ECE 481: Power Electronics

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University of Tennessee Knoxville
Fall 2015

ECE 481: Power Electronics

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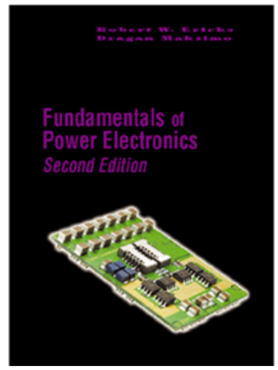
  - Telephone: (865) 974-3572
  - Email: dcostine@utk.edu
    - Please use **[ECE481]** in the subject line for all course-related e-mails.
  - Office Hours: W 1:30-3:00pm, R 9:00-10:00am

Course Materials

- Textbook:
  - Erickson and Maksimovic, *Fundamentals of Power Electronics*, second edition, Kluwer Academic Publishers, ISBN 0-7923-7270-0
  - Available through campus bookstore, online vendors, or online through UT libraries
- Course Website
  - **http://web.eecs.utk.edu/~dcostine/ECE481**
  - Includes lectures slides, handouts, supplemental notes, homework assignments, course announcements



Assignments

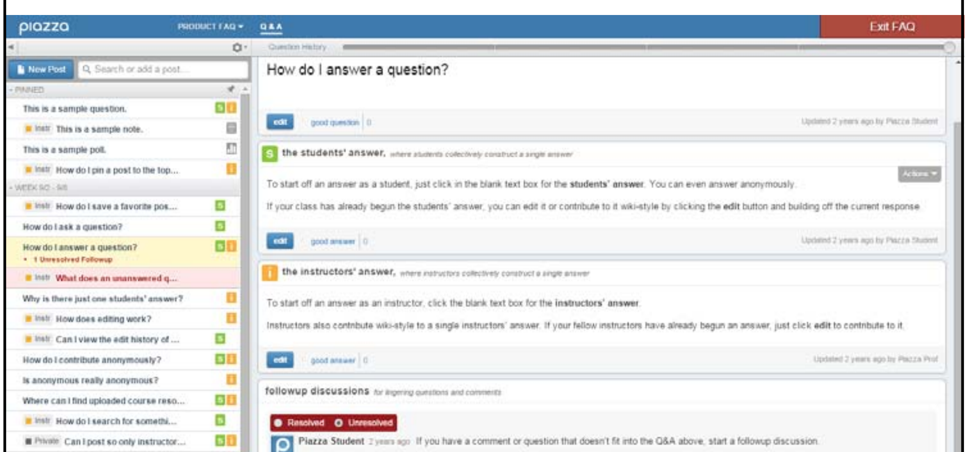
- Homework (40%)
  - Due at *beginning* of class on date listed on Lecture Schedule web page (Fridays)
  - No late work accepted except in cases of documented emergencies
  - Collaboration is encouraged on all homework assignments
  - must turn in *your own* work
- Exams
  - 1 Midterm: 25% of grade
  - 1 Final: 35% of grade

ECE 481 vs ECE 599

- Students enrolled in ECE 599 will have additional homework and exam problems
- Grading
  - Separate curving for ECE 481 and ECE 599
  - Extra credit is added to final grade after any curving

Piazza Forum

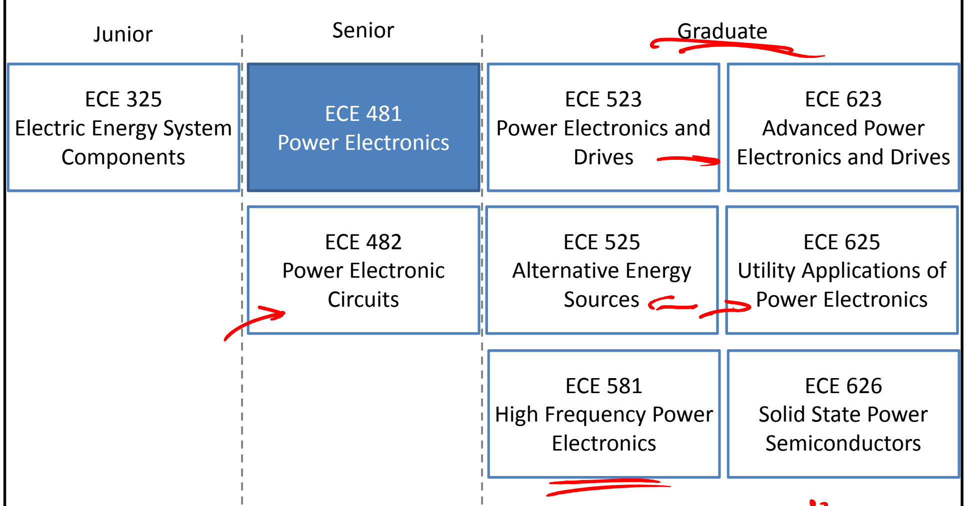
- New resource for ECE 481 this semester
- Additional method for collaborating on HW



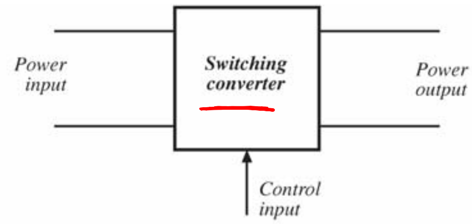
How to Succeed in ECE 481

- Attend all lectures
  - Participate; ask questions or ask for clarification
- Read textbook for clarification
- Complete all homework assignments
  - Work together in-person or using Piazza
  - Attempt homework alone prior to collaborating
  - Review and understand mistakes
  - ~12 assignments for 40% of the grade

Power Electronics Courses at UTK

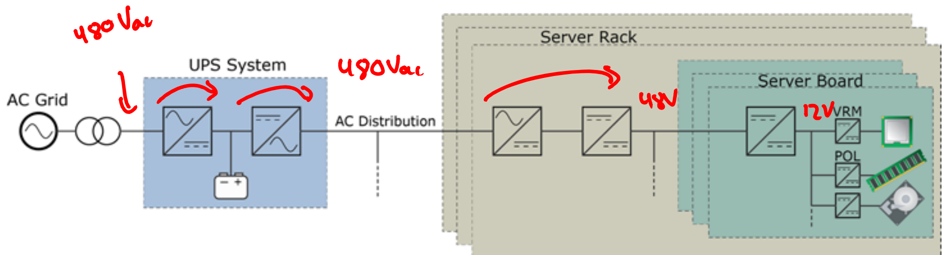


Introduction to Power Conversion

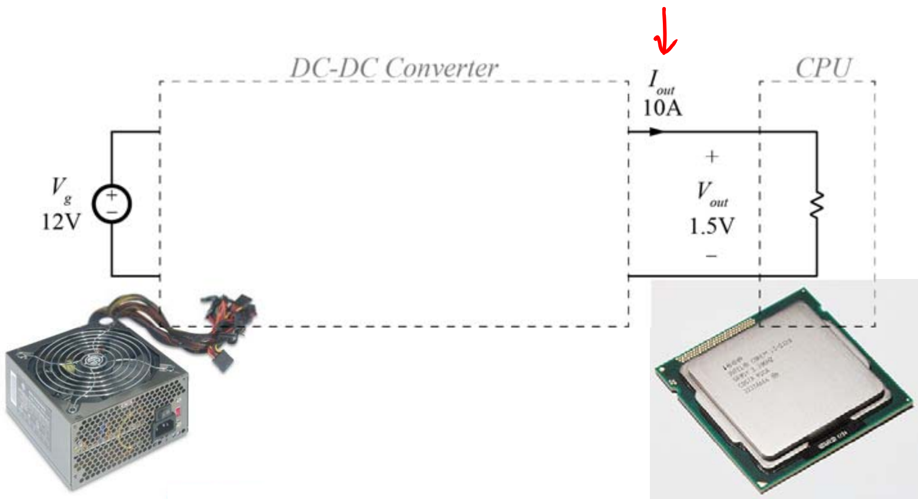


Dc-dc conversion:	Change and control voltage magnitude
Ac-dc rectification:	Possibly control dc voltage, ac current
Dc-ac inversion:	Produce sinusoid of controllable magnitude and frequency
Ac-ac cycloconversion:	Change and control voltage magnitude and frequency

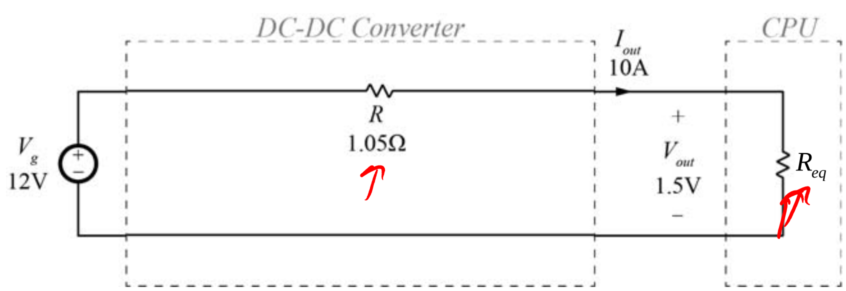
Example Server Power Distribution



Example VRM Design



Example VRM Design

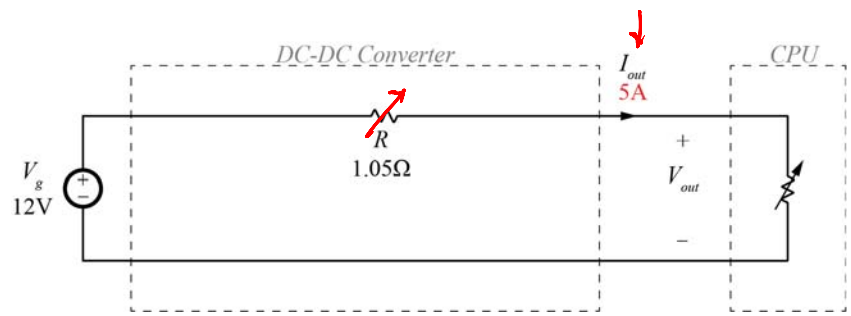


$$R_{eq} = \frac{V_{out}}{I_{out}} = 150m\Omega$$

$$V_{out} = V_g - I_{out} R$$

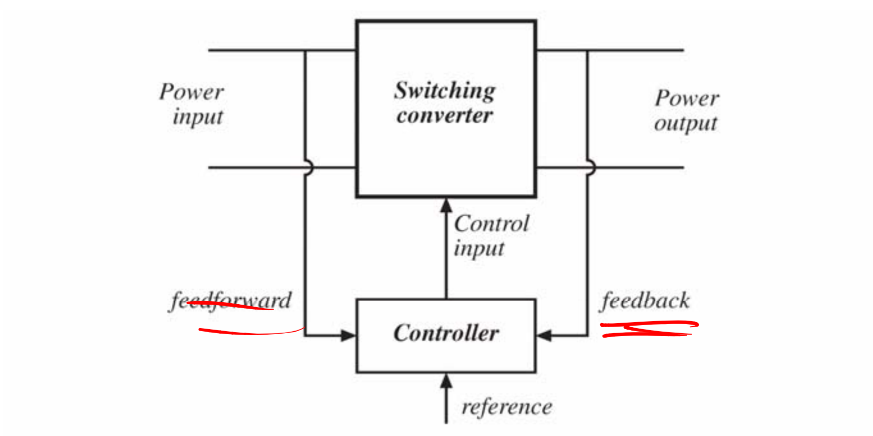
$$R = \frac{V_g - V_{out}}{I_{out}}$$

Variations in Load

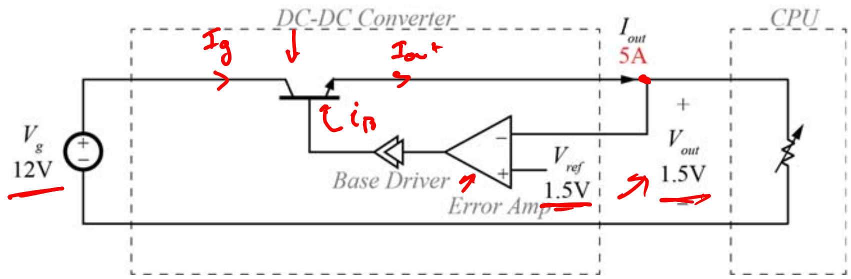


$$V_{out} = V_g - I_{out} R$$
$$V_{out} = 12\text{V} - (5\text{A})(1.05\Omega)$$
$$V_{out} = 6.75\text{V}$$

Control is Invariably Required



Linear Regulator



$$P_{in} = V_g I_g \approx V_g I_{out}$$
$$P_{in} = (5A)(12V)$$
$$P_{in} = 60W$$

$$P_{out} = V_{out} I_{out}$$
$$P_{out} = (5A)(1.5V)$$
$$P_{out} = 7.5W$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{7.5W}{60W} = 12.5\%$$

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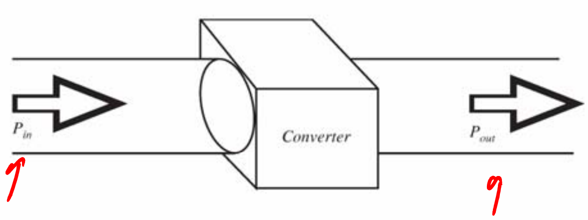
A High Efficiency Converter



A goal of current converter technology is to construct converters of small size and weight, which process substantial power at high efficiency

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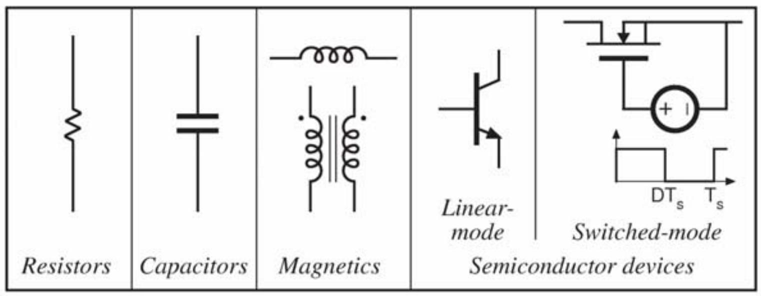
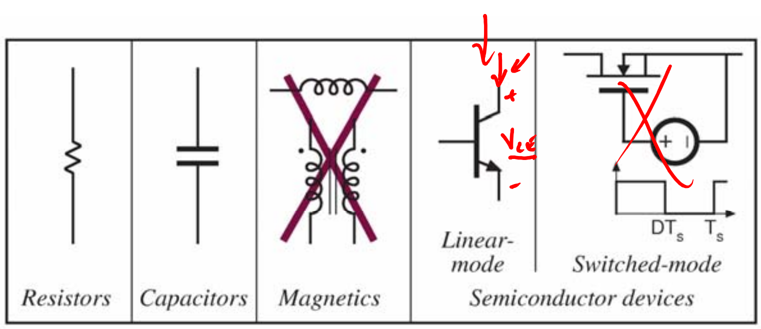
Devices Available to the Circuit Designer

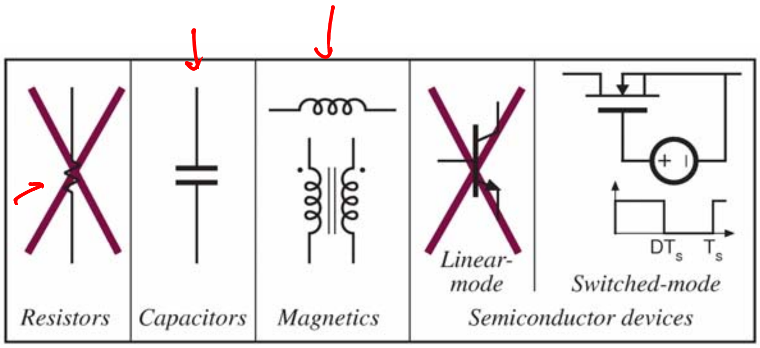


Devices Available to the Circuit Designer



Signal processing: avoid magnetics

Devices Available to the Circuit Designer



Power processing: avoid lossy elements

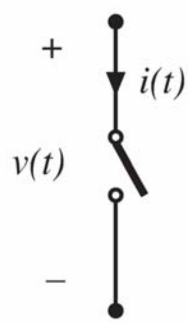
Power Loss in an Ideal Switch

Switch closed: $v(t) = 0$

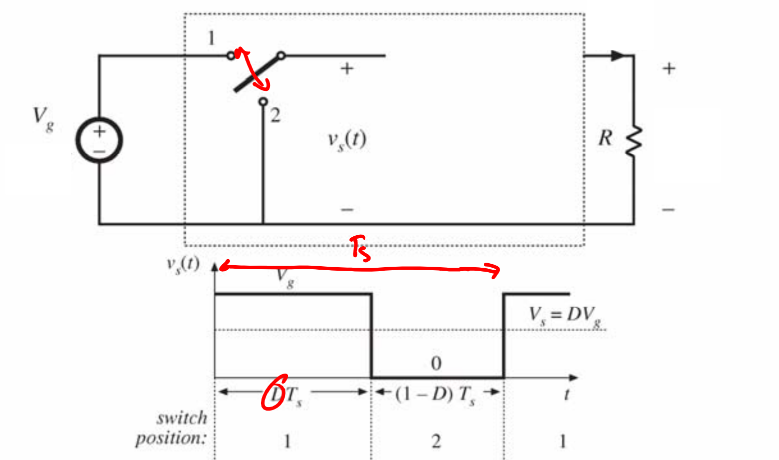
Switch open: $i(t) = 0$

In either event: $p(t) = v(t)\ i(t) = 0$

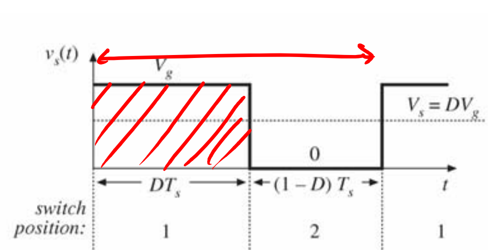
Ideal switch consumes zero power



Use of SPDT Switch



Controlling Duty Cycle



D = switch duty cycle
$0 \le D \le 1$

T_s = switching period

f_s = switching frequency
$= 1 / T_s$

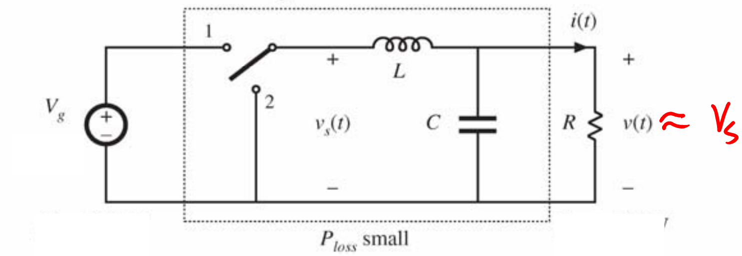
DC component of $v_s(t)$ = average value:

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

By controlling D
can get
$0 < V_s < V_g$

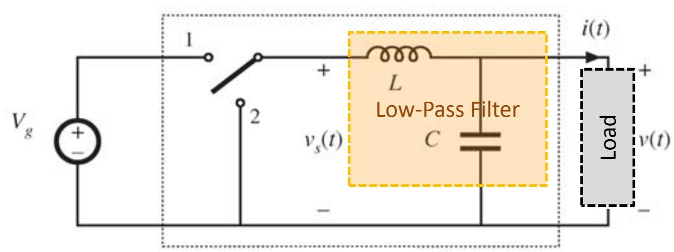
Addition of Low Pass Filter

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

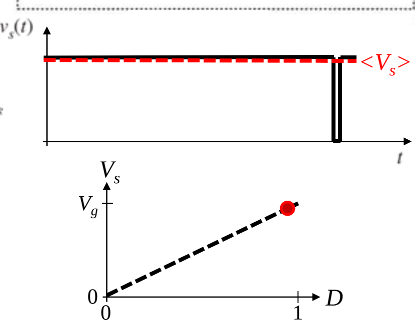


- Choose filter cutoff frequency f_0 much smaller than switching frequency f_s
- This circuit is known as the "buck converter"

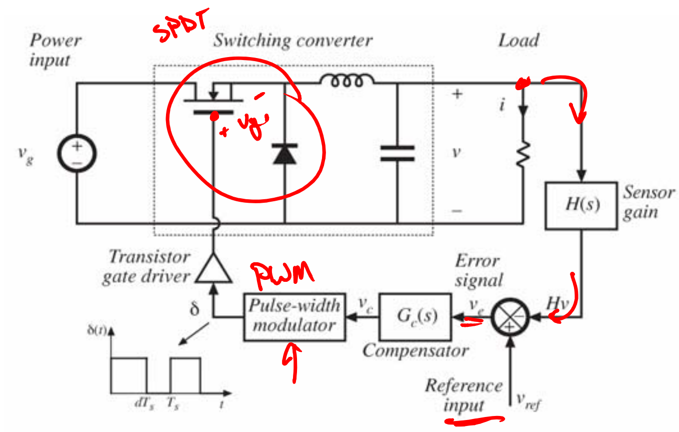
Duty Cycle Control



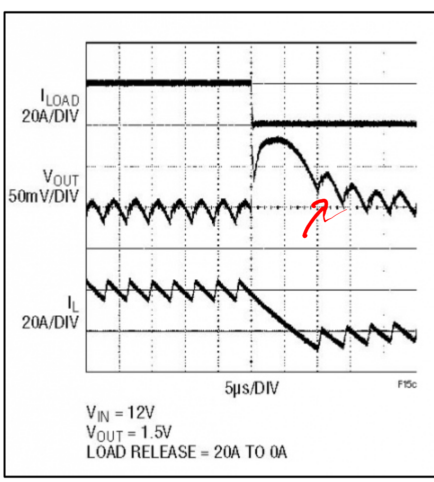
$$V_s = \frac{1}{T_s}\int_0^{T_s} v_s(t)\, dt = DV_g$$

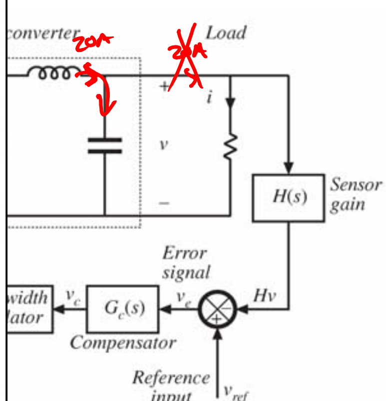


Control System for Voltage Regulation

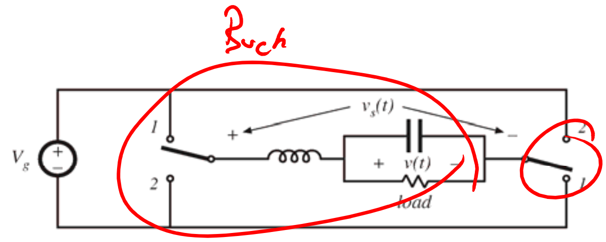


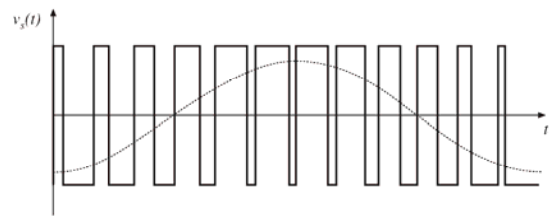
Dynamic Performance





Single Phase Inverter

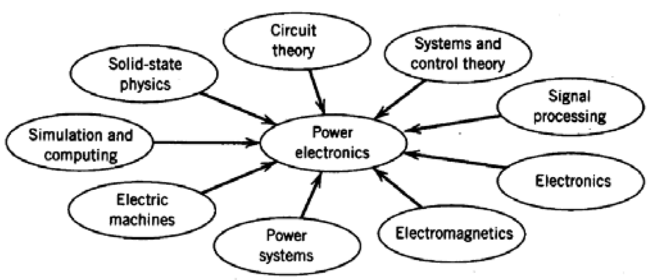


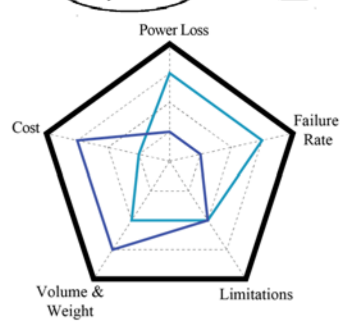


"H-bridge"

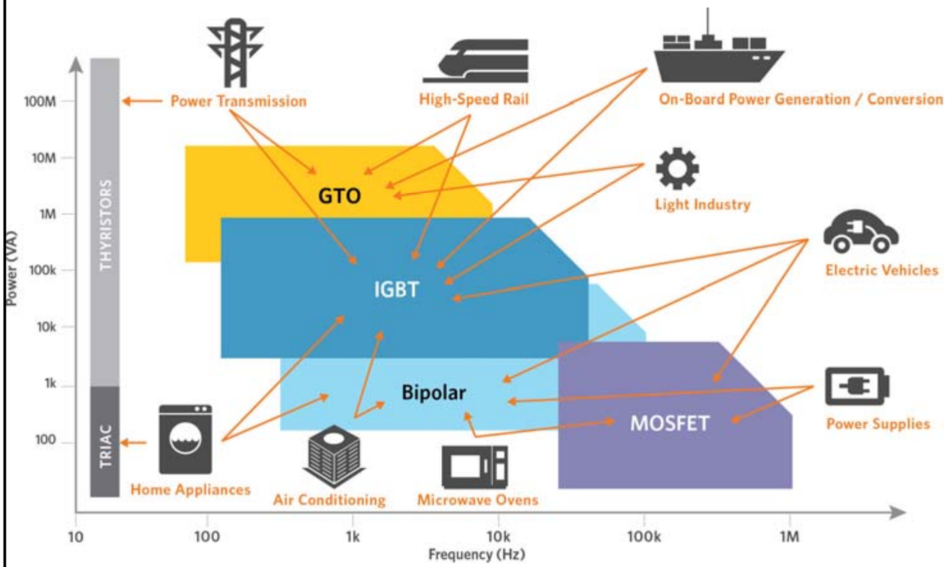
Modulate switch duty cycles to obtain sinusoidal low-frequency component

Power Electronics Overview

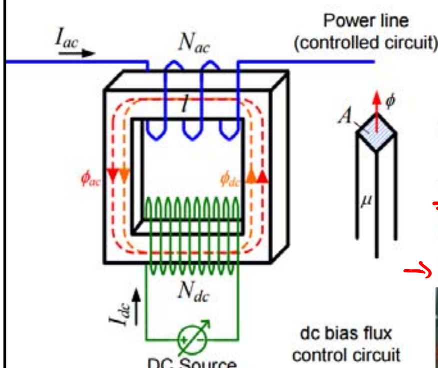




Some Power Electronics Applications



Power Transmission: Saturable Reactor

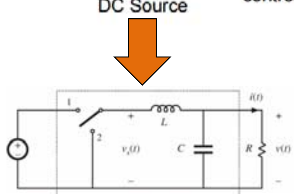


ac circuit inductance :

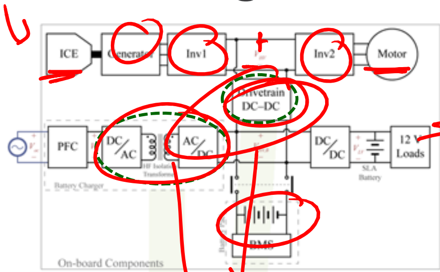
$$L_{ac} = \frac{\mu \cdot N_{ac}^2 \cdot A}{l} = const \cdot \mu$$

controlled by dc circuit current :

$$\mu = f(I_{dc})$$

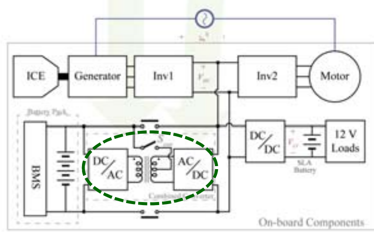


EVs: Integrated Converter

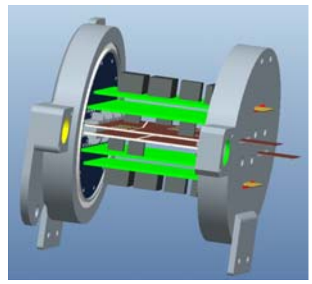


Traditional 2-stage drivetrain topology

5kW Scaled-Down Converter Prototype

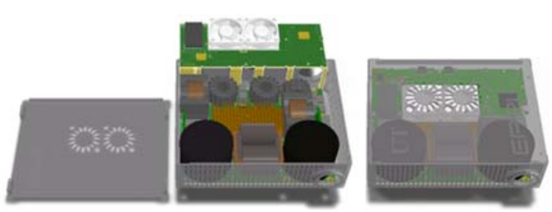


Combined isolated/non-isolated topology

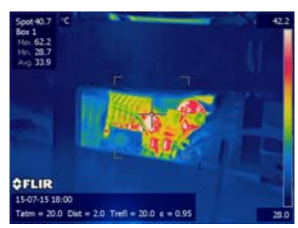


Full Power, 3D-Printed Module

Renewables: 2kW Power Dense Solar Inverter



CAD Model of Power-Dense Design

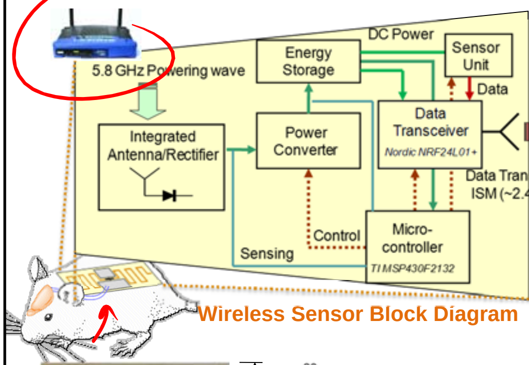


Thermal Test at Full Power

Protoype 2kW Solar Inverter

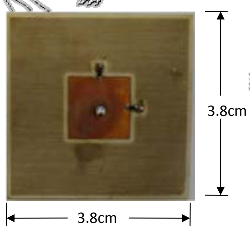
Commercial Product Size Comparison

Medical Devices: RF Energy Harvesting

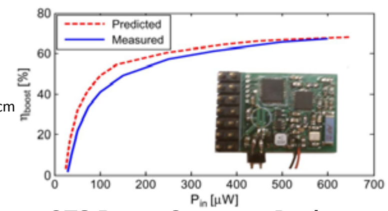


Wireless Sensor Block Diagram

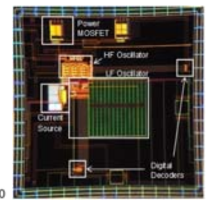
- Powered entirely by commercial 5.8GHz WiFi adapter
- Able to operate with ~5µW power using only off-the-shelf components
- Able to operate down to 100nW using a custom IC



5.8 GHz patch rectenna



OTS Power Converter Design

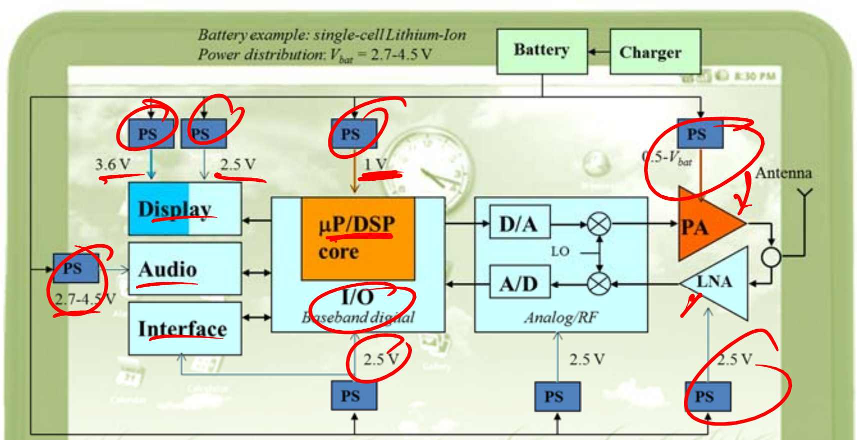


P_{out} (µW)	η_{boost} (%)
0.16	18.05
0.52	35.13
1.29	47.36
2.57	53.58
8.81	65.16
23.86	71.14
60.66	75.70
123.6	79.06

Custom harvester IC implementation

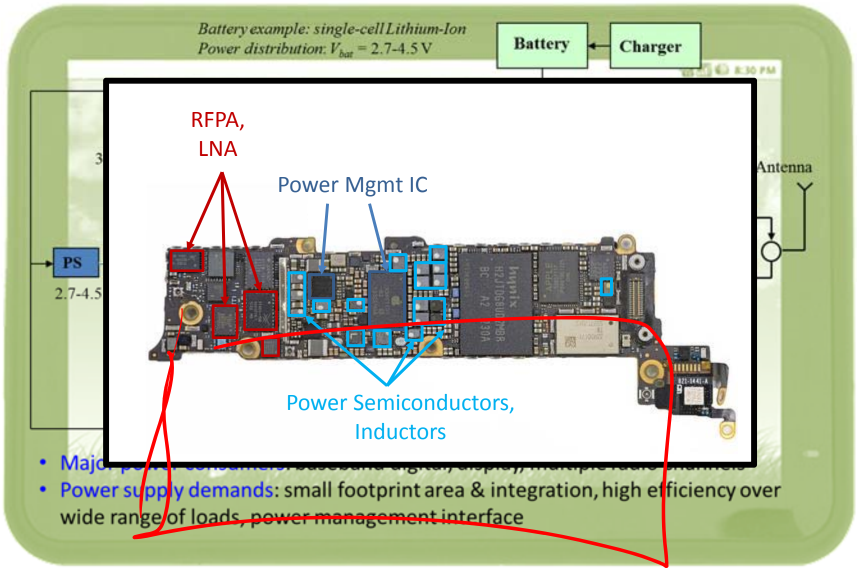
Popovic, Z.; Falkenstein, E.A.; Costinett, D.; Zane, R., "Low-Power Far-Field Wireless Powering for Wireless Sensors," *Proceedings of the IEEE* , vol.101, no.6, pp.1397,1409, June 2013
Paing, T.; Falkenstein, Erez; Zane, R.; Popovic, Z., "Custom IC for Ultralow Power RF Energy Scavenging," *Power Electronics, IEEE Transactions on* , vol.26, no.6, pp.1620,1626, June 2011

Mobile Electronics

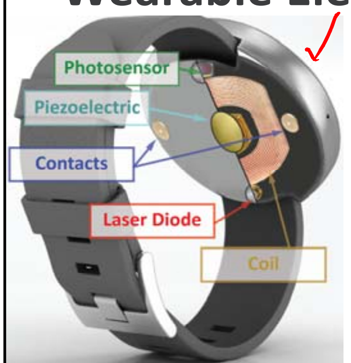


- Major power consumers: baseband digital, display, multiple radio channels
- Power supply demands: small footprint area & integration, high efficiency over wide range of loads, power management interface

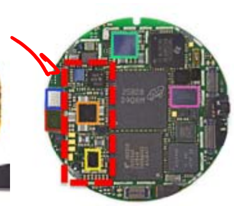
Mobile Electronics



Wearable Electronics: Medical Sensor



- Various biological markers can now be sensed through noninvasive methods
- Pulse, water content, GSR, blood glucose levels, oxygen content, etc.
- Precision integrated power electronics and low power circuit design techniques needed for future implementations



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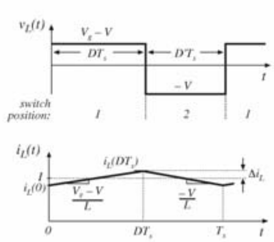
Part I: Converters in Equilibrium

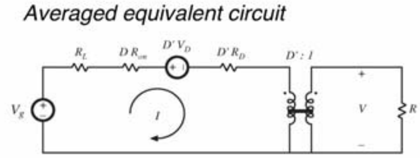
2. Principles of steady state converter analysis
3. Steady-state equivalent circuit modeling, losses, and efficiency
4. Switch realization
5. The discontinuous conduction mode
6. Converter circuits

Part I: Converters in Equilibrium

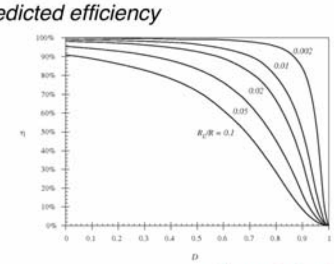
Inductor waveforms



Averaged equivalent circuit



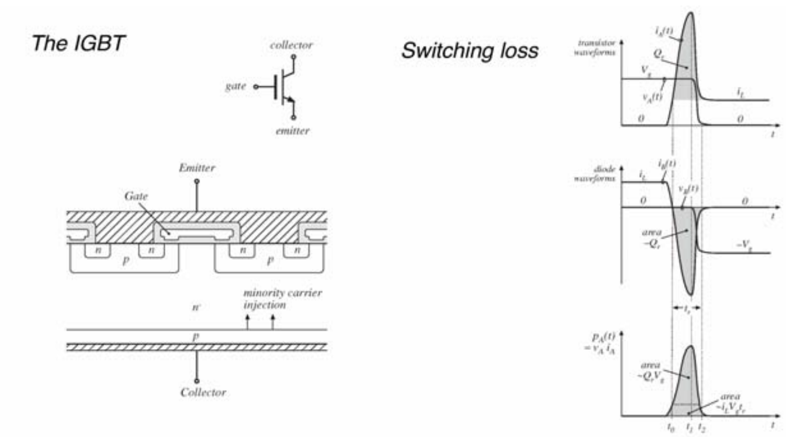
Predicted efficiency



Discontinuous conduction mode

Transformer isolation

Switch Realization: Semiconductor Devices



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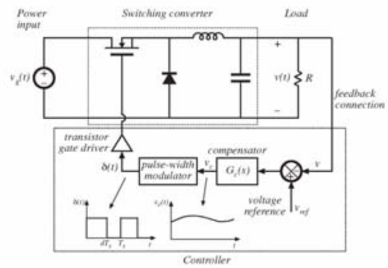
Part II: Converter Dynamics and Control

7. Ac modeling
8. Converter transfer functions
9. Controller design
10. Input filter design
11. Ac and dc equivalent circuit modeling of the discontinuous conduction mode
12. Current-programmed control

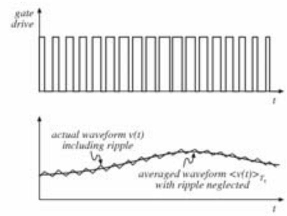
Fundamentals of Power Electronics 29 *Chapter 1: Introduction*

Part II: Converter Dynamics and Control

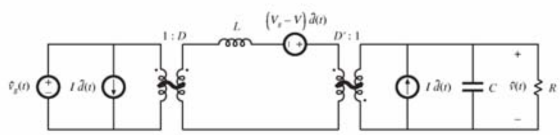
Closed-loop converter system



Averaging the waveforms



Small-signal averaged equivalent circuit

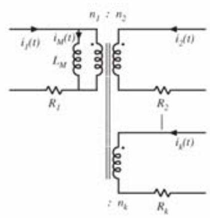


Part III: Magnetics

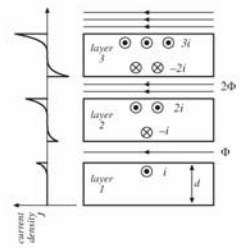
13. Basic magnetics theory
14. Inductor design
15. Transformer design

Part III: Magnetics

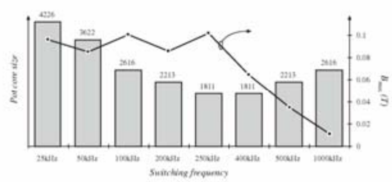
transformer design



the proximity effect



transformer size vs. switching frequency



Fundamentals of Power Electronics 30 *Chapter 1: Introduction*

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