It is later defeated by Garry Kasparov.



By moving from a single-stage of on-board power conversion (a) to two-stage power conversion (b), distributed power applications have reduced system costs by paying for isolation just once. The latter approach is commonly known as the intermediate bus architecture. Voltage levels shown are merely popular values.

48 V Telcom

12 V ?

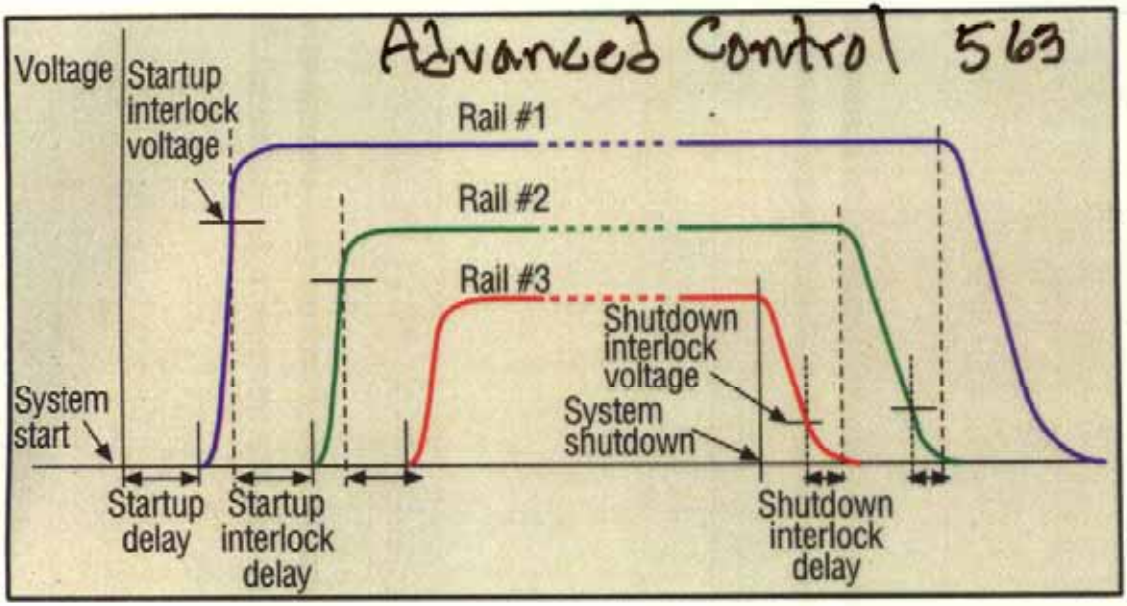


Fig. 3. *Sequencing using interlocks.*

Sequencing

old voltages and ti

1997:
The BlackBerry device is released by Research in Motion.

1999:
Napster brings peer-to-peer file sharing to the masses.

2001:
Apple introduces the iPod.

2005:
YouTube is launched.

2007:
Apple releases the iPhone.

1990:
Tim Berners-Lee introduces the World Wide Web to the public on 25 December.

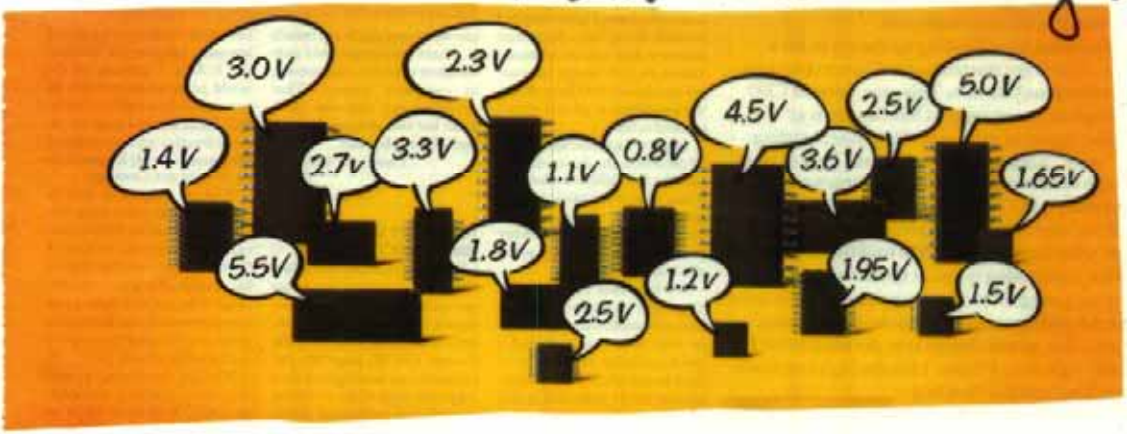
1997:
IEEE releases 802.11 (Wi-Fi) standard.

1998:
Google fires up its first server.

2004:
On 4 January, the NASA rover *Spirit* lands on Mars; *Opportunity* joins it on 25 January.

2005:
MareNostrum, a supercomputer with 20 terabytes of RAM, is installed in Spain.

How to get myriad of V's from one battery?



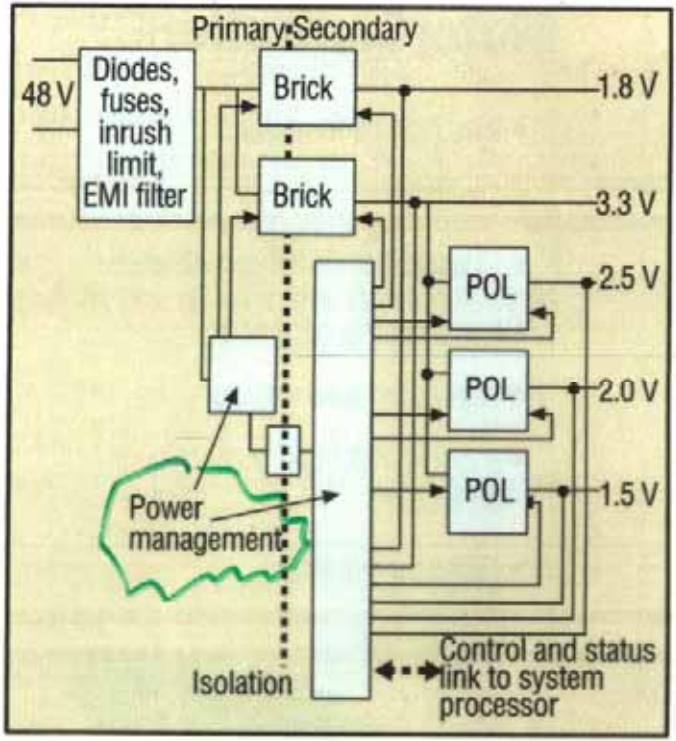
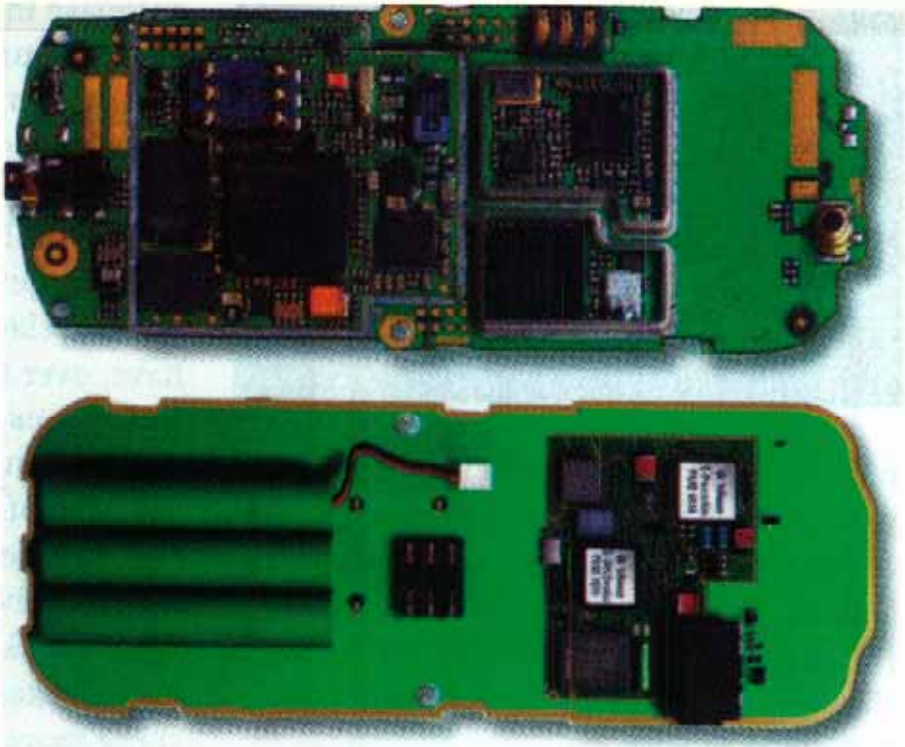


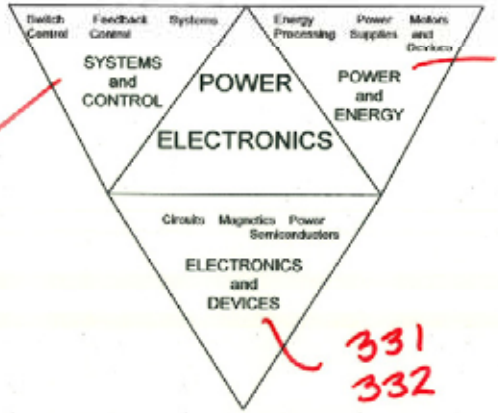
Fig. 1. *48-V card power block diagram.*



BEFORE AND AFTER: A new mobile phone prototype from Infineon [bottom] has half the number of components of a typical handset [top]. Integrating several ICs into one chip was the key.

In reality actual efficiency values are 85% to 90% due to losses in the parasitics.
The switching regulator generates very high transients of the electric and magnetic fields at 200 kHz. This generates both conducted and radiated electromagnetic noise. This noise can be easily higher than the 5% tolerance window of the supply voltage 3.1 V for the Pentium. To avoid malfunction of the processor it is necessary to filter this noise for all conditions. Moreover, this noise must not pollute the ac mains.

Which regulator, Example 1 or 2 is a best choice for a laptop computer?

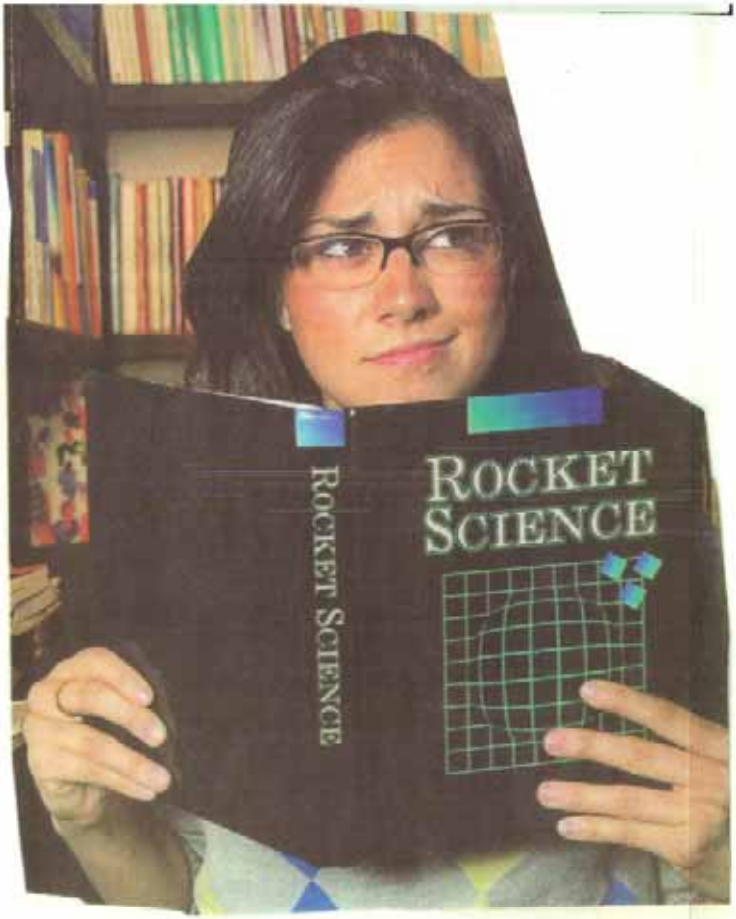


562
563

461

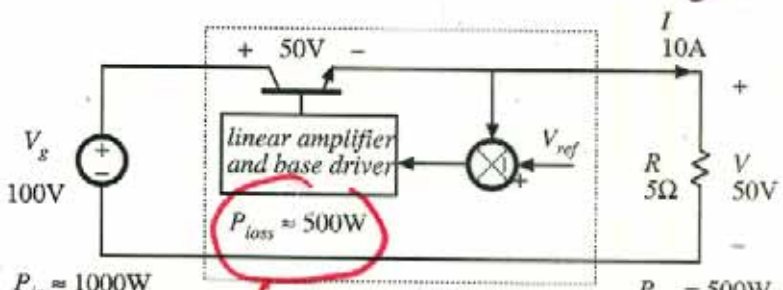
331
332

562
563


ROCKET SCIENCE
ROCKET SCIENCE

Dissipative realization

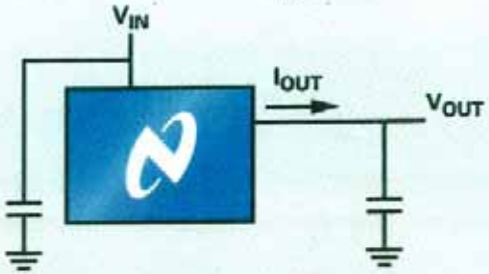
Series pass regulator: transistor operates in active region



Can we drop voltage w/o power loss?

Old standard

Linear regulator



Function: Step-down ($V_{OUT} < V_{IN}$)

When to use: Typically when $I_{OUT} < 1A$, ultra low-dropout, and low-noise applications

Characteristics: Excellent option where fixed output, low current, and low voltage drops are required. Easy to implement

Devices to use: Any low-dropout, linear regulat

Comments: Great for micropower applications

Paper #1 Topic

#2 Lab

Make a new SPICE lab

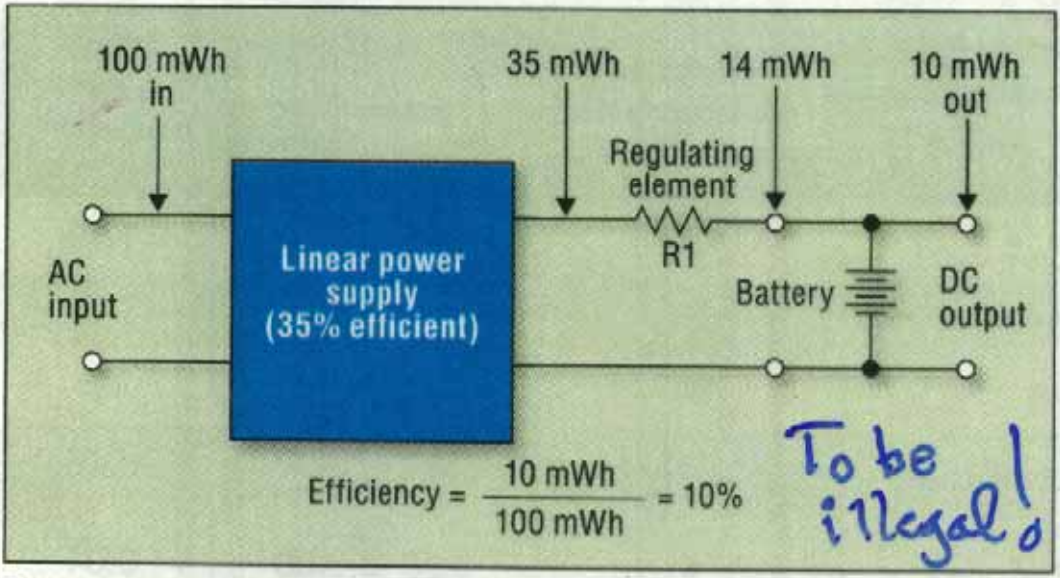


Fig. 4. *In a two-piece battery charger composed of a linear power supply and a resistive linear regulator, overall efficiency is typically around 10%.*

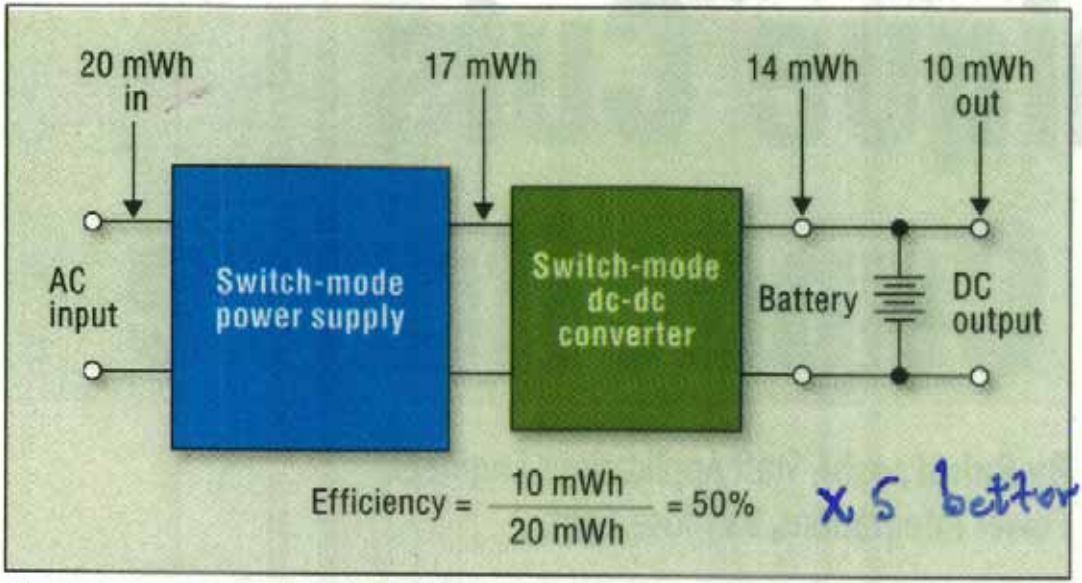
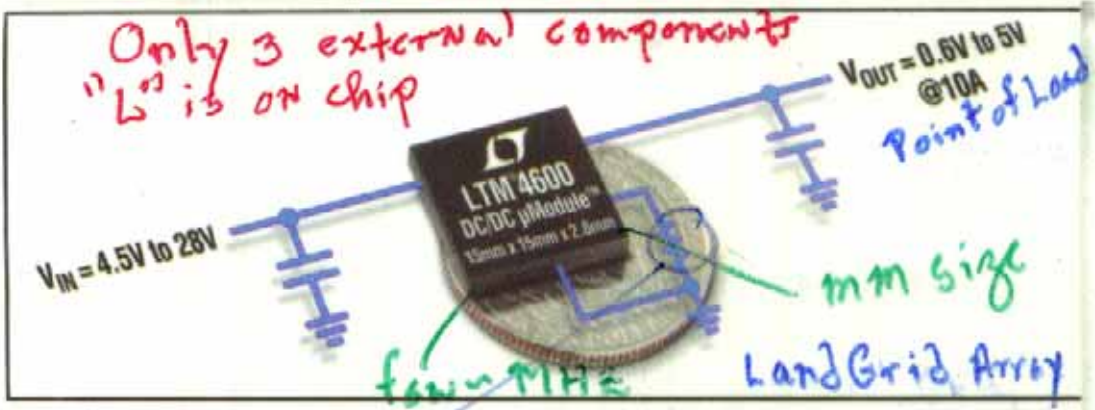


Fig. 5. *A two-piece charger with two-switch mode components improves efficiency over the linear charger significantly.*



Linear Technology's LTM4600 provides an instant 10-A power supply.

R sets V_{out}

Two in parallel $I_{out} = ?$

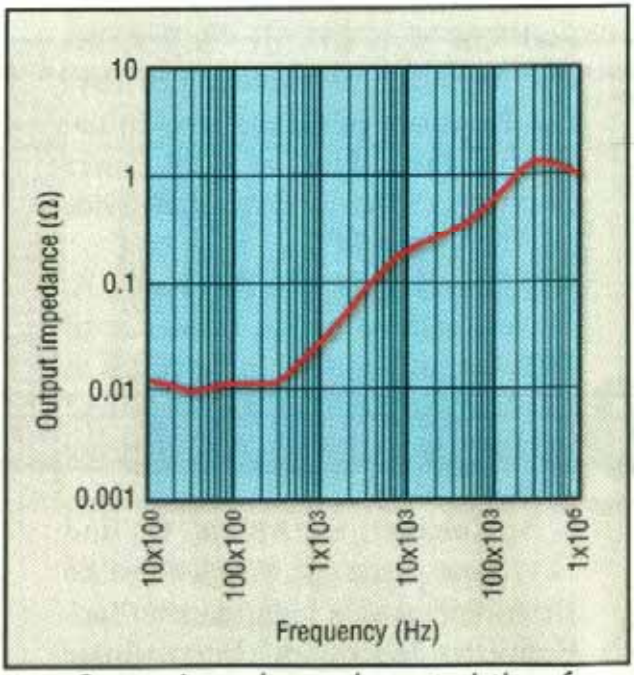
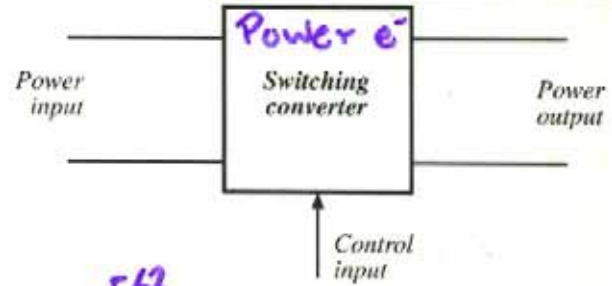


Fig. 1. *Output impedance characteristics of a linear regulator.*

1.1 Introduction to Power Processing



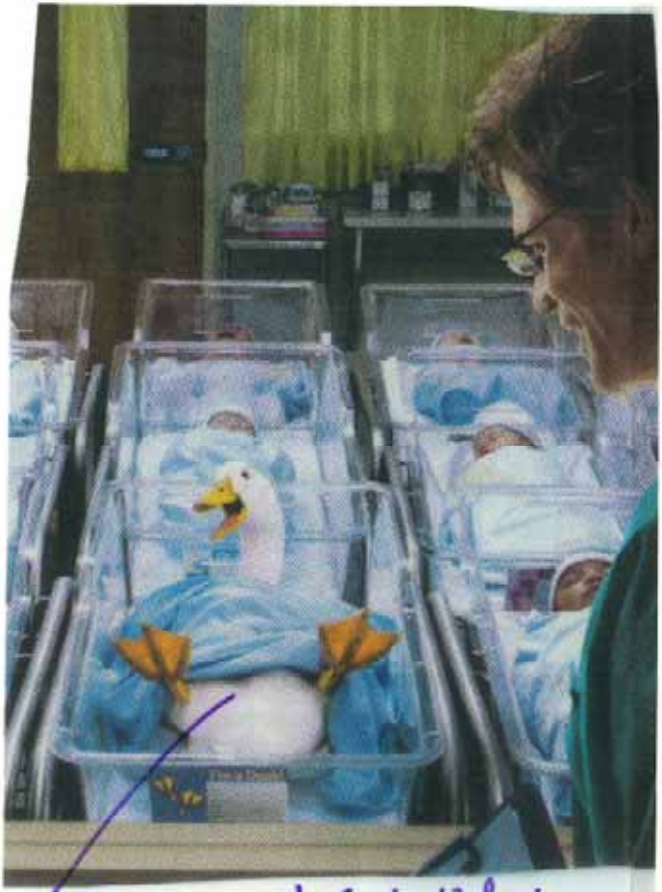
562

1. *Dc-dc conversion:* Change and control voltage magnitude
2. *Ac-dc rectification:* Possibly control dc voltage, ac current
3. *Dc-ac inversion:* Produce sinusoid of controllable magnitude and frequency

461

4. *Ac-ac cycloconversion:* Change and control voltage magnitude and frequency

461



Pe⁻ Uses L, C, Switches
A22 "low loss"

Overview prior to reading text

Chapter 2
Principles of Steady-State Converter Analysis

Assume Lossless L, C, switch

2.1. Introduction

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

Today

2.3. Boost converter example

2.4. Cuk converter example

read for next class

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

2.6. Summary of key points

Ch 3 add L, C losses / Sw losses!

Ch2

Objectives of this chapter

- Develop techniques for easily determining output voltage of an arbitrary converter circuit
- Derive the principles of *inductor volt-second balance* and *capacitor charge (amp-second) balance*
- Introduce the key *small ripple approximation*
- Develop simple methods for selecting filter element values
- Illustrate via examples

Choose L_{opt}

Choose C_{opt}

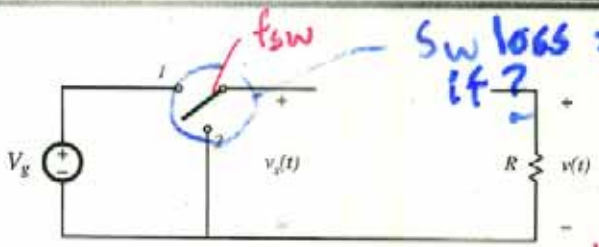
$\frac{e}{L} = \frac{di}{dt} \Rightarrow \int \frac{e}{L}\,dt \rightarrow i$ @ $t=0$ same @ $t=T_{SW}$

Balance $\Rightarrow$ no i drift

2.1 Introduction
Buck converter

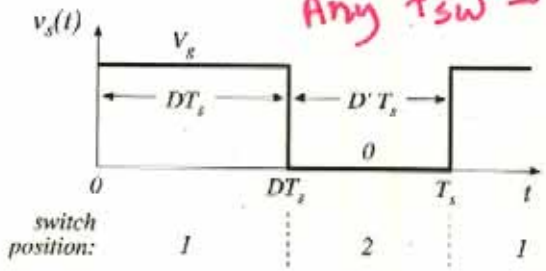
Fig 2.1 pg 13

SPDT switch changes dc component



Switch output voltage waveform

Any $f_{sw} = \frac{1}{T_{sw}}$



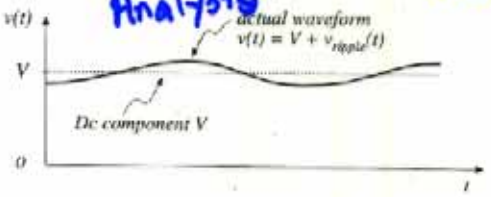
Duty cycle *D*:
$0 \le D \le 1$

complement D':
$D' = 1 - D$

The small ripple approximation

Avoids ① Spice Transient Analysis ② Complex Analysis

$$v(t) = V + v_{ripple}(t)$$



In a well-designed converter, the output voltage ripple is small. Hence, the waveforms can be easily determined by ignoring the ripple:

$$\left| v_{ripple} \right| << V$$

$$v(t) \approx V$$

Dc component of switch output voltage

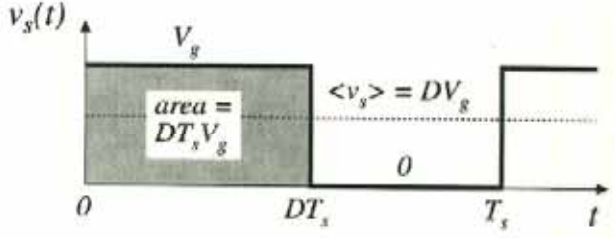


Fig 2.2
pg 14

Fourier analysis: Dc component = average value

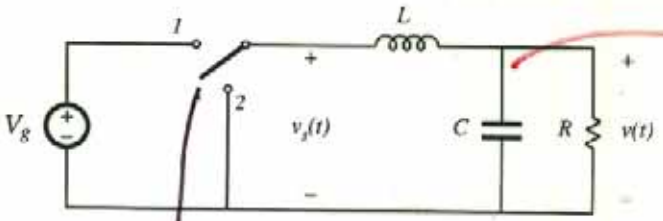
$$\langle v_s \rangle = \frac{1}{T_s}\int_0^{T_s} v_s(t)\,dt$$

$$\langle v_s \rangle = \frac{1}{T_s}(DT_sV_g) = DV_g$$

Very choppy DC without filter

Insertion of low-pass filter to remove switching harmonics and pass only dc component

f_{sw} noise ripple



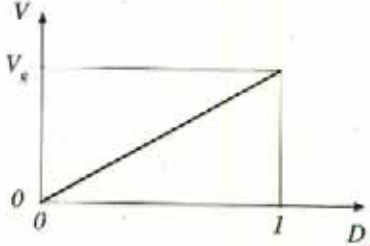
$\tau = \frac{L}{R}$

$\tau = RC$

f_{sw}

T_{sw}

$$v = \langle v_s \rangle = DV_g$$

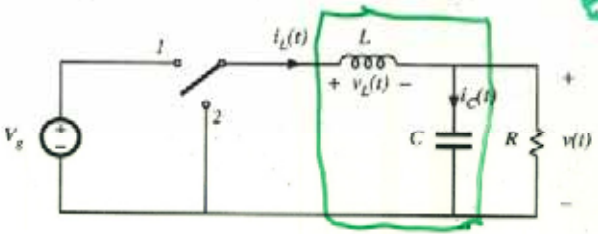


For filtering $T_{sw} \ll \tau_{RC}$ or τ_{LC}

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

Actual output voltage waveform, buck converter

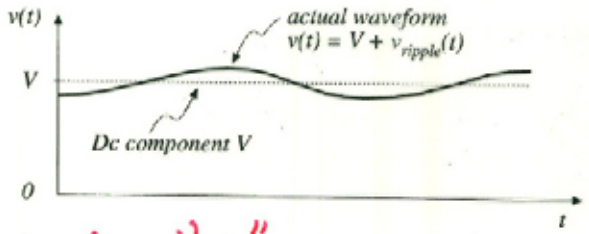
Buck converter containing practical low-pass filter



Both L & C are very big

Actual output voltage waveform

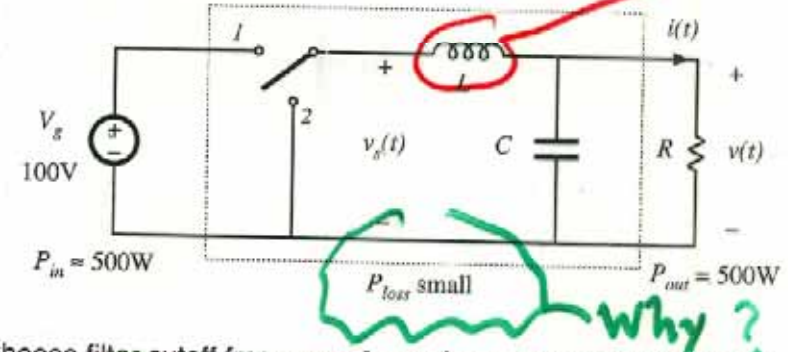
$$v(t) = V + v_{ripple}(t)$$



How to drive to "0"

Addition of low pass filter

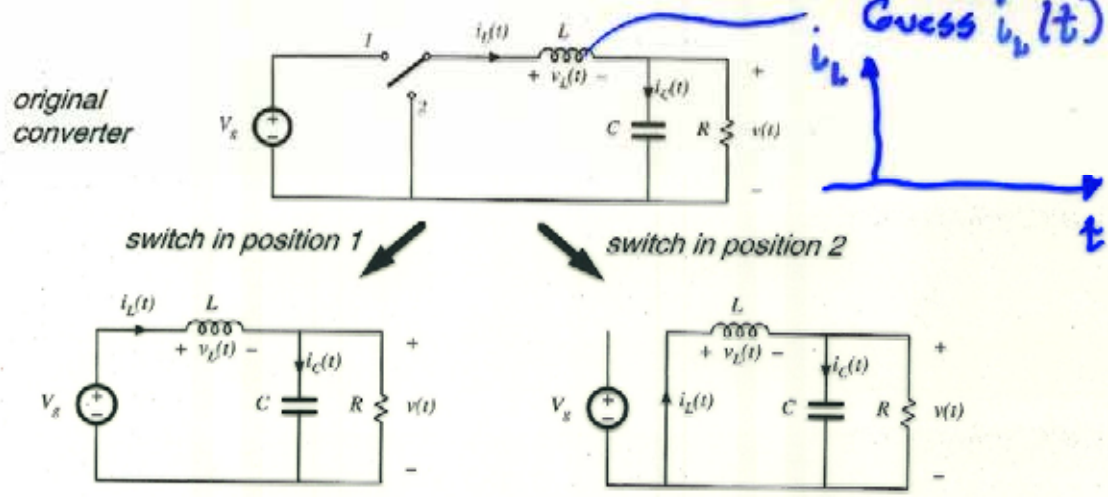
Addition of (ideally lossless) *L-C* low-pass filter, for removal of switching harmonics



- Choose filter cutoff frequency f_0 much smaller than switching frequency f_s
- This circuit is known as the "buck converter"

Buck converter analysis: inductor current waveform

Fig 2.8 P 17



Inductor voltage and current
Subinterval 1: switch in position 1

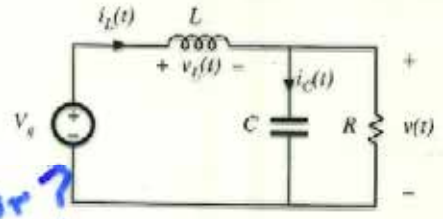
Inductor voltage

$$v_L = V_g - v(t)$$

Small ripple approximation:

$$v_L \approx V_g - V$$

≈ constant over ?



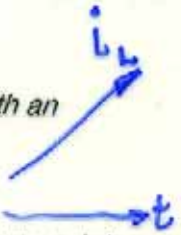
Knowing the inductor voltage, we can now find the inductor current via

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

Solve for the slope:

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

⇒ *The inductor current changes with an essentially constant slope*



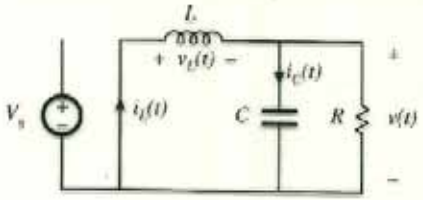
Inductor voltage and current
Subinterval 2: switch in position 2

Inductor voltage

$$v_L(t) = -v(t)$$

Small ripple approximation:

$$v_L(t) \approx -V$$ Constant



Knowing the inductor voltage, we can again find the inductor current via

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

Solve for the slope:

$$\frac{di_L(t)}{dt} = -\frac{V}{L}$$

⇒ *The inductor current changes with an essentially constant slope*

i_2

Assumes $T_{sw} \ll RC, \frac{L}{R}$

Inductor voltage and current waveforms

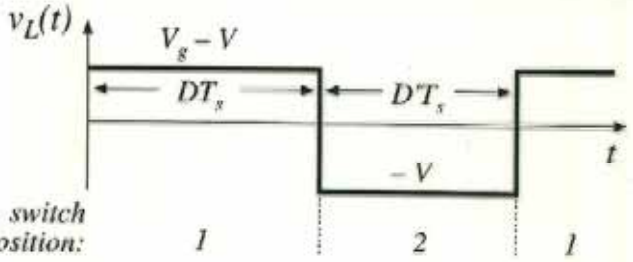
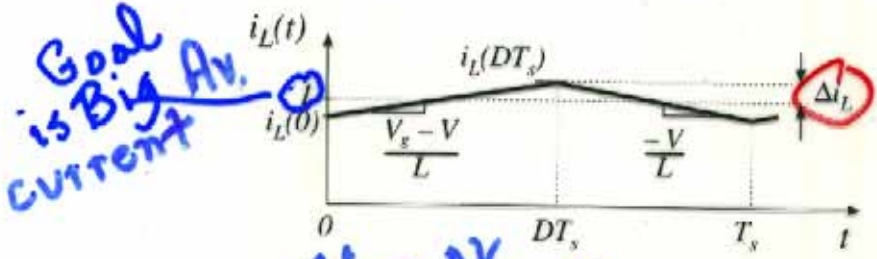


Fig 2.9 2.10 p 18



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

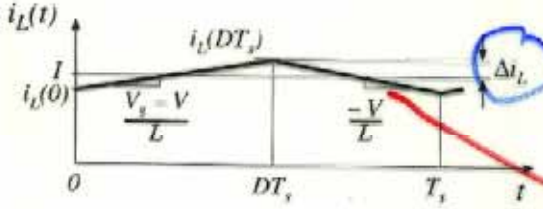
Goal is Big Av. current

Small goal

$$\Delta i = \frac{\Delta v_L}{L} \Delta t$$

Δi small $\Rightarrow$?

Determination of inductor current ripple magnitude



Defined

Spice Simulation DUE

Set Δi ripple by?

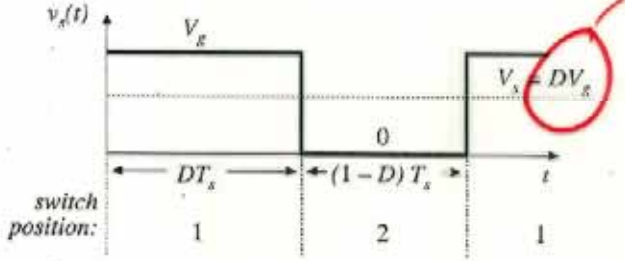
t_{ON} SW1

(change in i_L) = (slope)(length of subinterval)

$$\left(2\Delta i_L\right) = \left(\frac{V_g - V}{L}\right)\left(DT_s\right)$$

$$\Rightarrow \quad \Delta i_L = \frac{V_g - V}{2L} DT_s \qquad L = \frac{V_g - V}{2\Delta i_L} DT_s$$

The switch changes the dc voltage level



D = switch duty cycle

$0 \le D \le 1$

T_s = switching period

f_s = switching frequency

$= 1 / T_s$

DC component of $v_s(t)$ = average value:

$$V_s = \frac{1}{T_s}\int_0^{T_s} v_s(t)\,dt = DV_g$$

$\neq f(f_{sw})$ why

$f_s \uparrow$ good why?

z_c effects

z_2

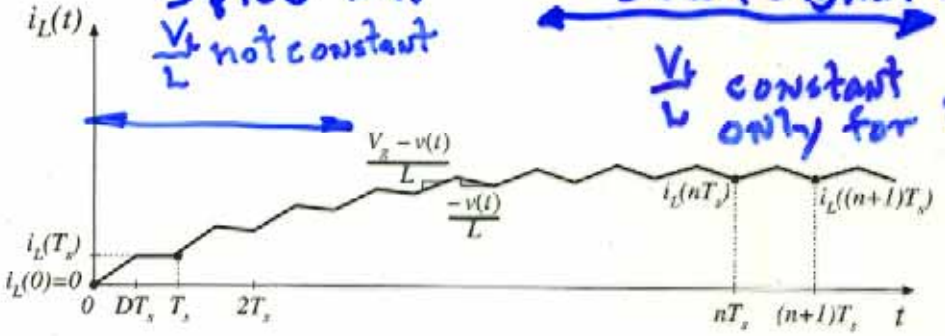
T_{rt} effects

Trend?

Inductor current waveform during turn-on transient

Early time
Spice Lab
$\frac{V_g}{L}$ not constant

Spice
Small signal Approx
$\frac{V_g}{L}$ constant only for long t

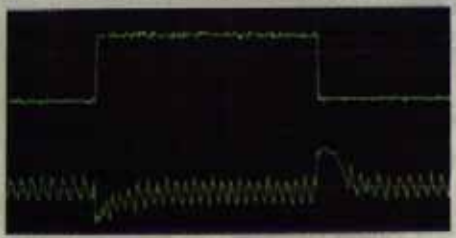


When the converter operates in equilibrium:

$$i_L((n+1)T_s) = i_L(nT_s)$$

563

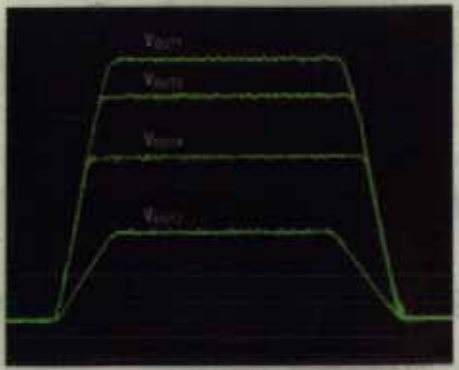
Fast Transient Response



V_{IN} = 15V
V_{OUT} = 2.5V
C_{OUT} = 2x330µF

20µs/DIV

Coincident or Ratiometric Tracking

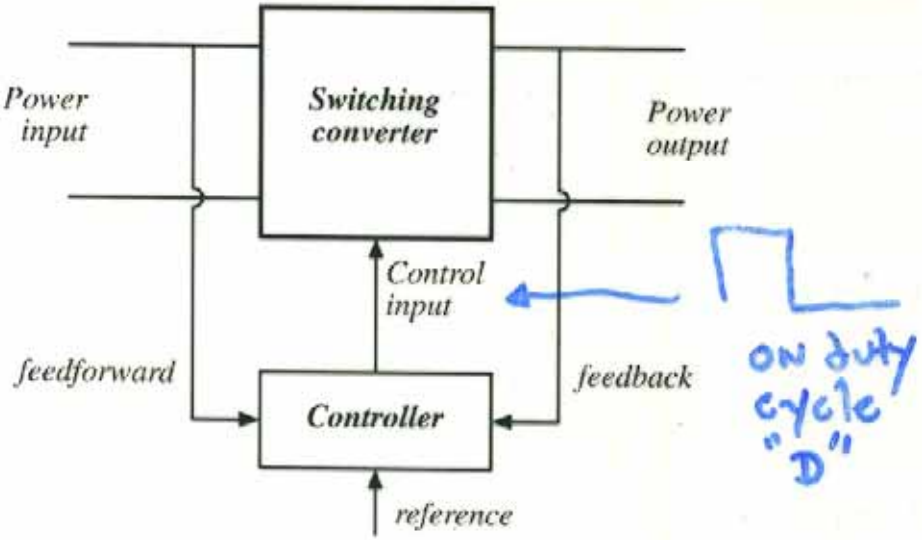


2ms/DIV

563

Control is invariably required

V_{out}, V_{in} } const during T_{sw}



The principle of inductor volt-second balance: Derivation

Inductor defining relation:

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

Integrate over one complete switching period:

$$i_L(T_s) - i_L(0) = \frac{1}{L} \int_0^{T_s} v_L(t)\, dt$$

In periodic steady state, the net change in inductor current is zero:

$$0 = \int_0^{T_s} v_L(t)\, dt$$

Hence, the total area (or volt-seconds) under the inductor voltage waveform is zero whenever the converter operates in steady state.

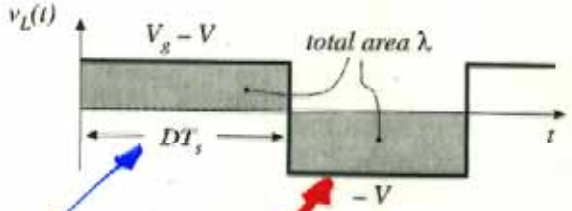
An equivalent form:

$$0 = \frac{1}{T_s} \int_0^{T_s} v_L(t)\, dt = \langle v_L \rangle$$

The average inductor voltage is zero in steady state.

Inductor volt-second balance: Buck converter example

Inductor voltage waveform, previously derived:



Integral of voltage waveform is area of rectangles:

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

Average voltage is SW 1 ON SW 2 ON

$$\langle v_L \rangle = \frac{\lambda}{T_s} = D(V_g - V) + D'(-V)$$

Equate to zero and solve for V:

$$0 = DV_g - (D + D')V = DV_g - V \quad \Rightarrow \quad V = DV_g$$

The principle of capacitor charge balance: Derivation

Capacitor defining relation:

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

Integrate over one complete switching period:

$$v_C(T_s) - v_C(0) = \frac{1}{C} \int_0^{T_s} i_C(t)\, dt$$

In periodic steady state, the net change in capacitor voltage is zero:

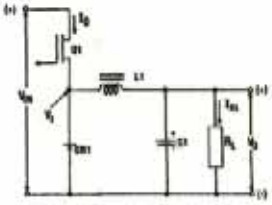
$$0 = \frac{1}{T_s} \int_0^{T_s} i_C(t)\, dt = \langle i_C \rangle$$

Hence, the total area (or charge) under the capacitor current waveform is zero whenever the converter operates in steady state. The average capacitor current is then zero.

TYPE OF CONVERTER

Buck (Step Down)

CIRCUIT CONFIGURATION



IDEAL TRANSFER FUNCTION

$$\frac{V_O}{V_{IN}} = \frac{t_{on}}{T_S} = D$$

PEAK DRAIN CURRENT *

$$I_{DMAX} = I_{RL} + \frac{\Delta I_{L1}}{2}$$

CAN make → 0

PEAK DRAIN VOLTAGE *

$$V_{DS} = V_{IN} + V_D$$

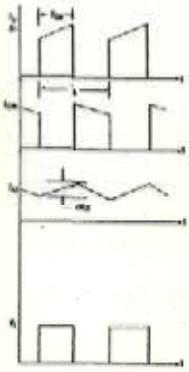
AVERAGE DIODE CURRENTS *

$$I_{CR1} = I_{RL}\,(1-D)$$

DIODE VOLTAGES (VRM) *

$$V_{1M} = V_{IN}$$

VOLTAGE AND CURRENT WAVEFORMS



ADVANTAGES

High efficiency, simple, no transformer, low switch stress. Small output filter, low ripple.

DISADVANTAGES

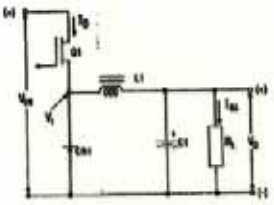
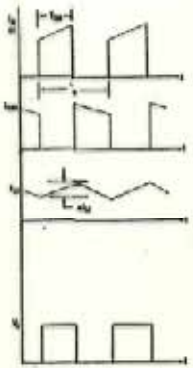
No isolation between input and output. Potential over-voltage if Q1 snorts. Only one output possible. High-side switch drive required. High input ripple current.

TYPICAL APPLICATIONS

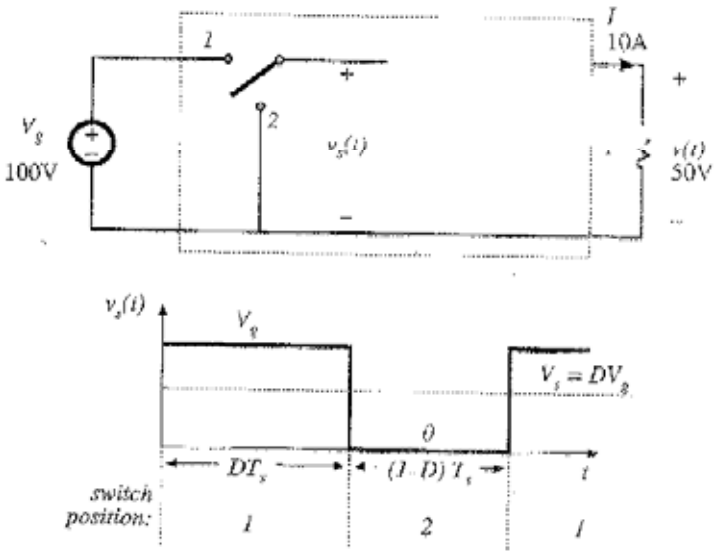
Small size, imbedded systems.

APPLICABLE HARRIS PRODUCTS

HIP5600 w/P IGBT For off line CKTS.

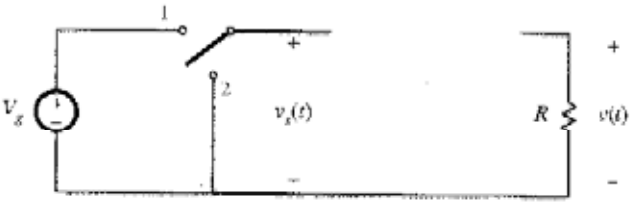
TYPE OF CONVERTER	**Buck (Step Down)**
CIRCUIT CONFIGURATION	
IDEAL TRANSFER FUNCTION	$\frac{V_O}{V_{IN}} = \frac{t_{on}}{T_S} = D$
PEAK DRAIN CURRENT *	$I_{DMAX} = I_{RL} + \frac{\Delta I_{L1}}{2}$
PEAK DRAIN VOLTAGE *	$V_{DS} = V_{IN} + V_D$
AVERAGE DIODE CURRENTS *	$I_{CR1} = I_{RL}\,(1\text{-}D)$
DIODE VOLTAGES (VRM) *	$V_{RM} = V_{IN}$
VOLTAGE AND CURRENT WAVEFORMS	 PSpice Simulation Lab #1
ADVANTAGES	High efficiency, simple, no transformer, low switch stress. Small output filter, low ripple.
DISADVANTAGES	No isolation between input and output. Potential over-voltage if Q1 saets. Only one output possible. High-side switch drive required. High input ripple current.
TYPICAL APPLICATIONS	Small size, imbedded systems.
APPLICABLE HARRIS PRODUCTS	HIP5600 w/P-IGBT For off line CKTS.

Use of a SPDT switch

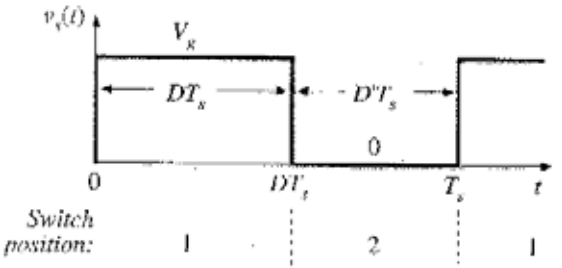


2.1 Introduction
Buck converter

SPDT switch changes dc component



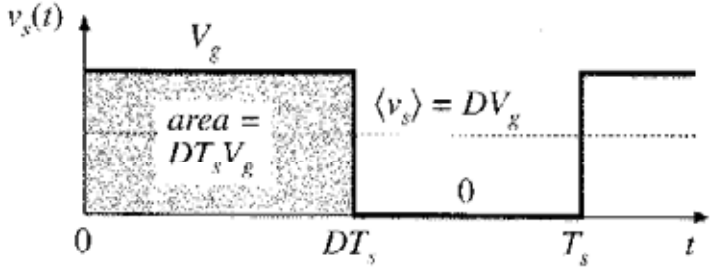
Switch output voltage waveform



Duty cycle D:
$0 \le D \le 1$

complement D':
$D' = 1 - D$

Dc component of switch output voltage



Fourier analysis: Dc component = average value

$$\langle v_s \rangle = \frac{1}{T_s}\int_0^{T_s} v_s(t)\,dt$$

$$\langle v_s \rangle = \frac{1}{T_s}\,(DT_sV_g) = DV_g$$

How to Set up Pspice at CSU

- Using Window NT explorer

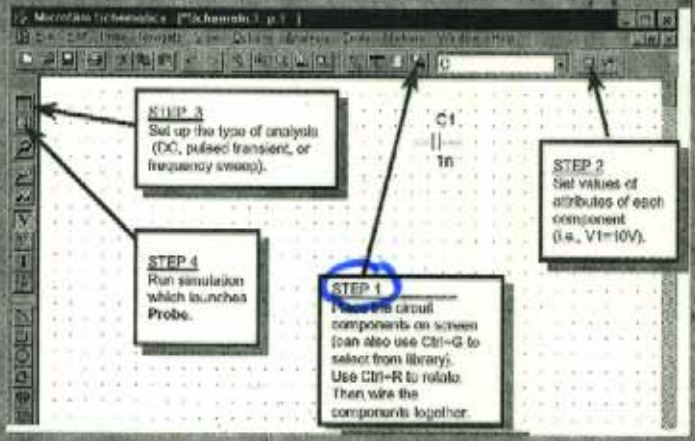
  s: Application Pspice SV 91 CSU setup Pspice

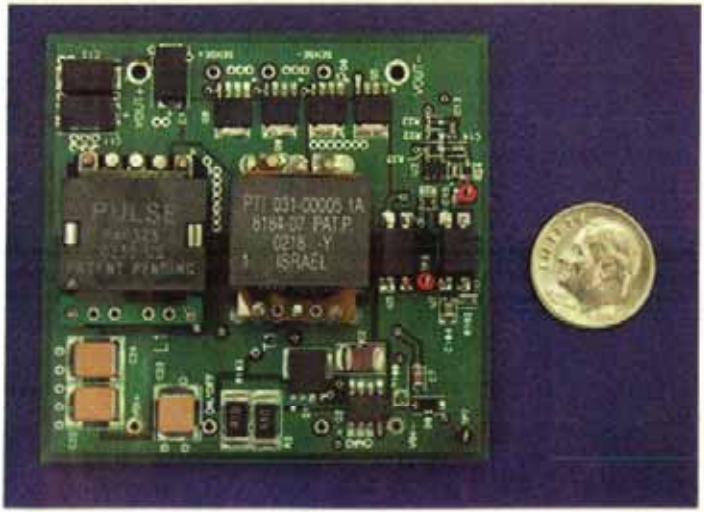
  – T drive -> Classes -> EE562 -> Pspice folder (Pspice SV and PspiceEEV.ini)

- Copy the Pspice folder and its sub_files into your u drive, using right mouse button to drag and drop.

Steps of create a circuit

- Open the schematic
  - To start, double click on the Pspice SV icon
  - And Pspice schematic will open
  - Use it to create your circuit diagram (a process called schematic capture)
- Major steps





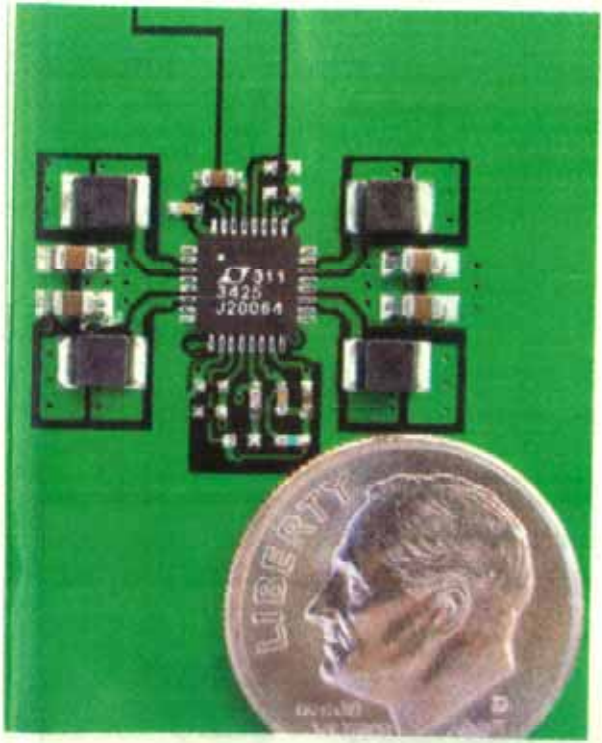
g. 5. *A 100-Watt active-clamp forward converter.*

V_{in} : 48 $\quad 36 \leq V_{IN} \leq 60$

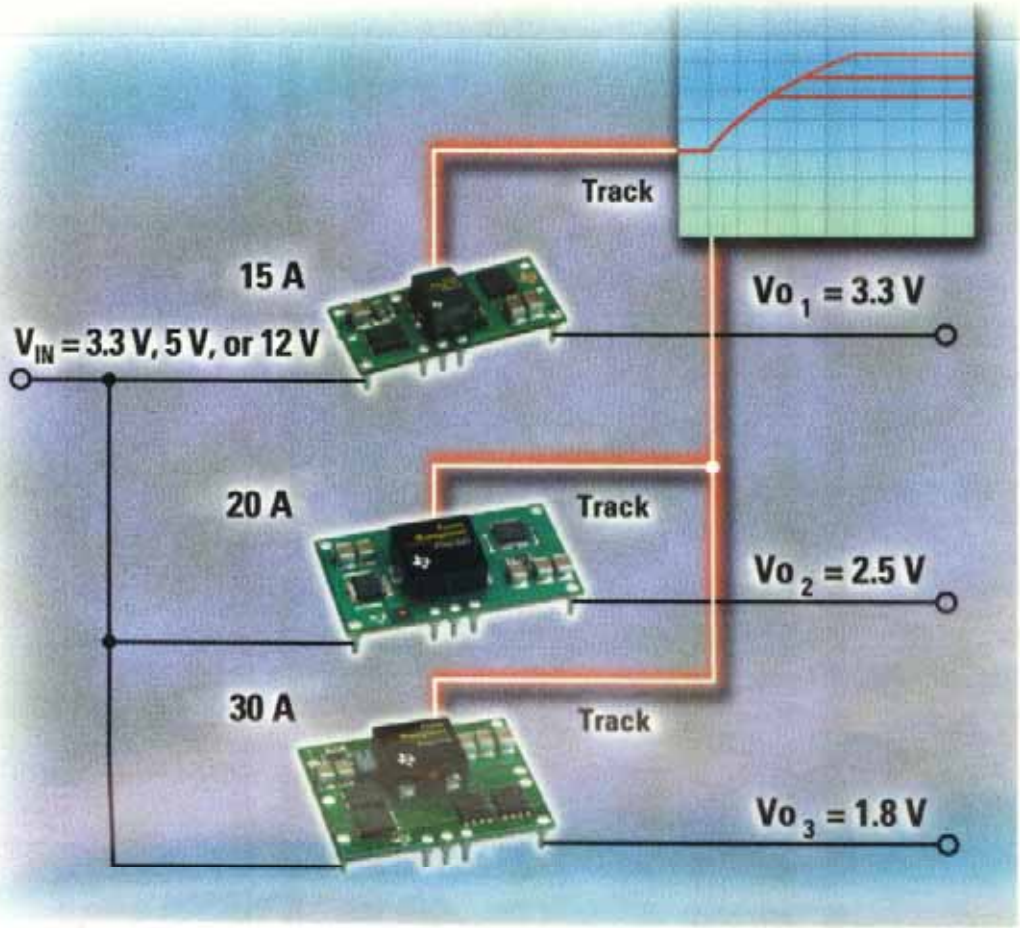
V_o 1, 3, 5 etc

forward = buck + trf. isolation

Ch 6

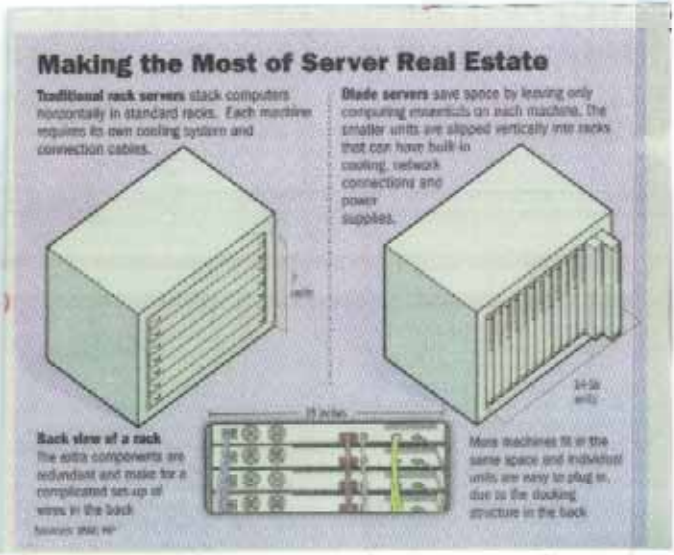


Demonstration board LTC3425


Track
15 A
V_{IN} = 3.3 V, 5 V, or 12 V
Vo_1 = 3.3 V
20 A
Track
Vo_2 = 2.5 V
30 A
Track
Vo_3 = 1.8 V

100 A processor * 10^2 processors

⇒ ? KA



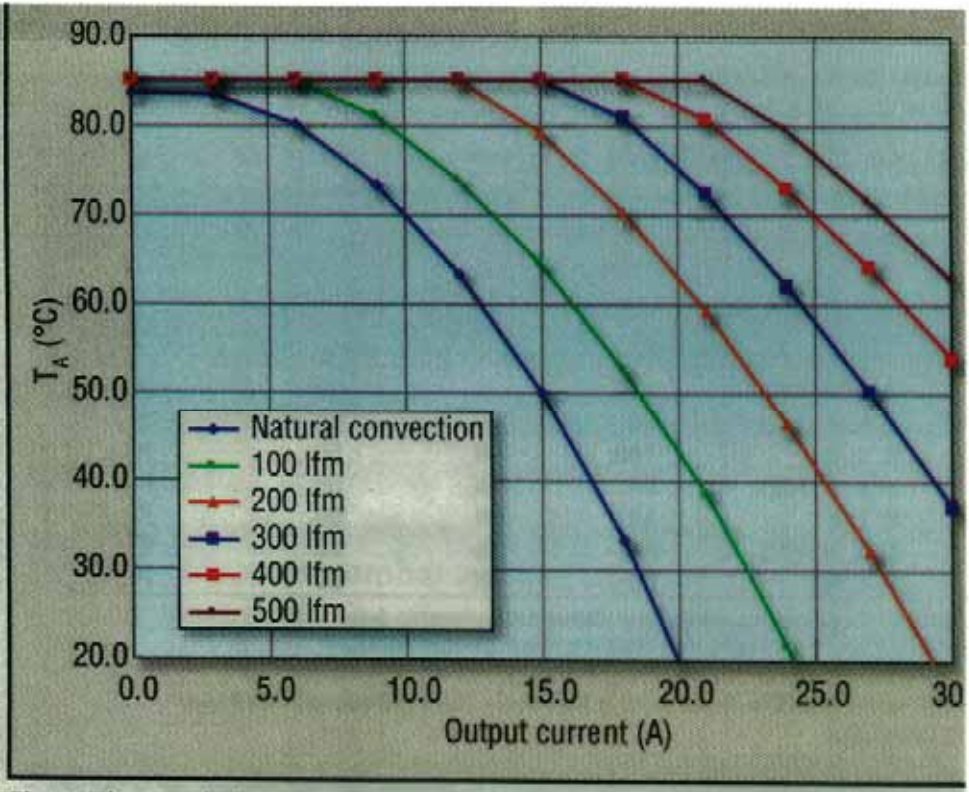
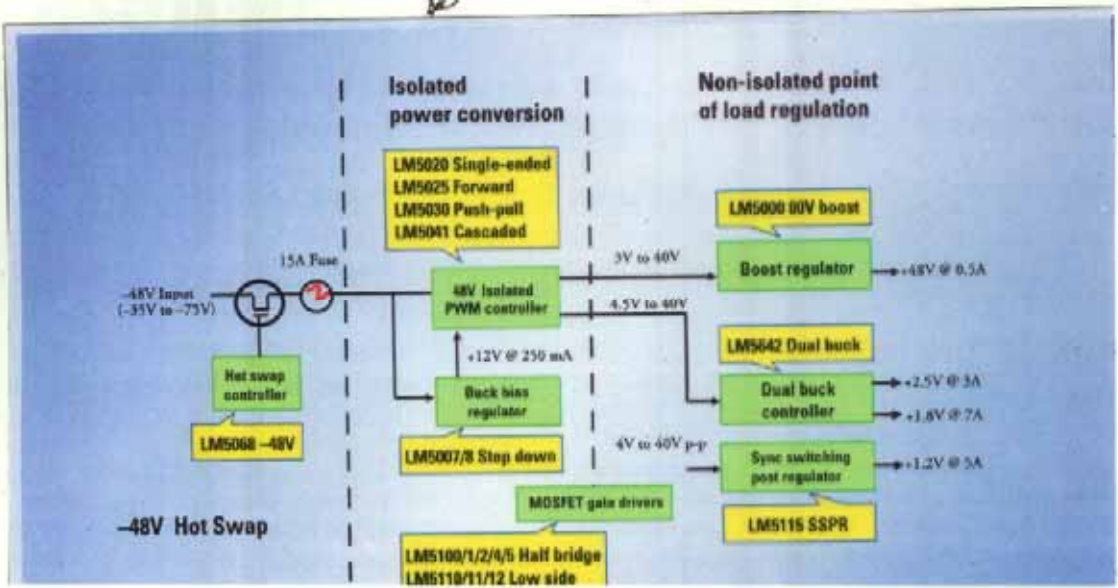


Fig. 1. *Thermal-derating curves specify the maximum current a dc-dc converter can deliver at different airflow speeds and ambient temperatures.*

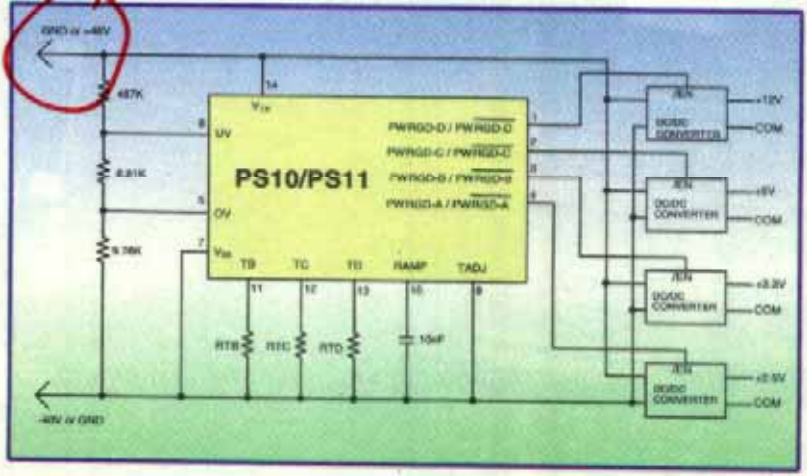
8/27/17

LM5000 family, the complete solution for distributed power architectures



Telcom Why?

PS10/PS11 Quad Power Sequencing Controller



- ✔ Turns on up to 4 DC-DC converters sequentially
- ✔ Eliminates the need for optocouplers
- ✔ Timing can be programmed using external resistors
- ✔ Programmable UV and OV

asserting a fault condition.

running, without interrupting the

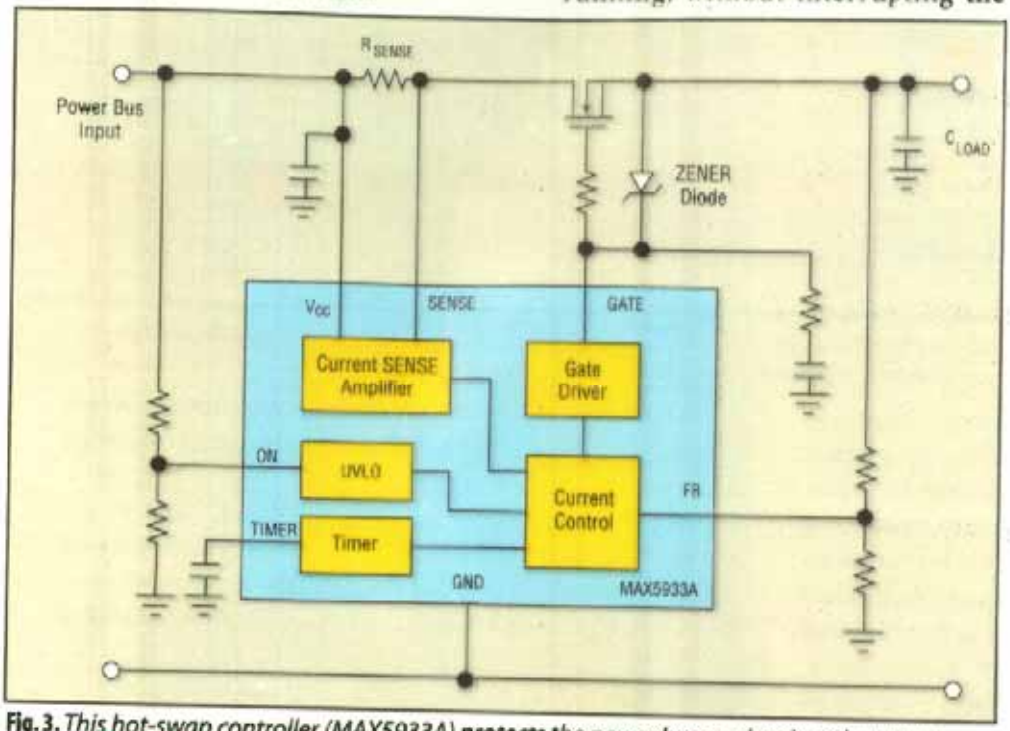


Fig. 3. *This hot-swap controller (MAX5933A) protects the power bus against inrush current spikes and short-circuit faults.*

Features

- 15mm x 15mm x 2.8mm LGA with 15°C/W Θ_{JA}
- Pb-Free (e4), RoHS Compliant
- Only C_{BULK} Required
- Standard and High Voltage:
  LTM4600EV: $4.5V \leq V_{IN} \leq 20V$
  LTM4600HVEV: $4.5V \leq V_{IN} \leq 28V$
- $0.6V \leq V_{OUT} \leq 5V$
- I_{OUT}: 10A DC, 14A Peak
- Parallel Two µModules for 20A Output

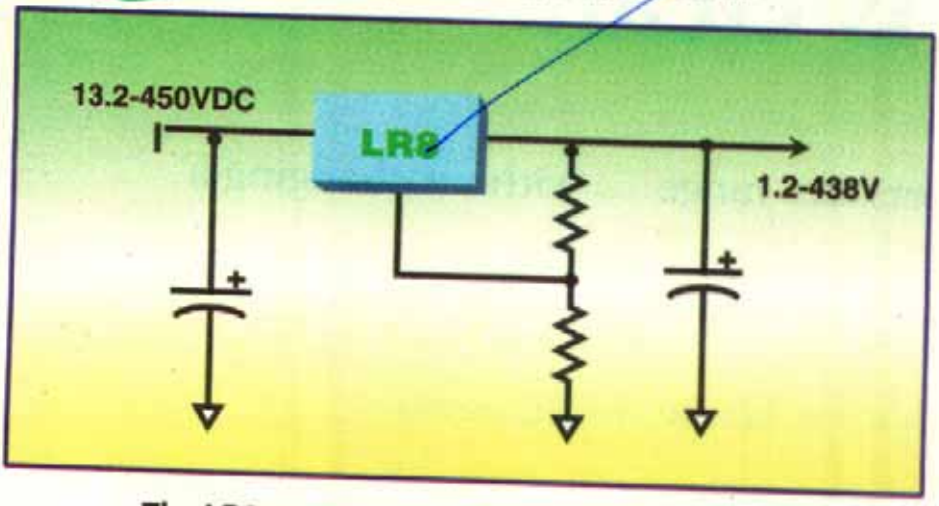
Ultrafast Transient Response
2% ΔV_{OUT} with a 5A Step

V_{IN} = 12V, V_{OUT} = 1.5V, 0A to 5A Load Step
(C_{OUT} = 3 x 22µF CERAMICS, 470µF POS CAP)

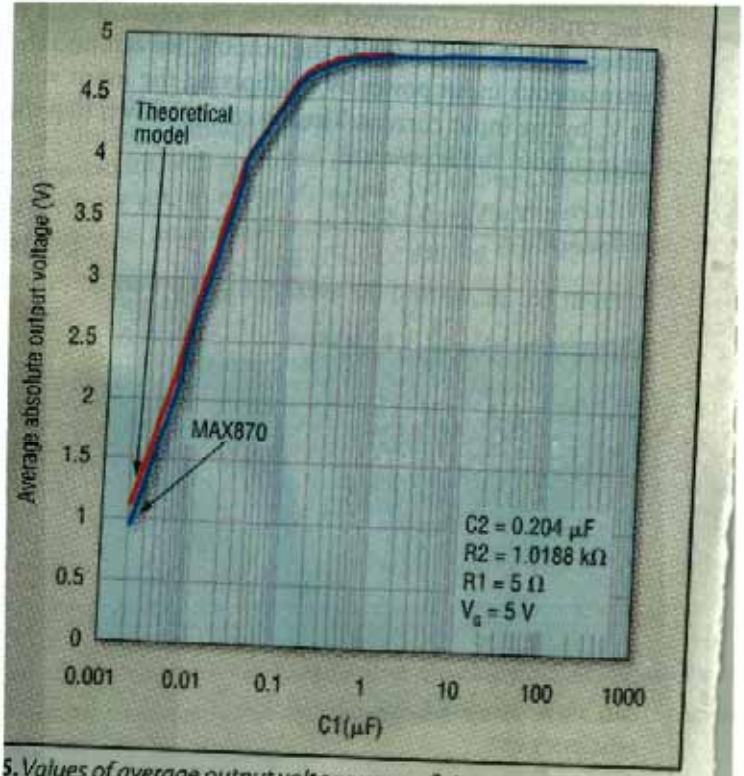
LR8: HV Adjustable Linear Regulator

V_{LR8} & η

The LR8 is a 3-terminal adjustable linear regulator just like an LM317 capable of input voltages up to 450V.



The LR8 can be used as a stand-alone linear regulator or as a PWM start-up circuit



5. *Values of average output voltage versus flying capacitance (C1) ulated using the theoretical model are close to the actual results ained with the MAX870.*

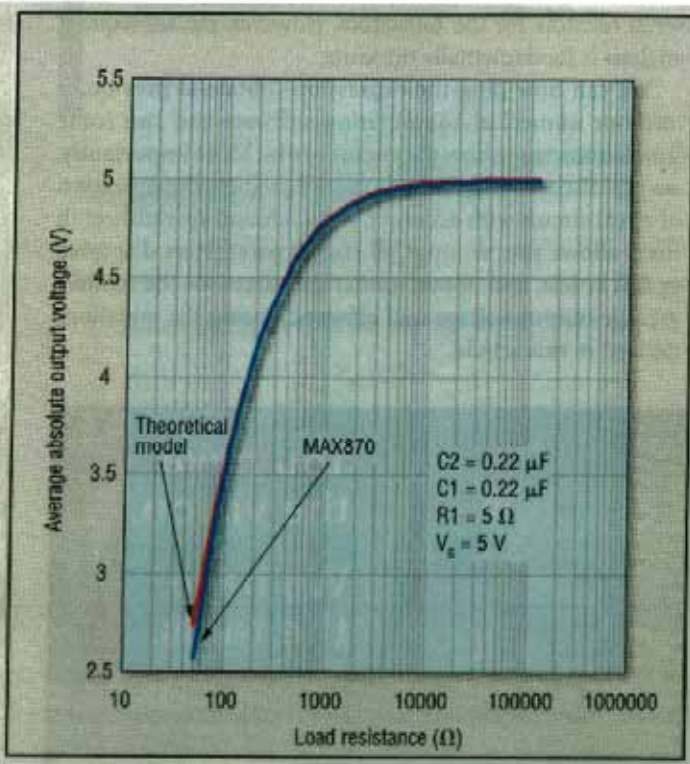


Fig. 4. *A plot of the average output voltage versus load resistance (R2) for the theoretical model agrees closely with the actual results obtained with a switched-capacitor voltage inverter (MAX870).*

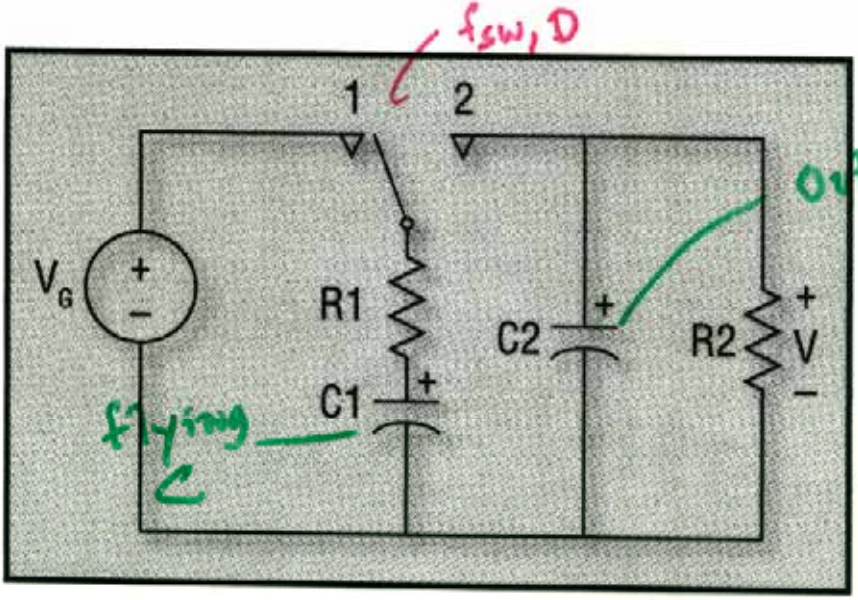
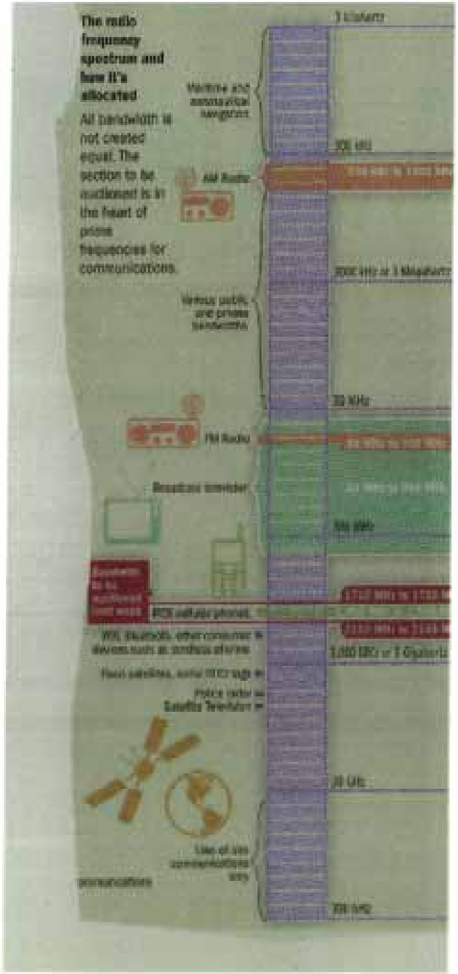
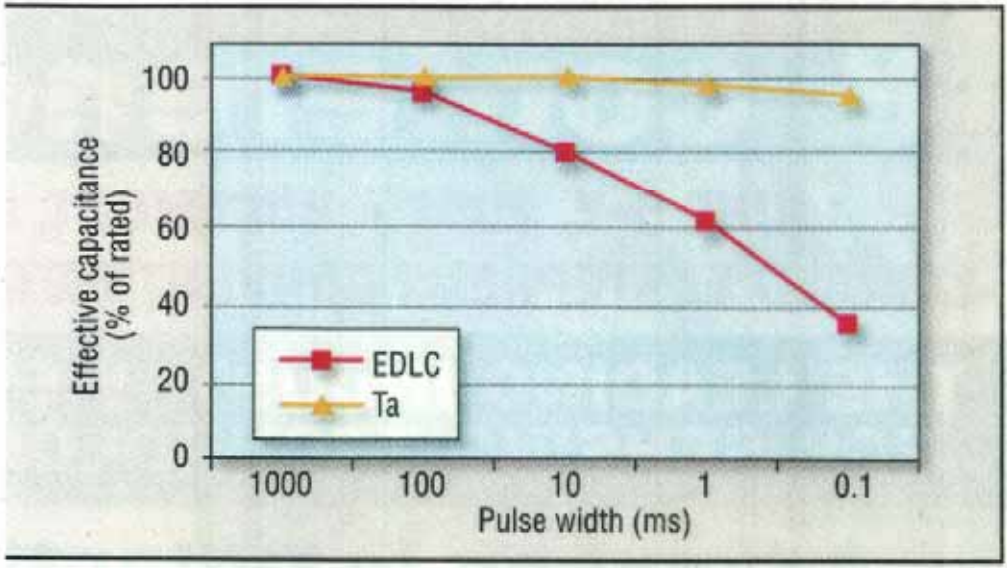


Fig. 1. *The basic charge-pump circuit can be used for regulated stepdown charge pumps, inverting regulated charge pumps and inverting unregulated charge pumps.*


The radio frequency spectrum and how it's allocated
All bandwidth is not created equal. The section to be auctioned is in the heart of prime frequencies for communications.
AM Radio
30 MHz
FM Radio
Broadcast television
PCS cellular phones
Satellite Television
communications



ig. 3. *The effective capacitance of different capacitor technologies varies as a function of pulse width.*

Design parameters \ Capacitor options (Fig. 2)	Option 1 3 x 2200-µF, 6.3-V tantalums	Option 2 2 x 2200-µF, 6.3-V tantalums	Option 3 1 x 22,000-µF, 4.5-V EDLCs	Option 4 1 x 35,000-µF, 5.5-V EDLCs
Rated capacitance (mF)	6.6	4.4	22	35
Effective capacitance (mF)	6.6	4.4	11	17
Effective ESR (mΩ) at 20°C	12	18	200	150
Overall size L x W x H (mm)	14.5 × 22.5 × 2	14.5 × 15 × 2	26 × 15 × 2.1	26 × 15 × 4.8
Printed circuit board mounting	SMD	SMD	Hand soldered	Hand soldered
Voltage drop (V), GSM pulse	0.19	0.30	0.50	0.37

Table 2. *Four potential solutions to the design problem.*

Design parameter	Value
PCMCIA voltage	3.3 V max
PCMCIA current	1.0 A max
PA input voltage	3.0 V min
PA peak input current	2.0 A max
GSM pulse width	577 µs min

Table 1. *Design problem summary.*

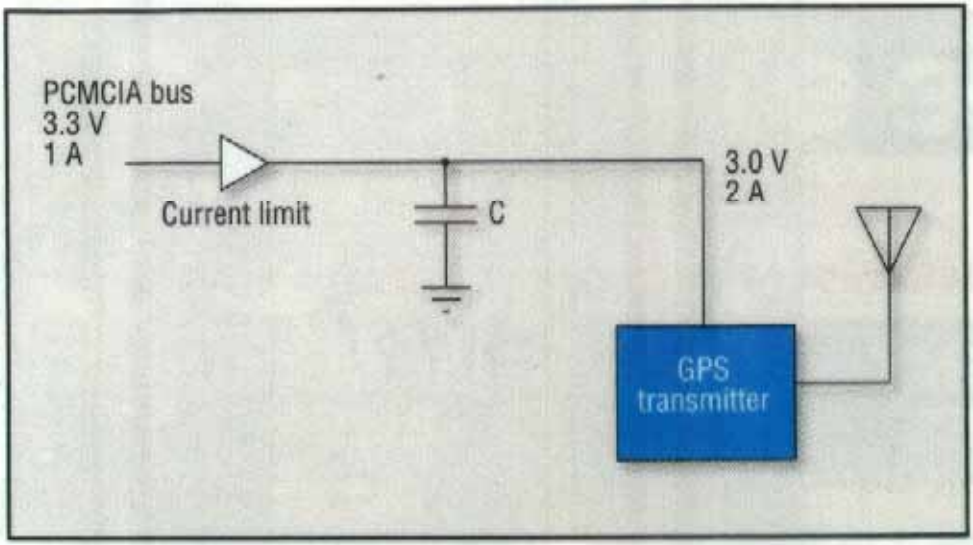


Fig. 2. *The capacitor in this simplified circuit diagram must deliver the required current to the GSM transmitter while limiting the voltage drop to 0.3 V or less.*

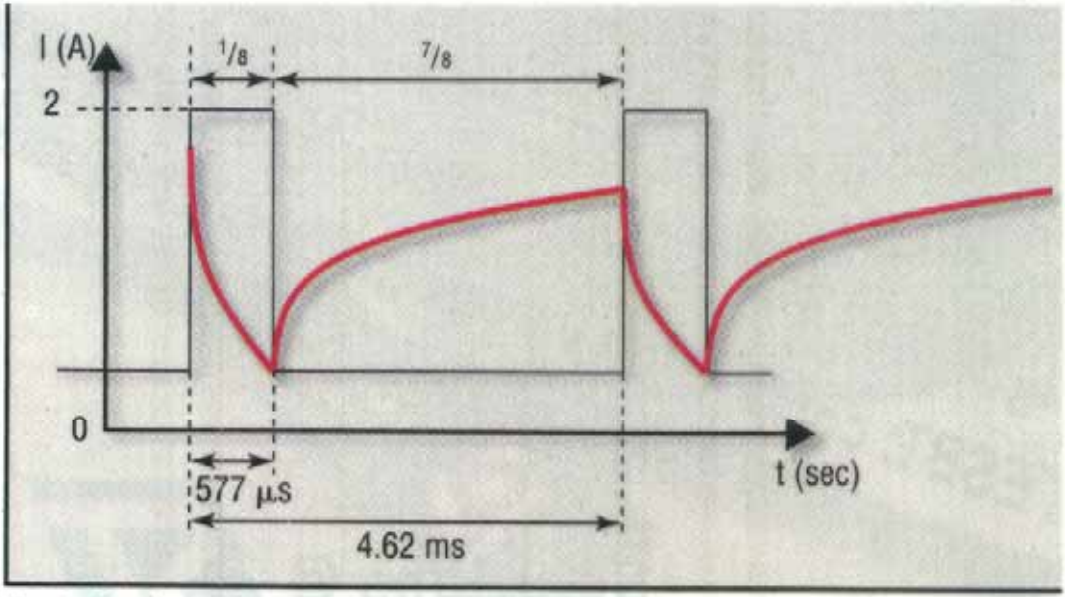


Fig. 1. *During GSM transmissions, the power amplifier transmits a pulse lasting 577 µs. The capacitor supplying this current must charge during the remaining portion of the cycle.*

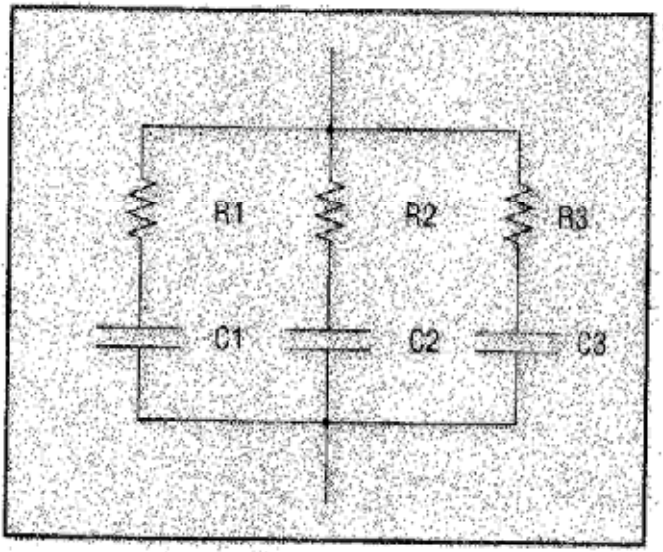


Fig. 4. *Paralleling three tantalum capacitors provides 6.6 mF of capacitance with an effective ESR of 12 mΩ.*