ECE 481: Power Electronics

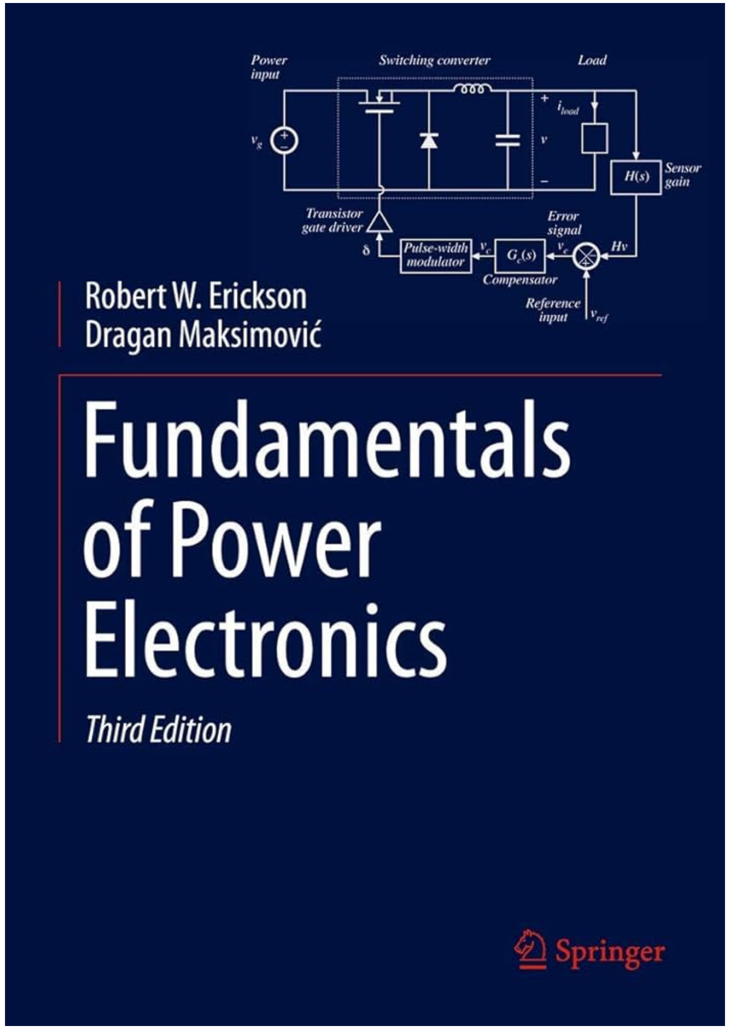
Prof. Daniel Costinett
Department of Electrical Engineering and Computer Science
University of Tennessee Knoxville
Fall 2024

Contact Information

- Instructor: Prof. Daniel Costinett
  - Office: MK504
  - Telephone: (865) 974-3572
  - Email: dcostine@utk.edu
    - Please use **[ECE481]** in the subject line for all course-related e-mails.
  - Office Hours: TBD, or by appointment

Textbook and Materials

- Textbook:
  - Erickson and Maksimovic, *Fundamentals of Power Electronics*, 3rd edition, Springer, ISBN 3-0304-3879-1
    - 2nd edition acceptable
  - 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



Course Website

ECE 202: Circuits II

Course Schedule

Updated **13:25 January 22, 2024**. Tentative lecture schedule, including links to lecture slides and notes, and links to assignments. The schedule is subject to change, please check frequently.

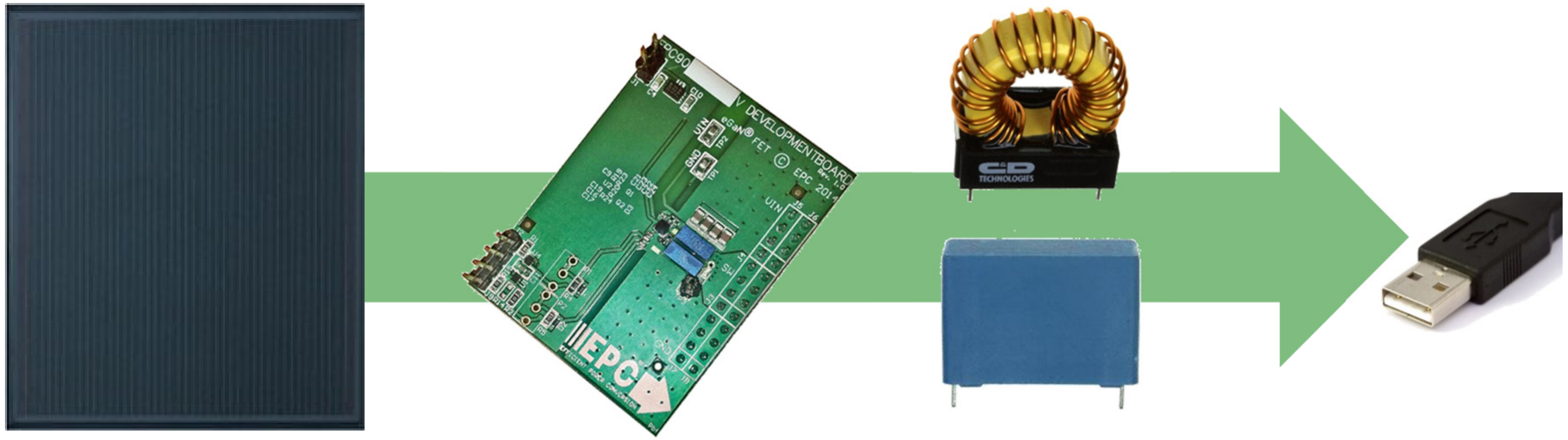
Monday	Wednesday	Friday
Jan. 22 Snow Day	L1 - Jan. 24 Course Introduction	L2 - Jan. 26 Mutual Inductance *Sections 13.1-13.2 (ignore "phasor" notation)*
L3 - Jan. 29 Coupling Coefficient The Transformer Ideal Transformer Model *Sections 13.3 (ignore "phasor" notation)*	L4 - Jan. 31 Transformer Reflection Transformer Equivalent Circuits *Sections 13.4 (ignore "phasor" notation)*	L5 - Feb. 2 Examples of Transformer and Coupled Inductors Homework 1 Due

Grading

- **Homework** (35%)
  - Weekly, due on Fridays *before* the start of lecture
  - Submitted by uploading a **single pdf** to canvas
- **Midterms and Labs** (35%)
  - One midterm
  - ~3 experiments done in groups outside of class
- **Final** (30%)

ECE 481 Lab Sequence

- Hands-on experience testing and controlling GaN-based converter
- 3-lab sequence in modeling, open-loop control and analysis, and closed-loop control
- Completed in groups of 2-3 outside of normal lecture hours



Power Electronics Courses at UTK

Junior

- ECE 325 Electric Energy System Components
- ECE 335 Electronic Devices

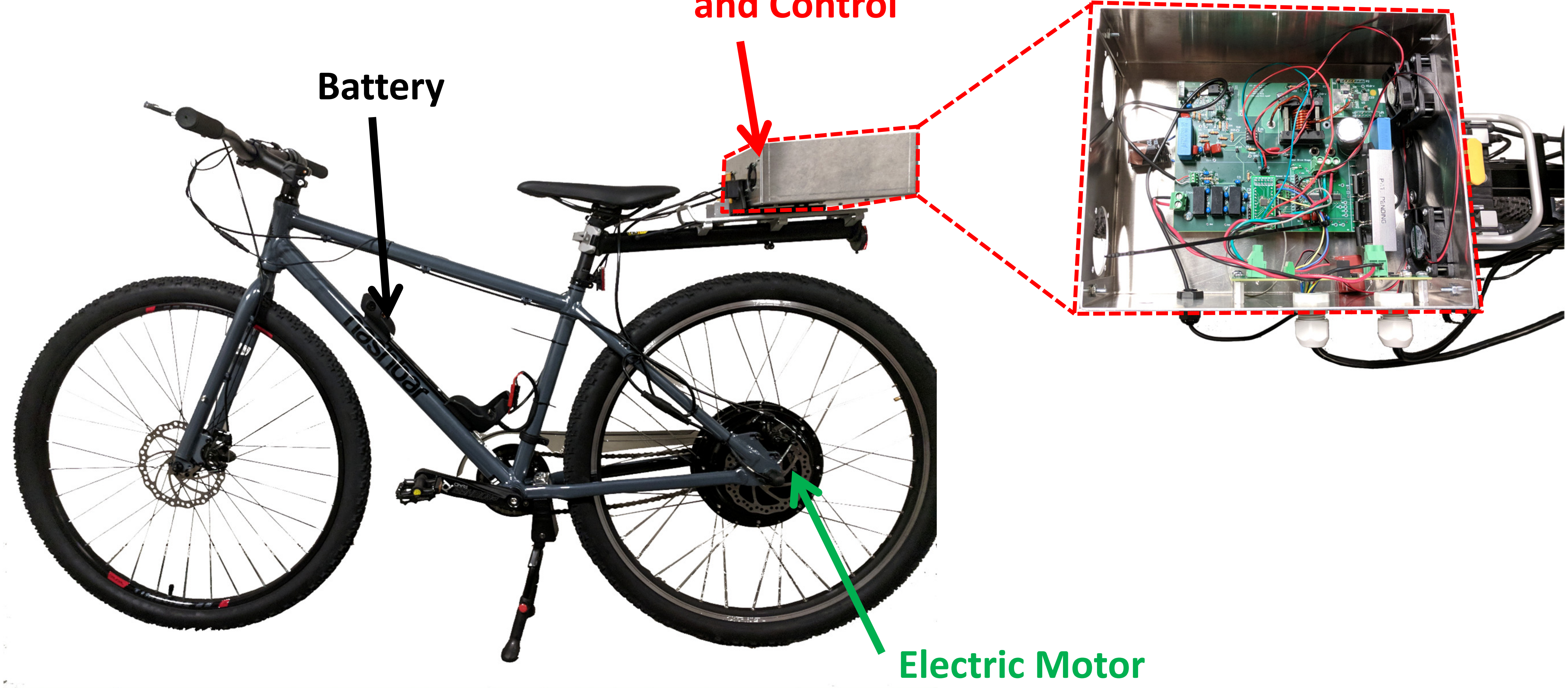
Senior

- **ECE 481 Power Electronics**
- ECE 482/582 Power Electronic Circuits

Graduate

- ECE 581 High Frequency Power Electronics
- ECE 686 Solid State Power Semiconductors
- ECE 692 DT Modeling of Power Electronics
- ECE 583 Modeling and Control of Drives
- ECE 683 Advanced Power Electronics and Drives
- ECE 682 Power Electronics Technologies
- ECE 585 Electric Vehicles
- ECE 586 WBG Characterization
- ECE 684 Power Electronics Packaging
- ECE 525 Alternative Energy Sources
- ECE 625 Utility Applications of Power Electronics

ECE 482: Power Electronics Circuits



Power Conversion and Control

Battery

Electric Motor

Course Policy

- No late work will be accepted except in cases of documented medical emergency
- Collaboration encouraged on Labs and Homework
  - Must submit your own work on all assignments
  - Adhere to Student Code of Conduct
- Attendance is required in all lectures

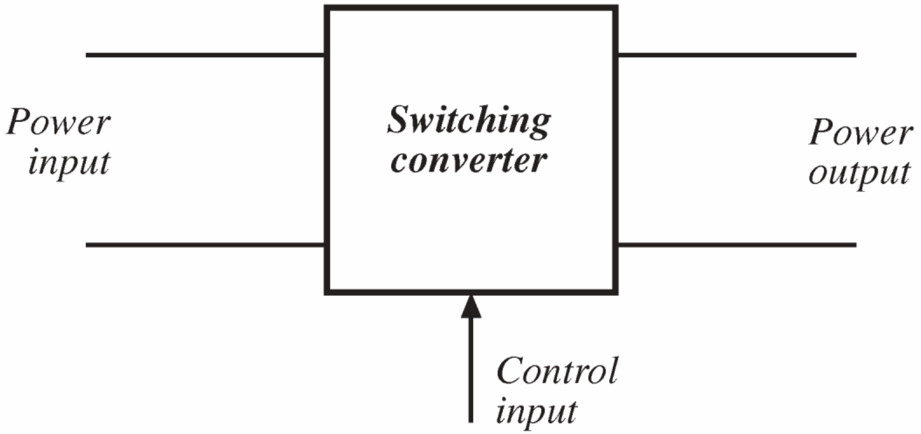
How to Succeed in ECE 481

- Attend all lectures
  - Participate; ask questions or ask for clarification
- Read textbook for additional explanation
- Complete all homework assignments
  - Attempt homework alone prior to collaborating
  - Review and understand mistakes

Introduction to Power Conversion

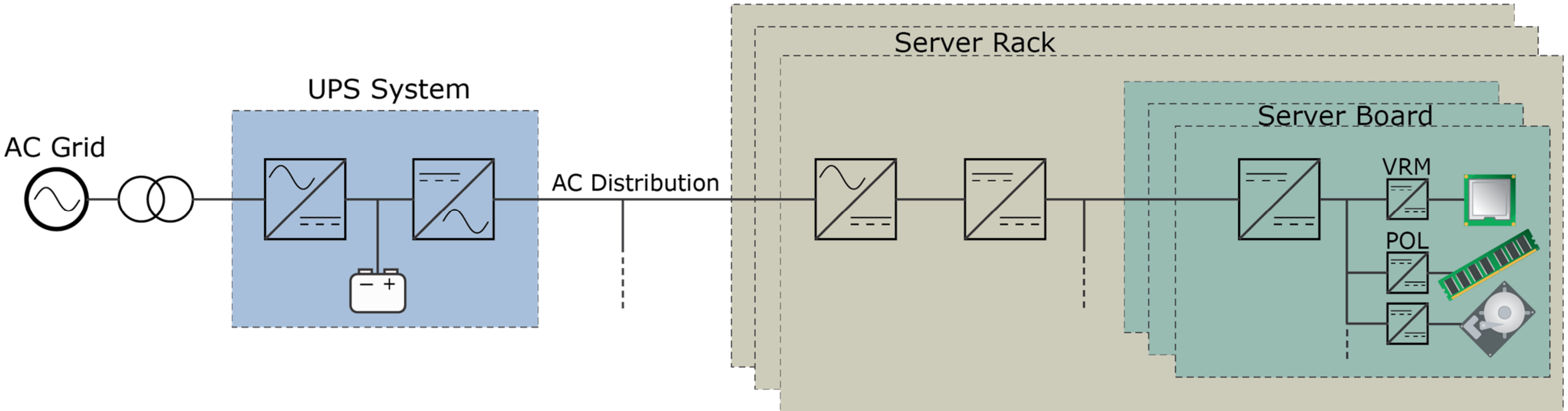
COURSE CONTENT INTRODUCTION

Introduction to Power Conversion

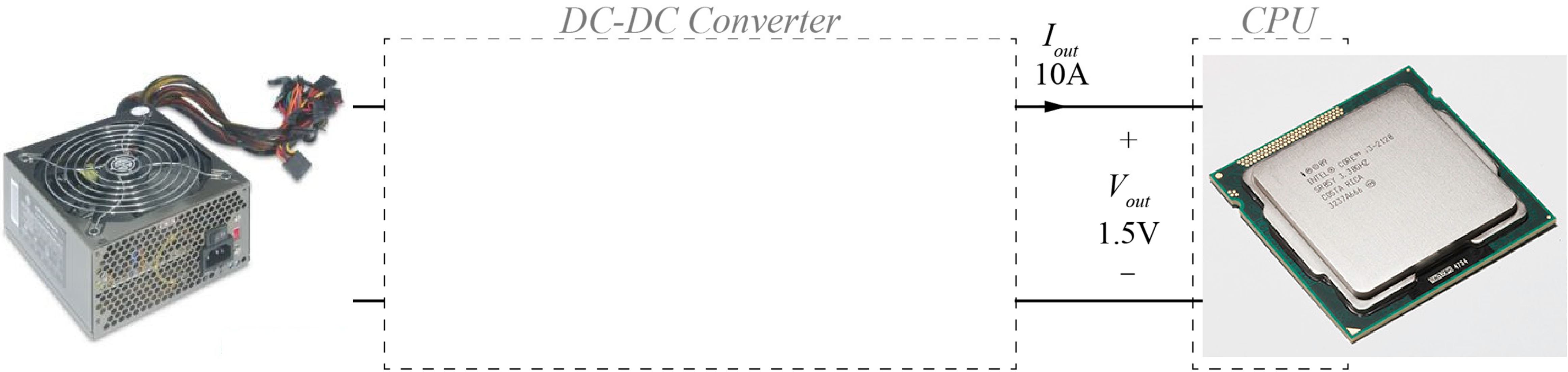


Dc-dc conversion:	Change and control voltage magnitude
Ac-dc rectification:	Possibly control dc voltage, ac current
Dc-ac inversion:	Produce sinusoid of controllable magnitude and frequency
Ac-ac cycloconversion:	Change and control voltage magnitude and frequency

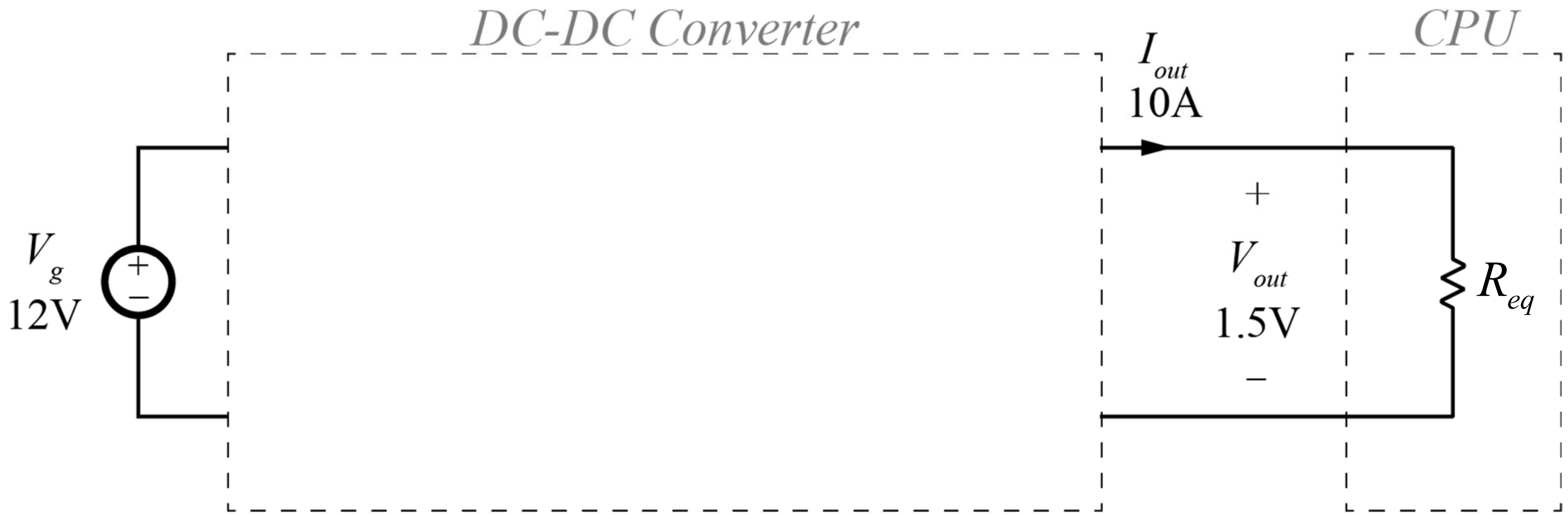
Example Server Power Distribution



Example VRM Design

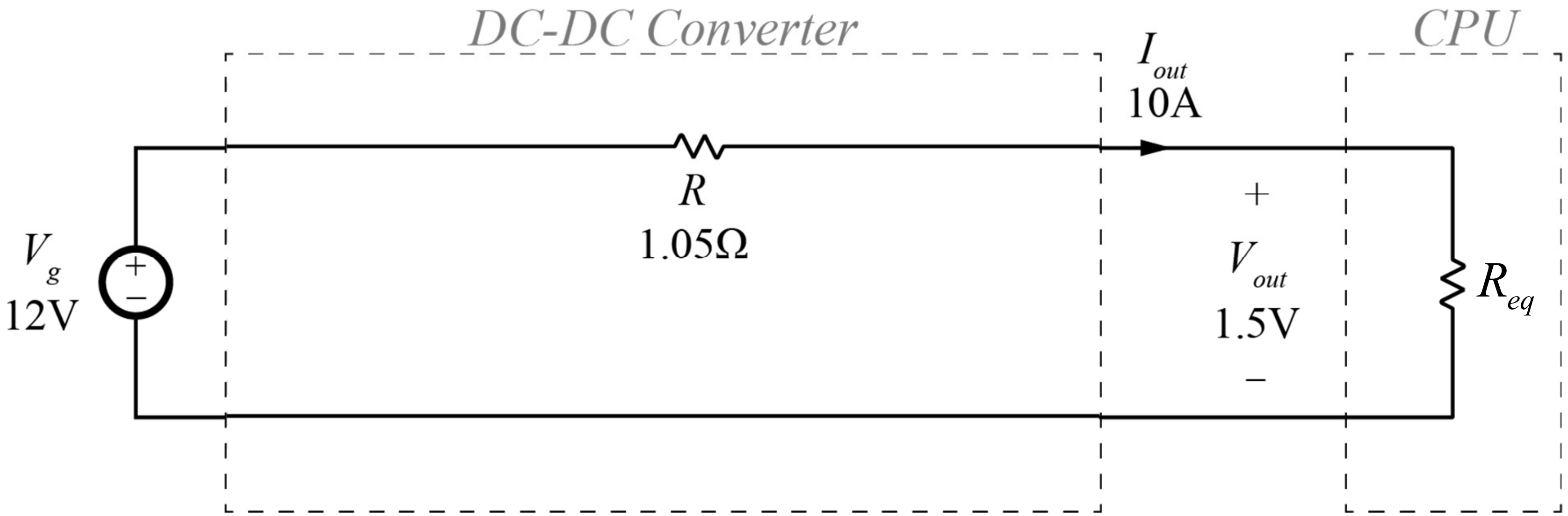


Example VRM Design



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

Example VRM Design

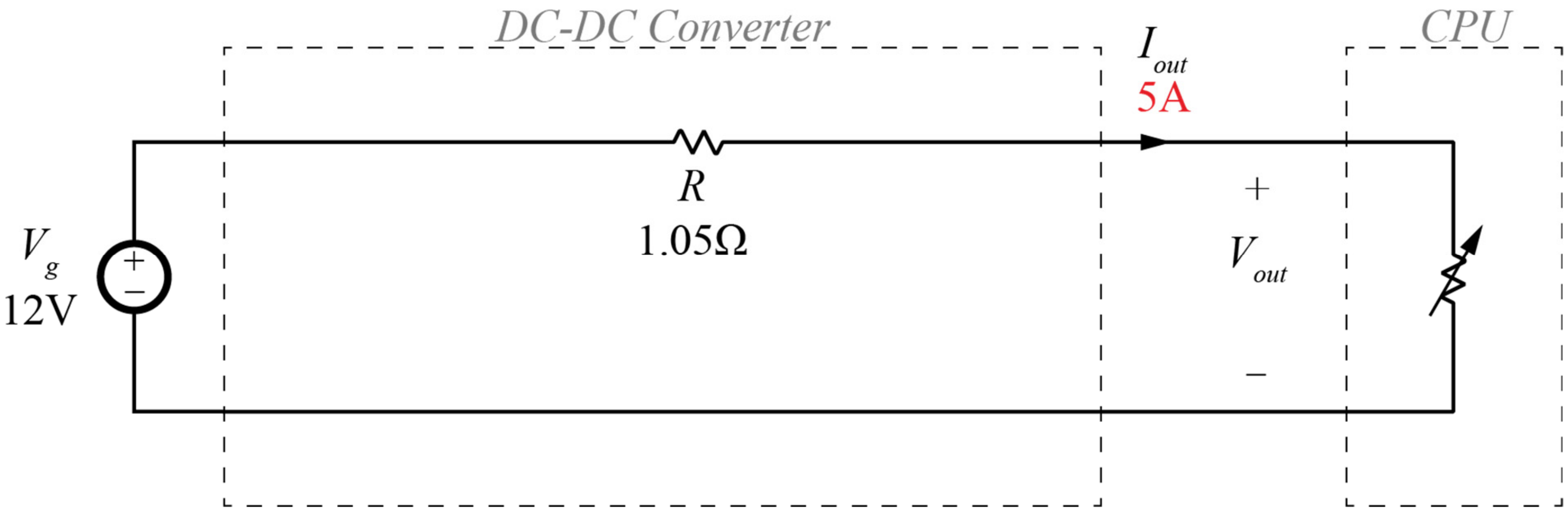


$$R_{eq} = \frac{V_{out}}{I_{out}} = 150m\Omega$$

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

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

Variations in Load

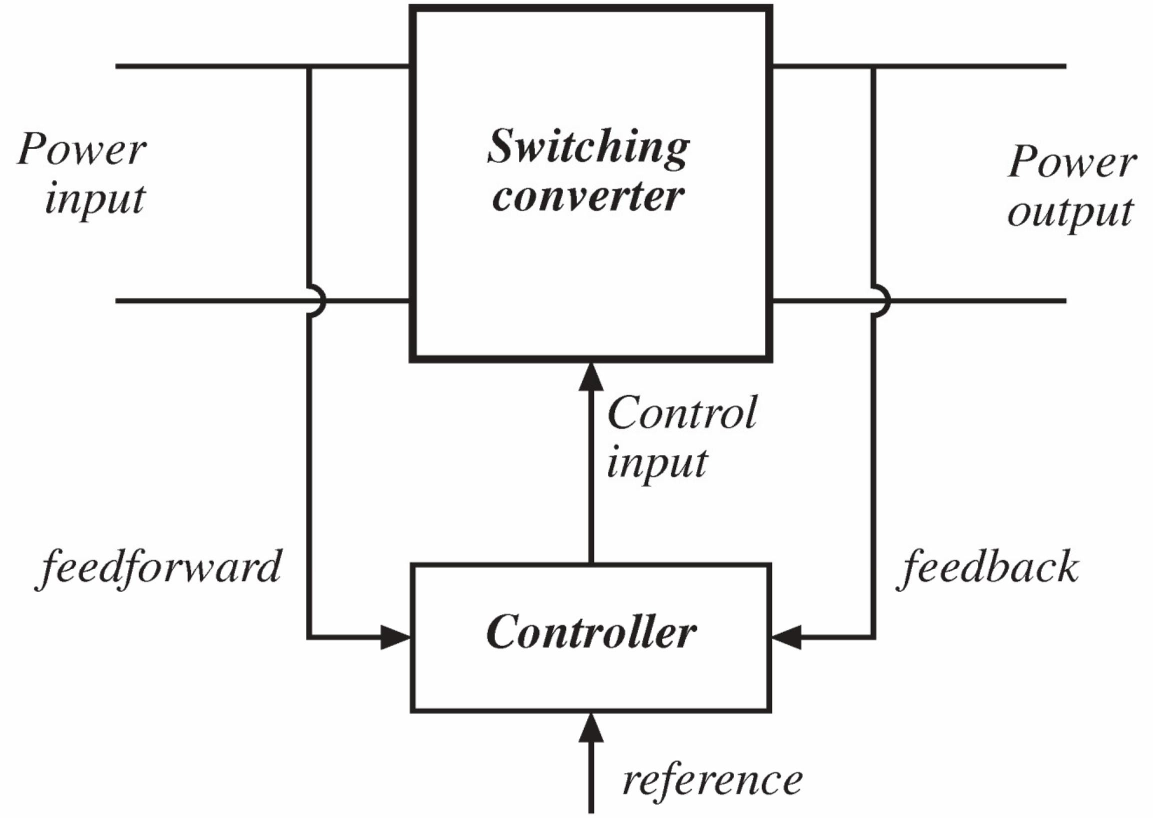


$$V_{out} = V_g - I_{out} R$$

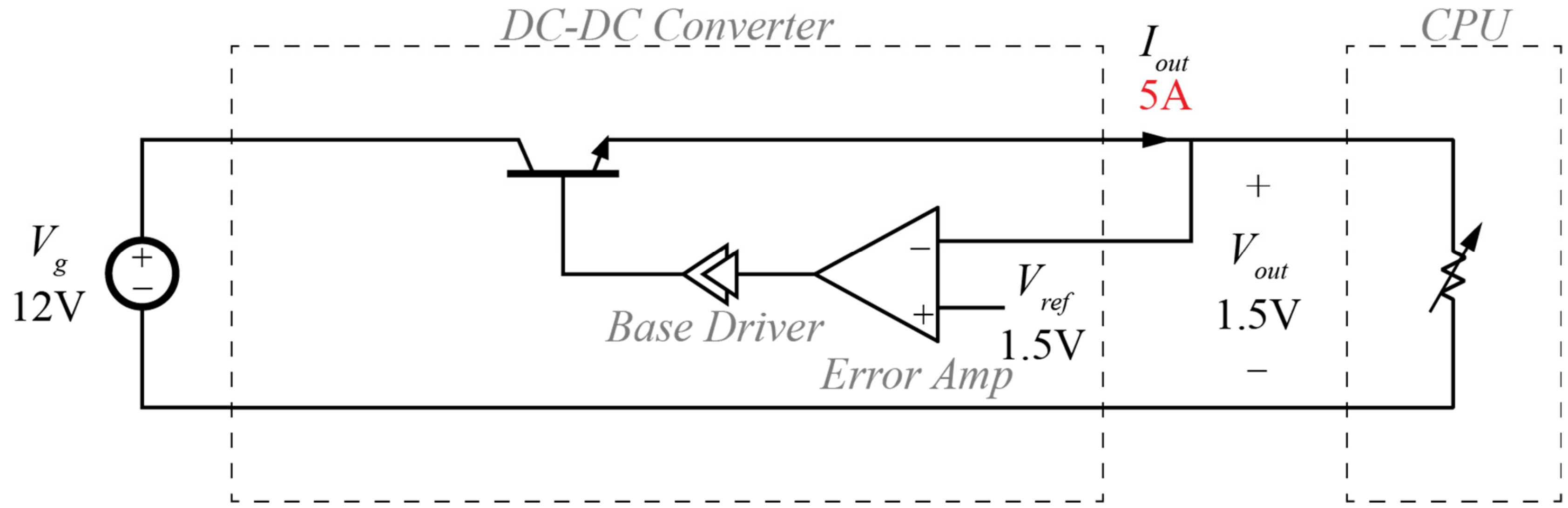
$$V_{out} = 12\text{V} - (5\text{A})(1.05\Omega)$$

$$V_{out} = 6.75\text{V}$$

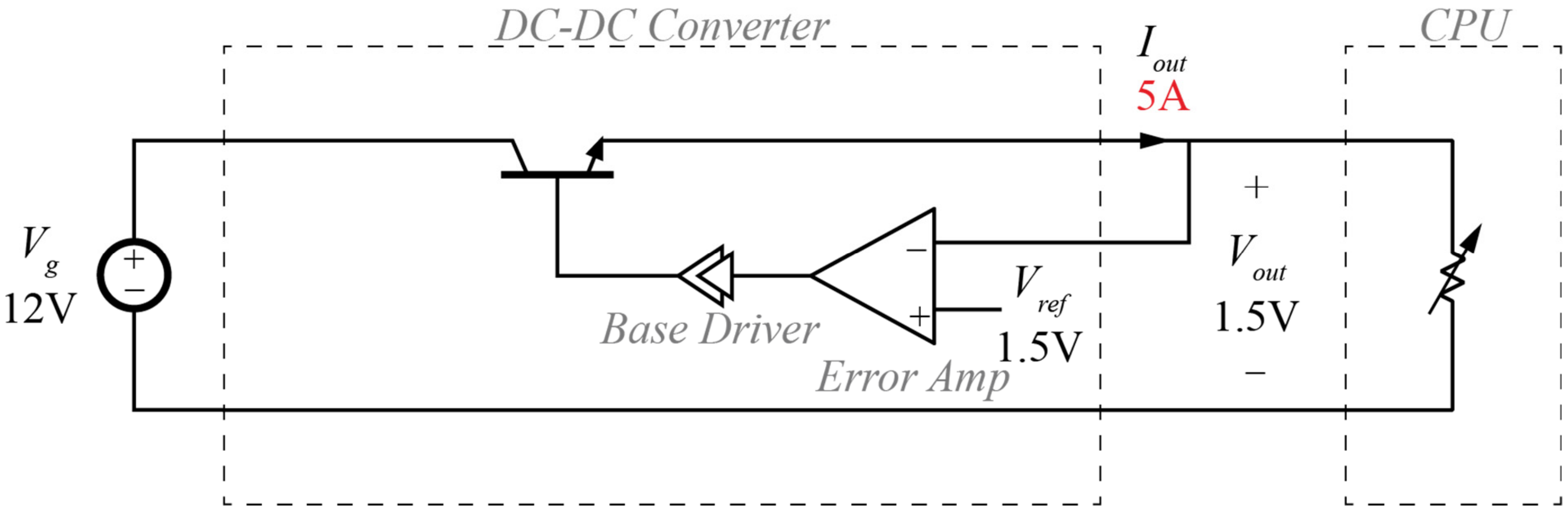
Control is Invariably Required



Linear Regulator



Linear Regulator



$$P_{in} = V_g I_g \approx V_g I_{out}$$

$$P_{in} = (5\text{A})(12\text{V})$$

$$P_{in} = 60\text{W}$$

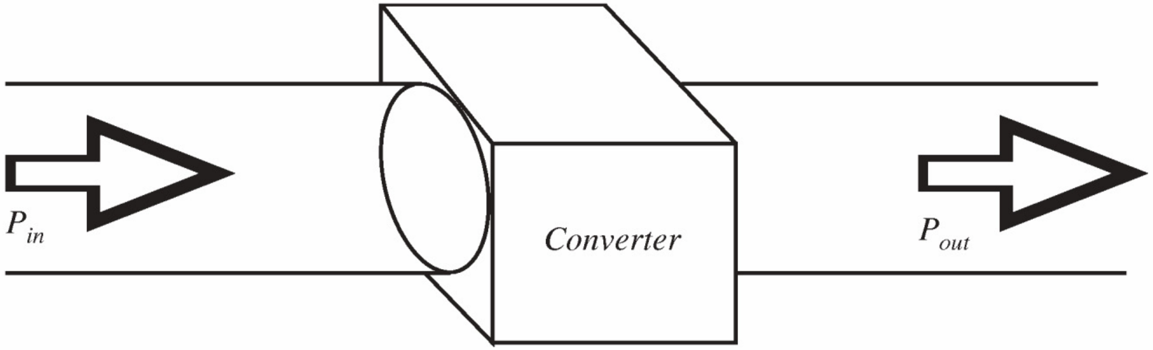
$$P_{out} = V_{out} I_{out}$$

$$P_{out} = (5\text{A})(1.5\text{V})$$

$$P_{out} = 7.5\text{W}$$

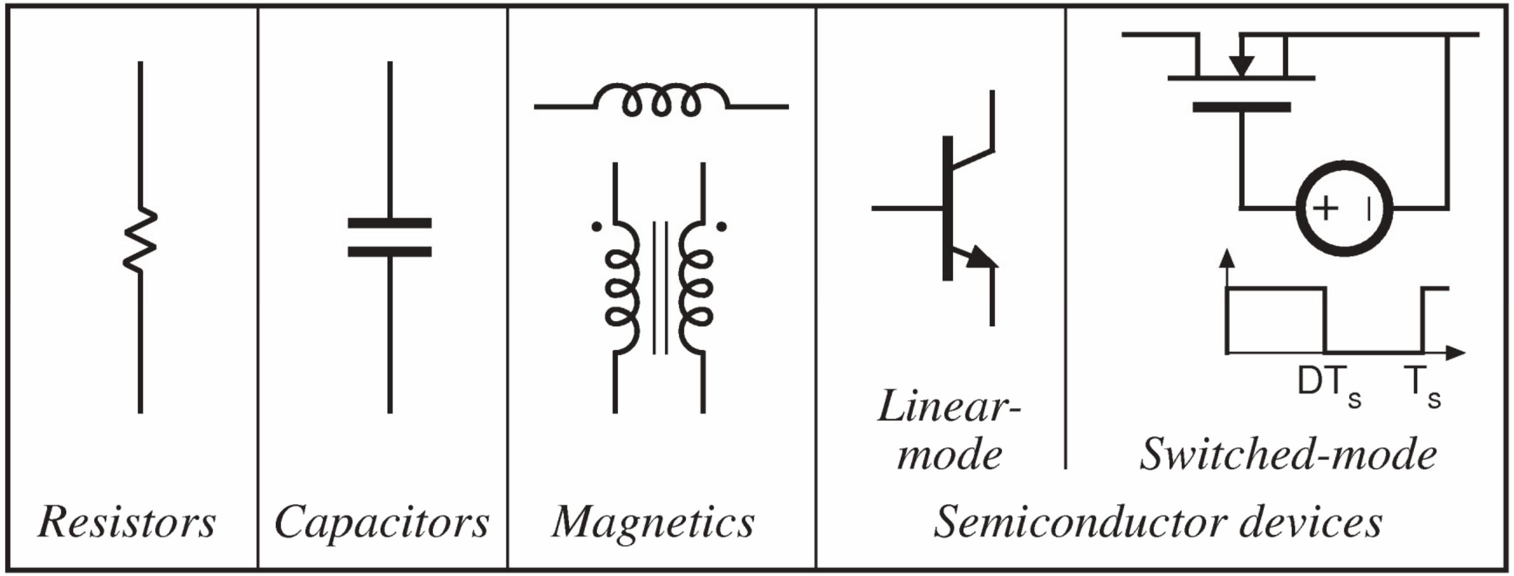
$$\boxed{\eta = \frac{P_{out}}{P_{in}} = \frac{7.5\text{W}}{60\text{W}} = 12.5\%}$$

A High Efficiency Converter

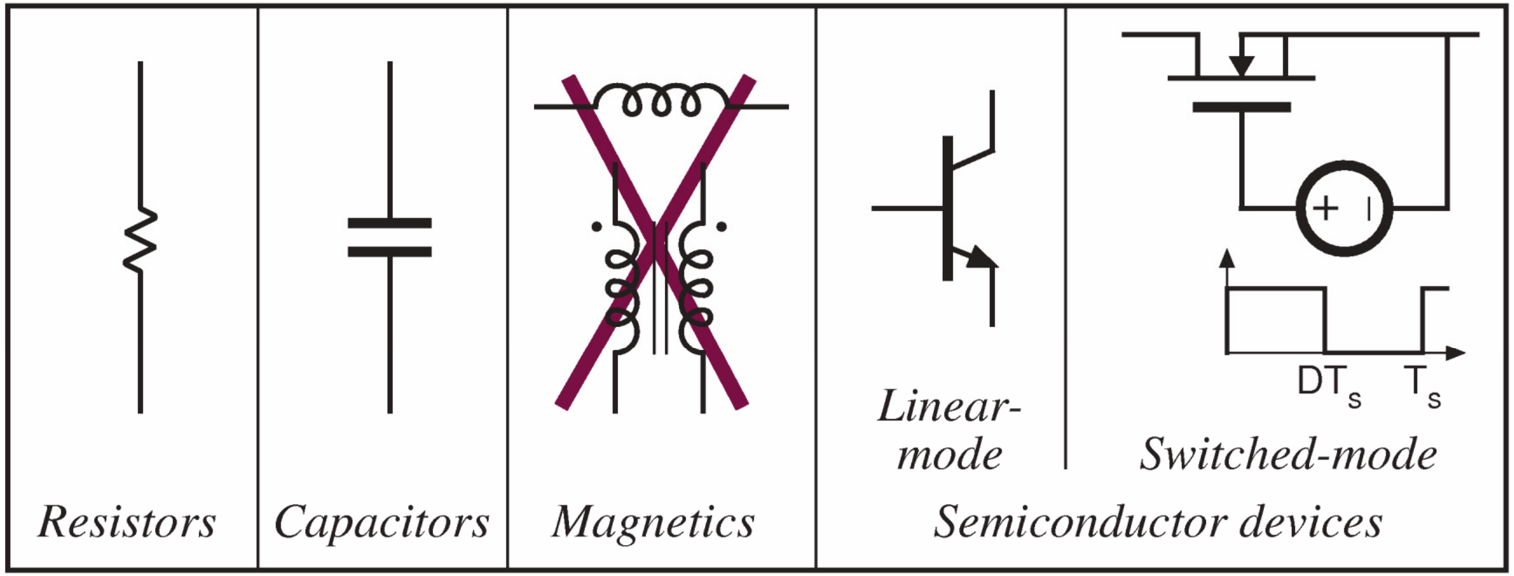


A goal of current converter technology is to construct converters of small size and weight, which process substantial power at high efficiency

Devices Available to the Circuit Designer

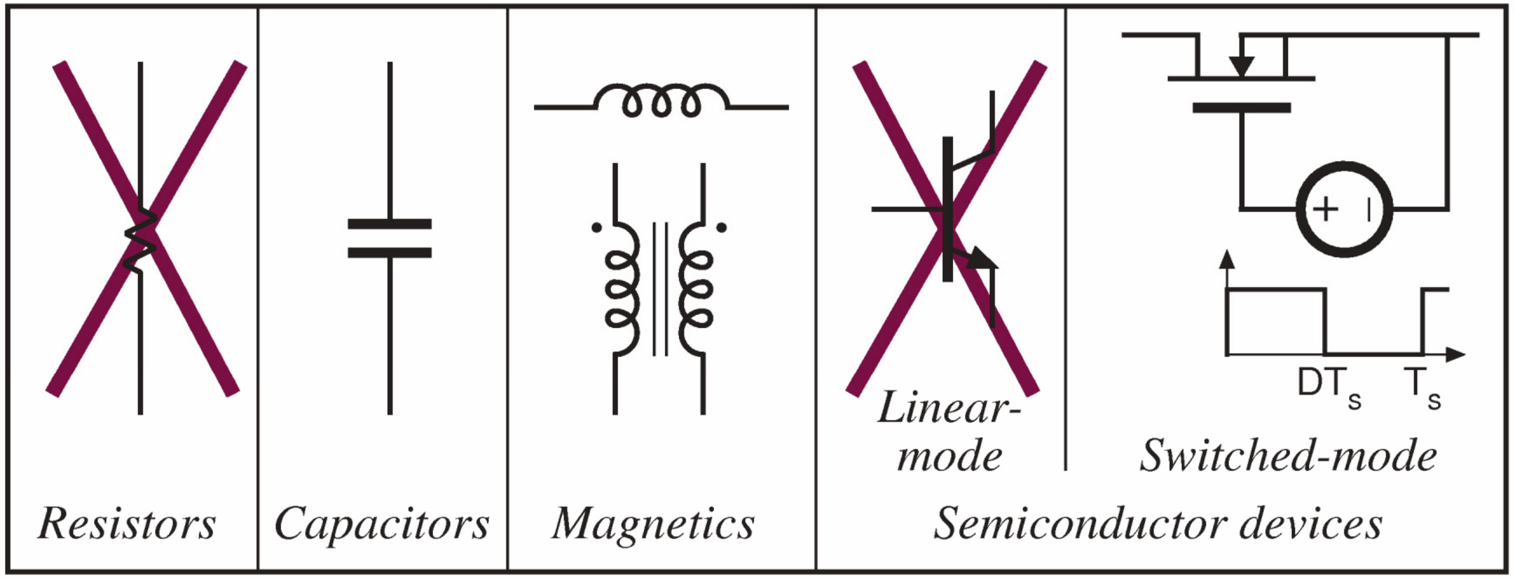


Devices Available to the Circuit Designer



Signal processing: avoid magnetics

Devices Available to the Circuit Designer



Power processing: avoid lossy elements

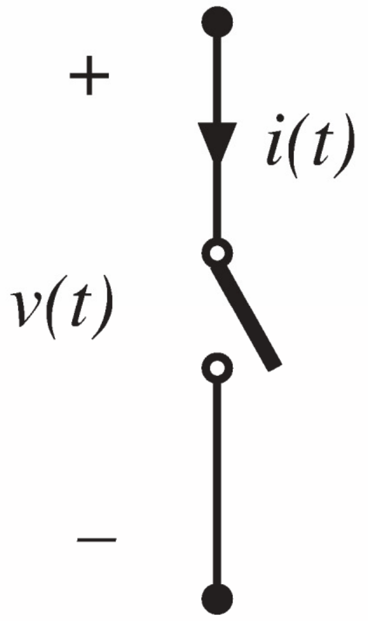
Power Loss in an Ideal Switch

Switch closed: $v(t) = 0$

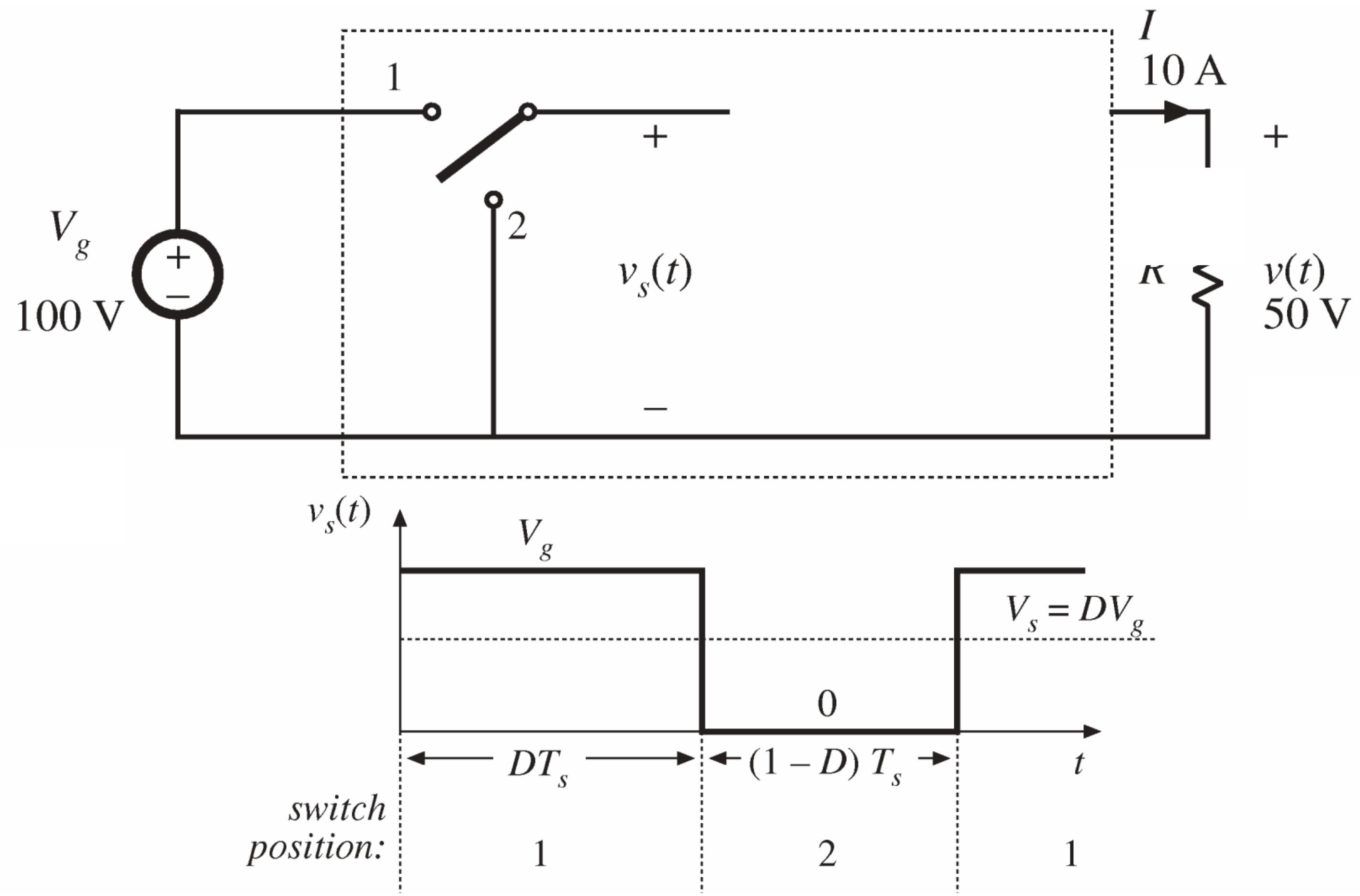
Switch open: $i(t) = 0$

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

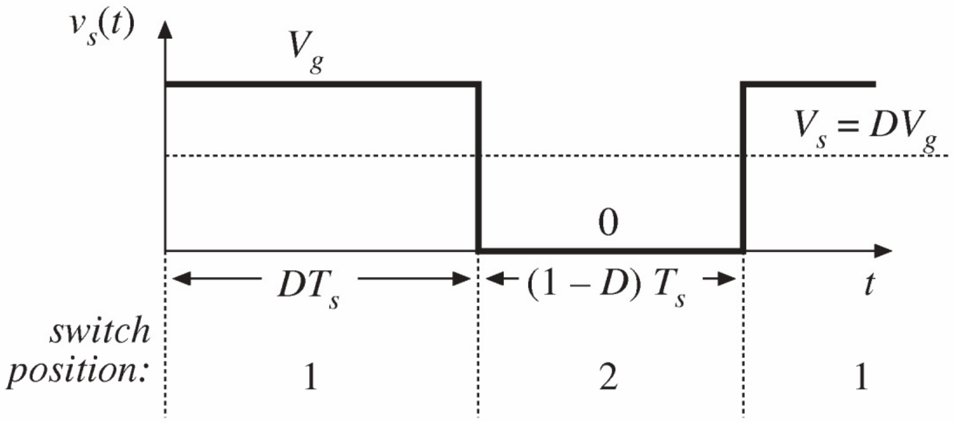
Ideal switch consumes zero power



Use of SPDT Switch



Controlling Duty Cycle



D = switch duty cycle

$0 \le D \le 1$

T_s = switching period

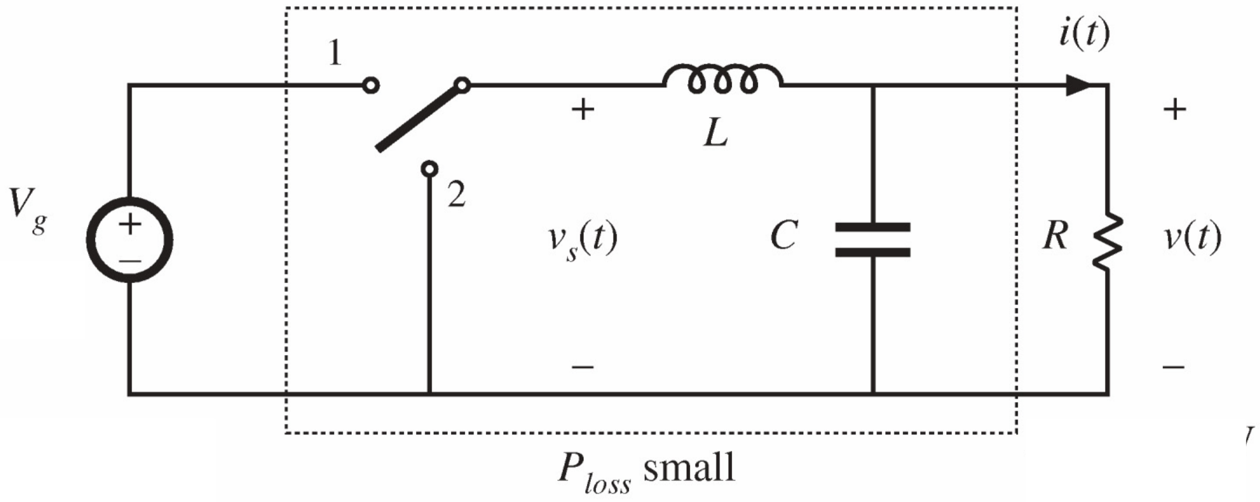
f_s = switching frequency
$= 1 / T_s$

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

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

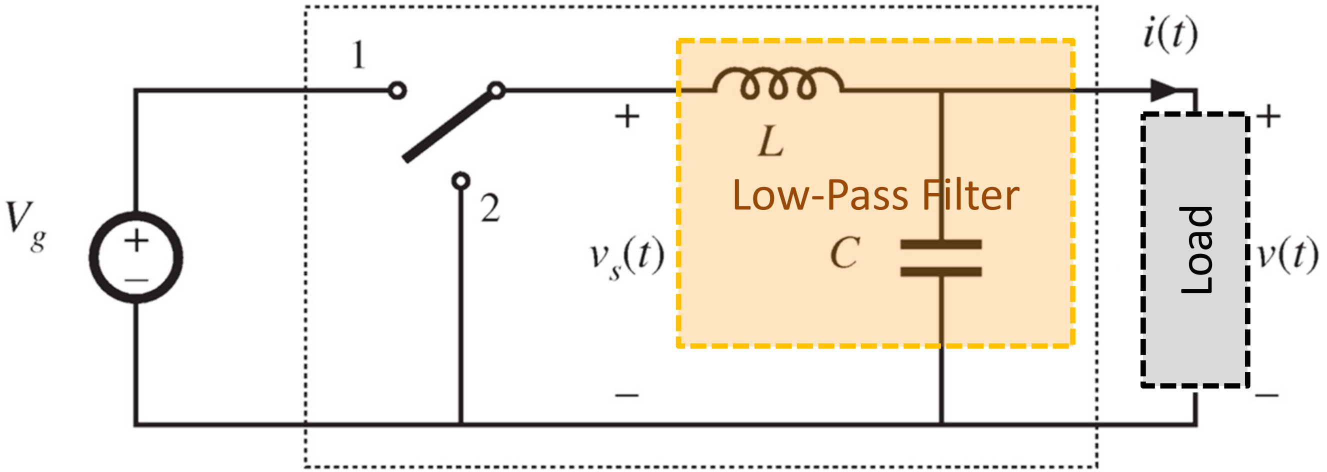
Addition of Low Pass Filter

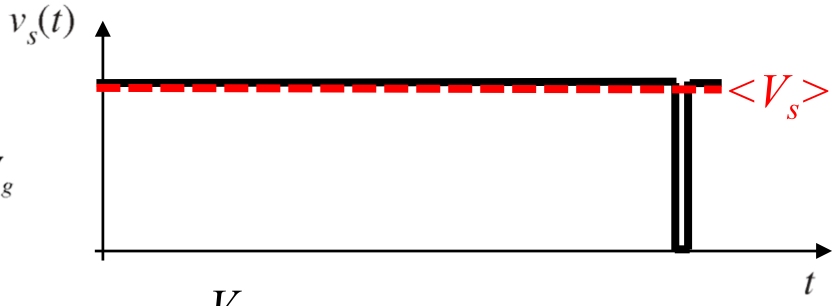
Addition of (ideally lossless) L-C low-pass filter, for removal of switching harmonics:



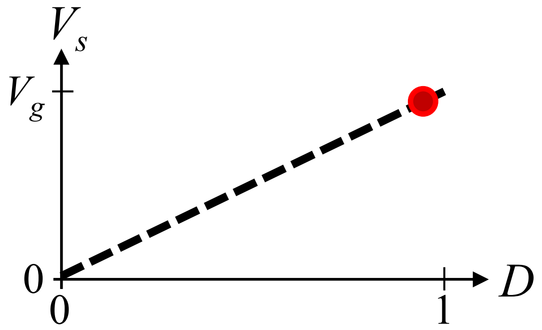
- Choose filter cutoff frequency f_0 much smaller than switching frequency f_s
- This circuit is known as the “buck converter”

Duty Cycle Control

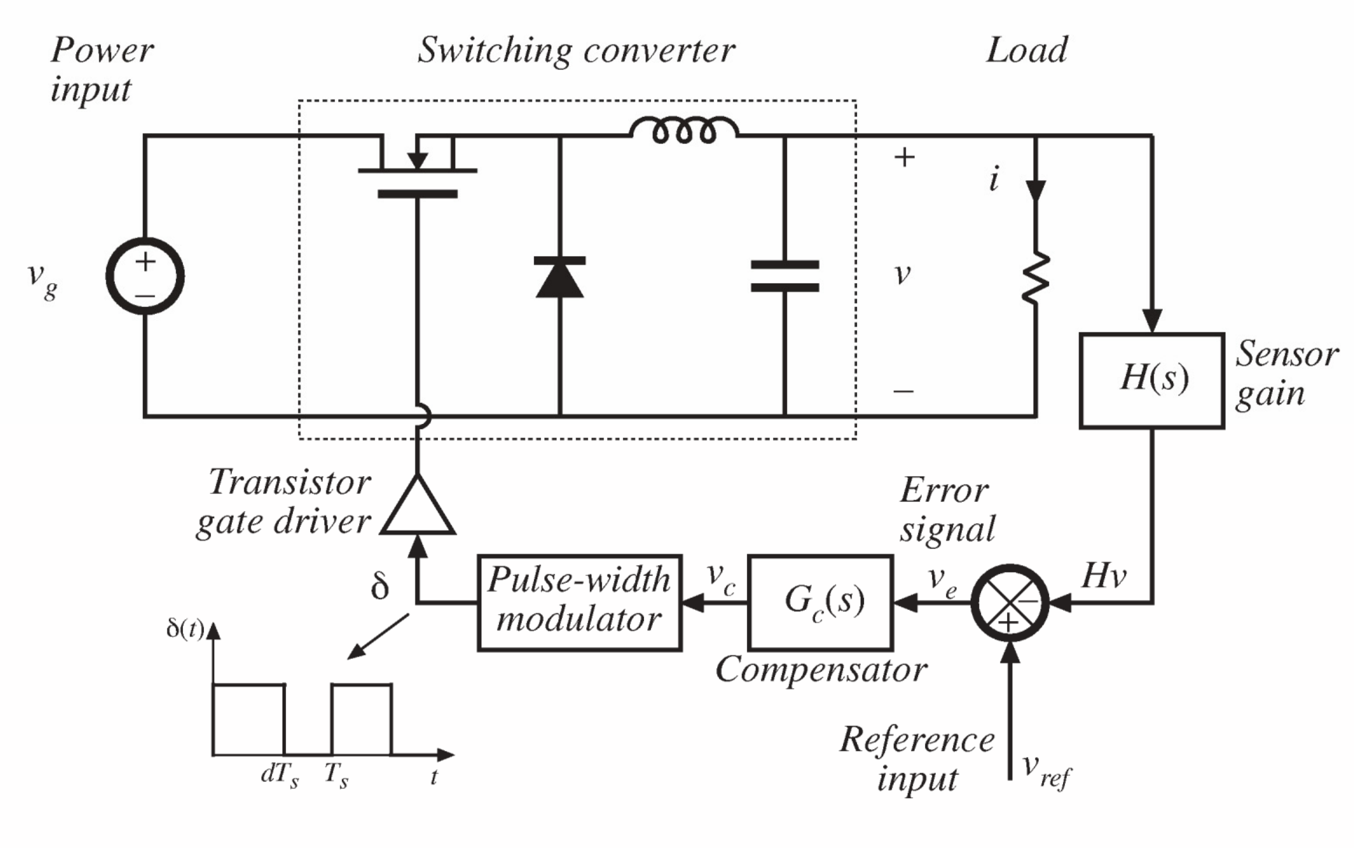




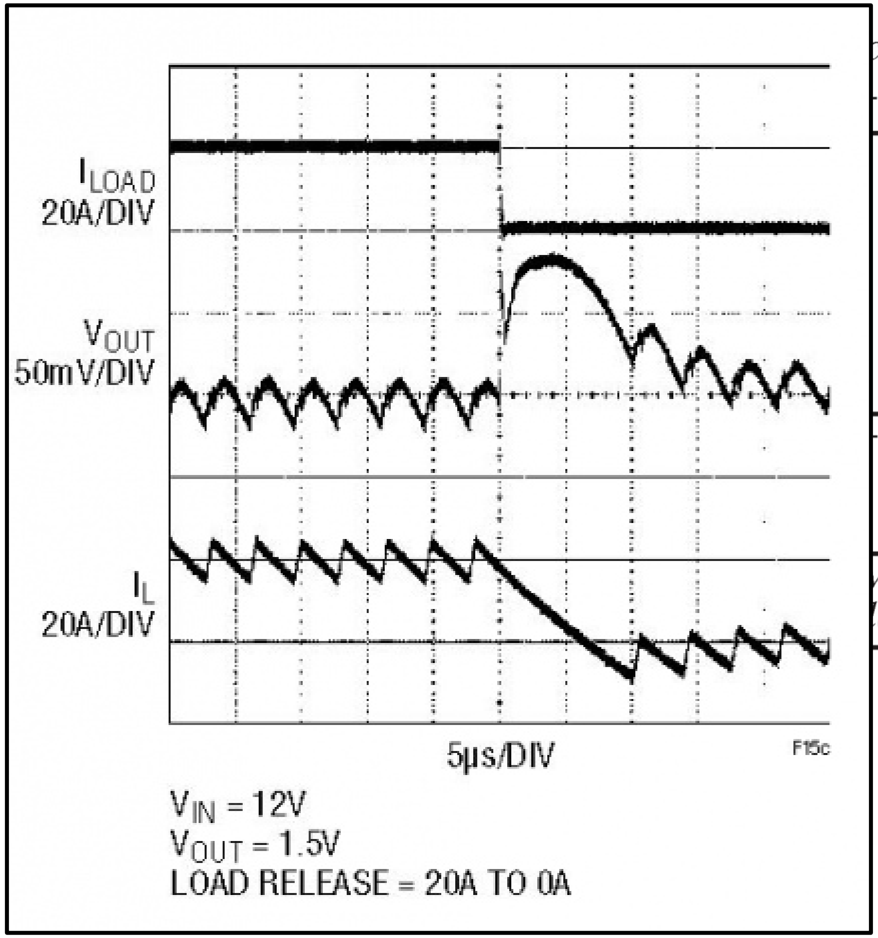
$$V_s = \frac{1}{T_s}\int_0^{T_s} v_s(t)\,dt = DV_g$$

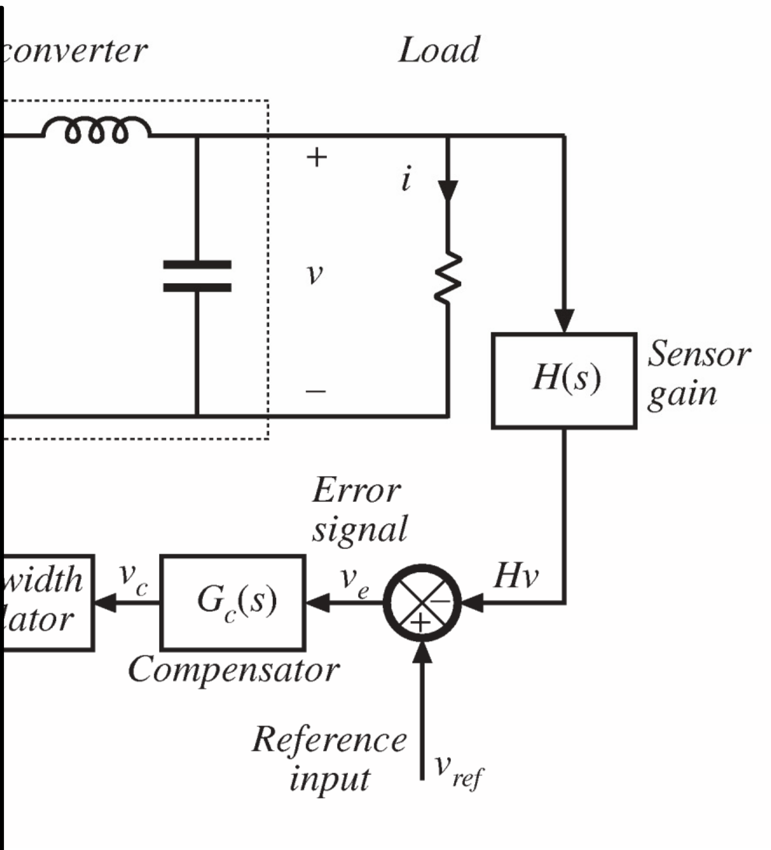


Control System for Voltage Regulation

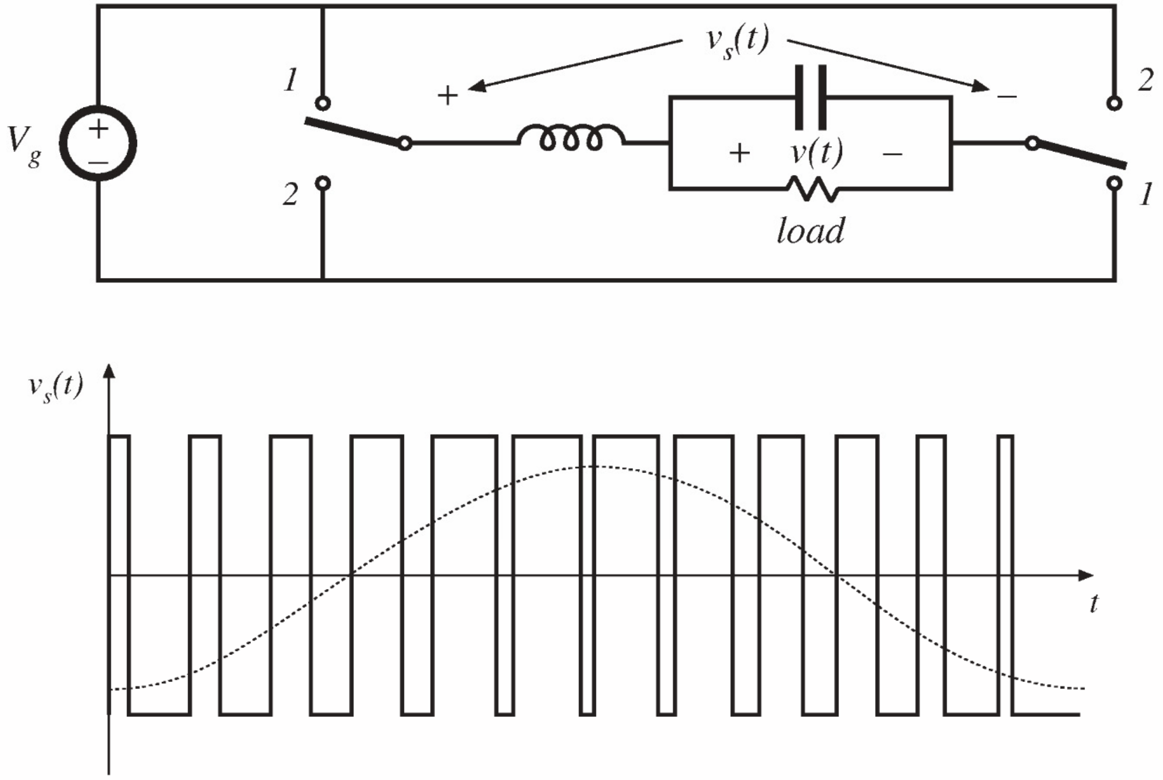


Dynamic Performance





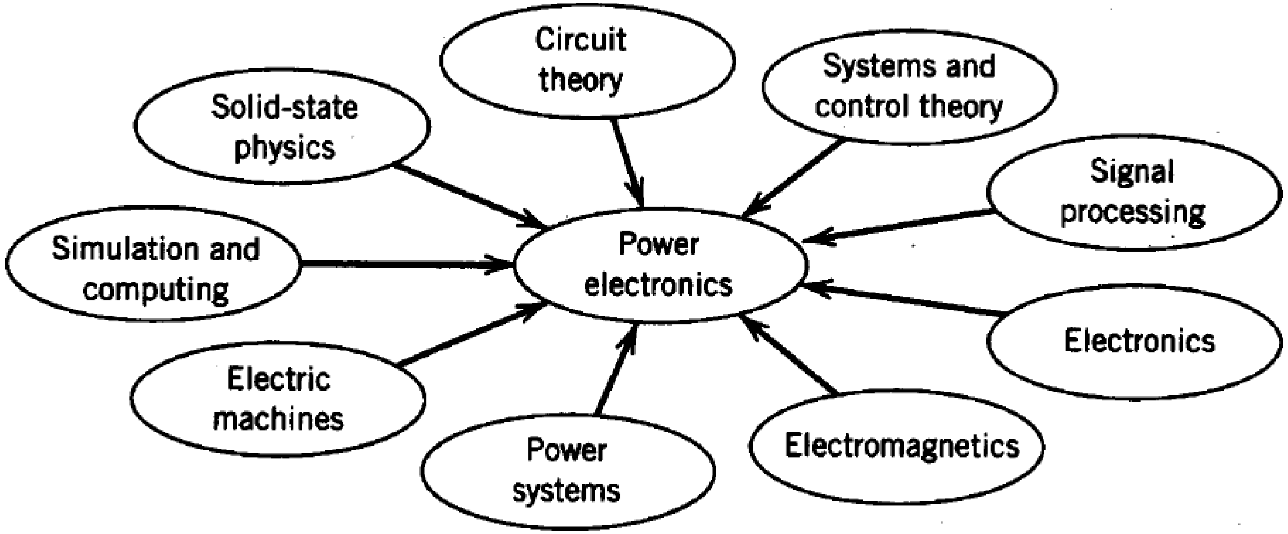
Single Phase Inverter

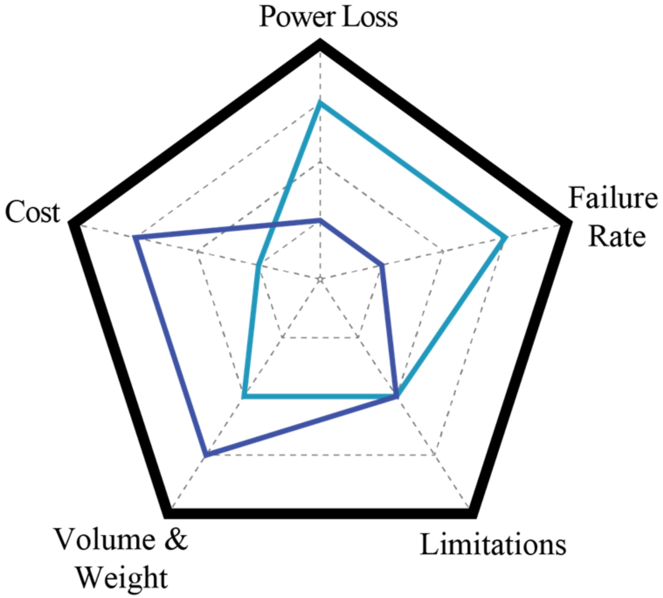


“H-bridge”

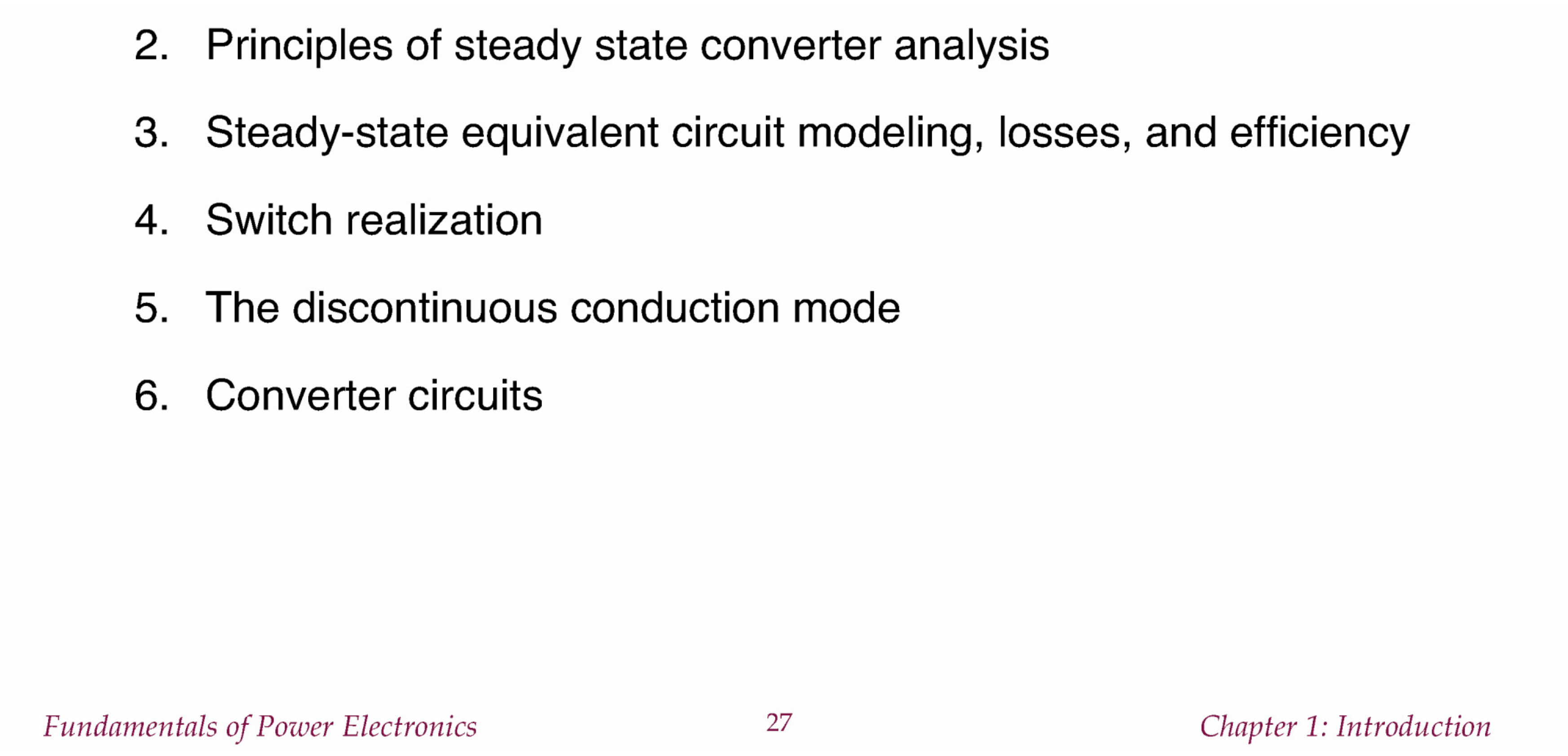
Modulate switch duty cycles to obtain sinusoidal low-frequency component

Power Electronics Overview



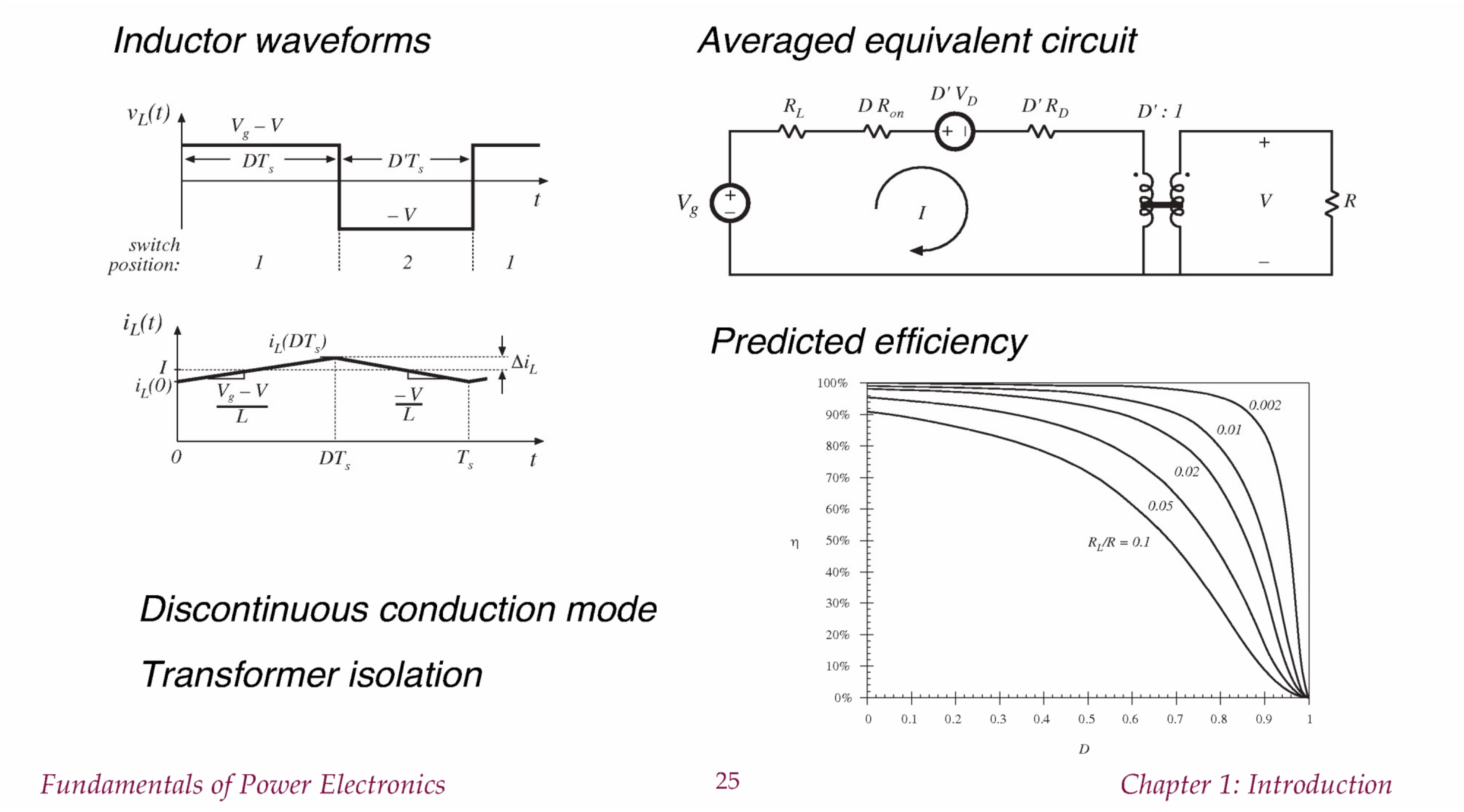


Part I: Converters in Equilibrium



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

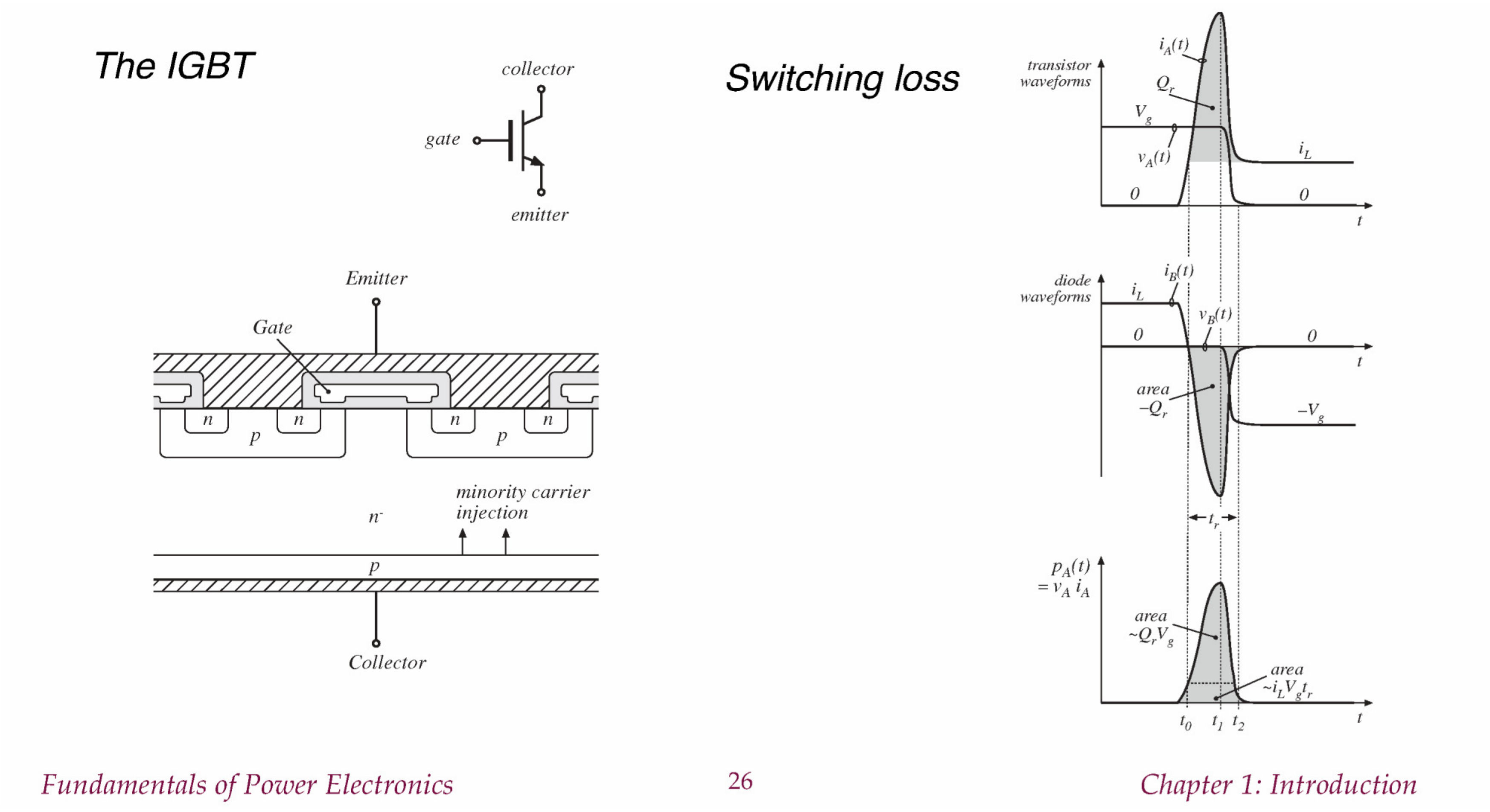
Averaged equivalent circuit

Predicted efficiency

Discontinuous conduction mode

Transformer isolation

Switch Realization: Semiconductor Devices

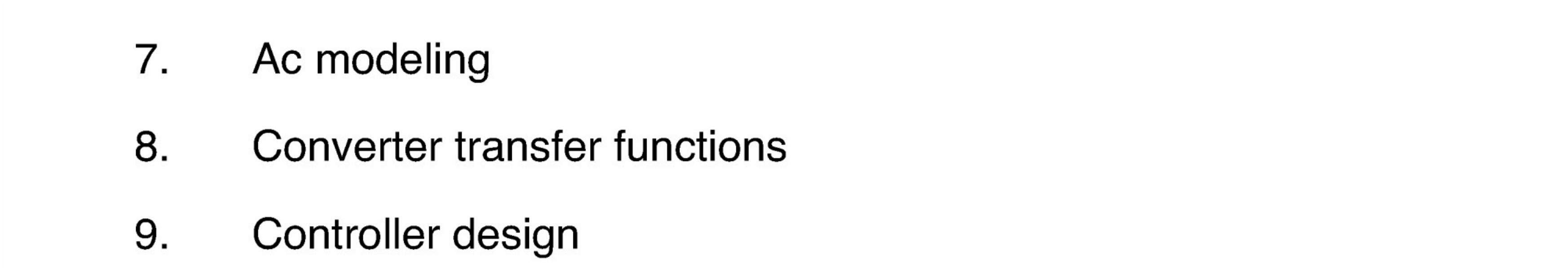


The IGBT

Switching loss

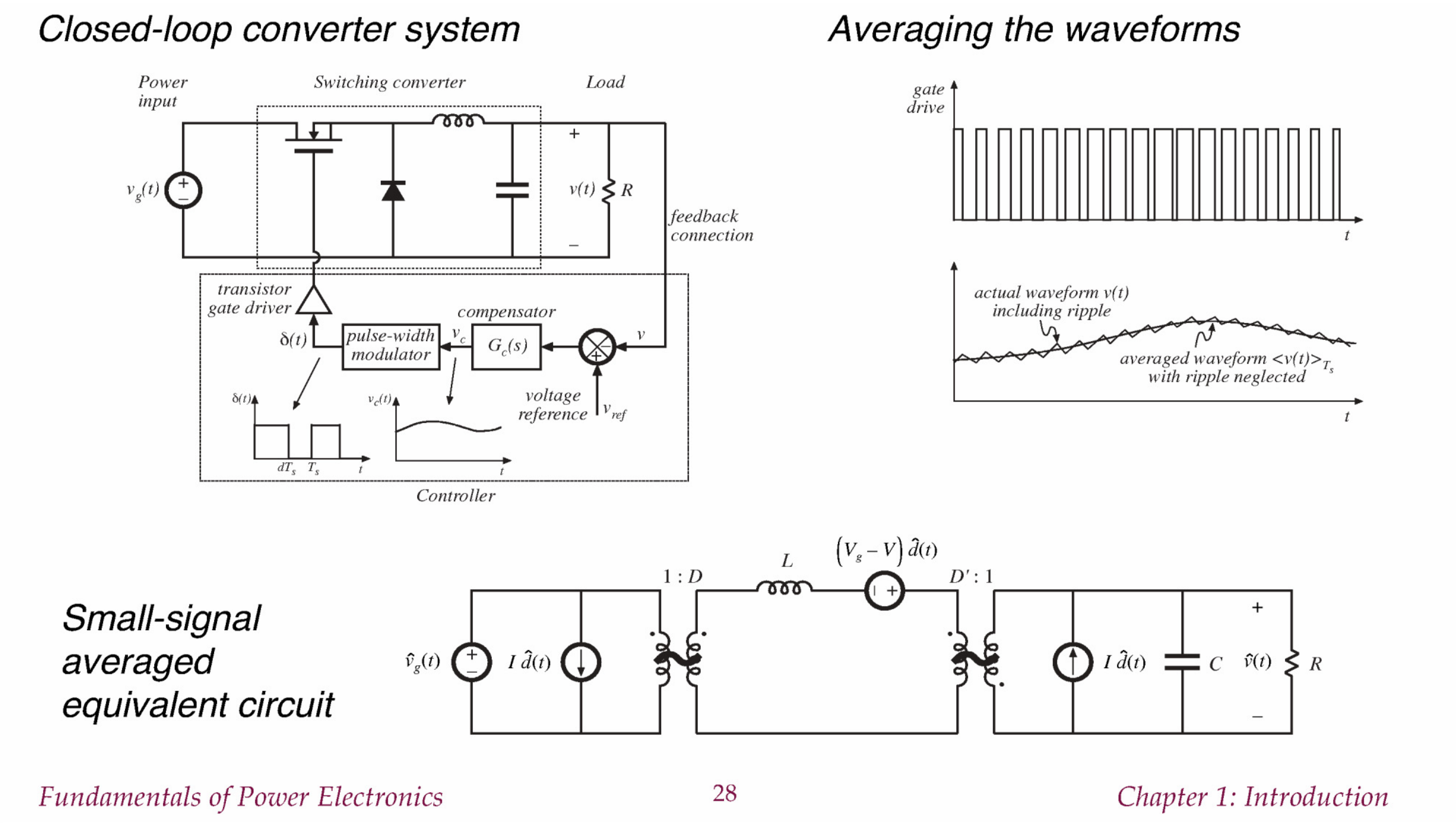
Fundamentals of Power Electronics 26 *Chapter 1: Introduction*

Part II: Converter Dynamics and Control



7. Ac modeling
8. Converter transfer functions
9. Controller design

Part II: Converter Dynamics and Control



Closed-loop converter system

Averaging the waveforms

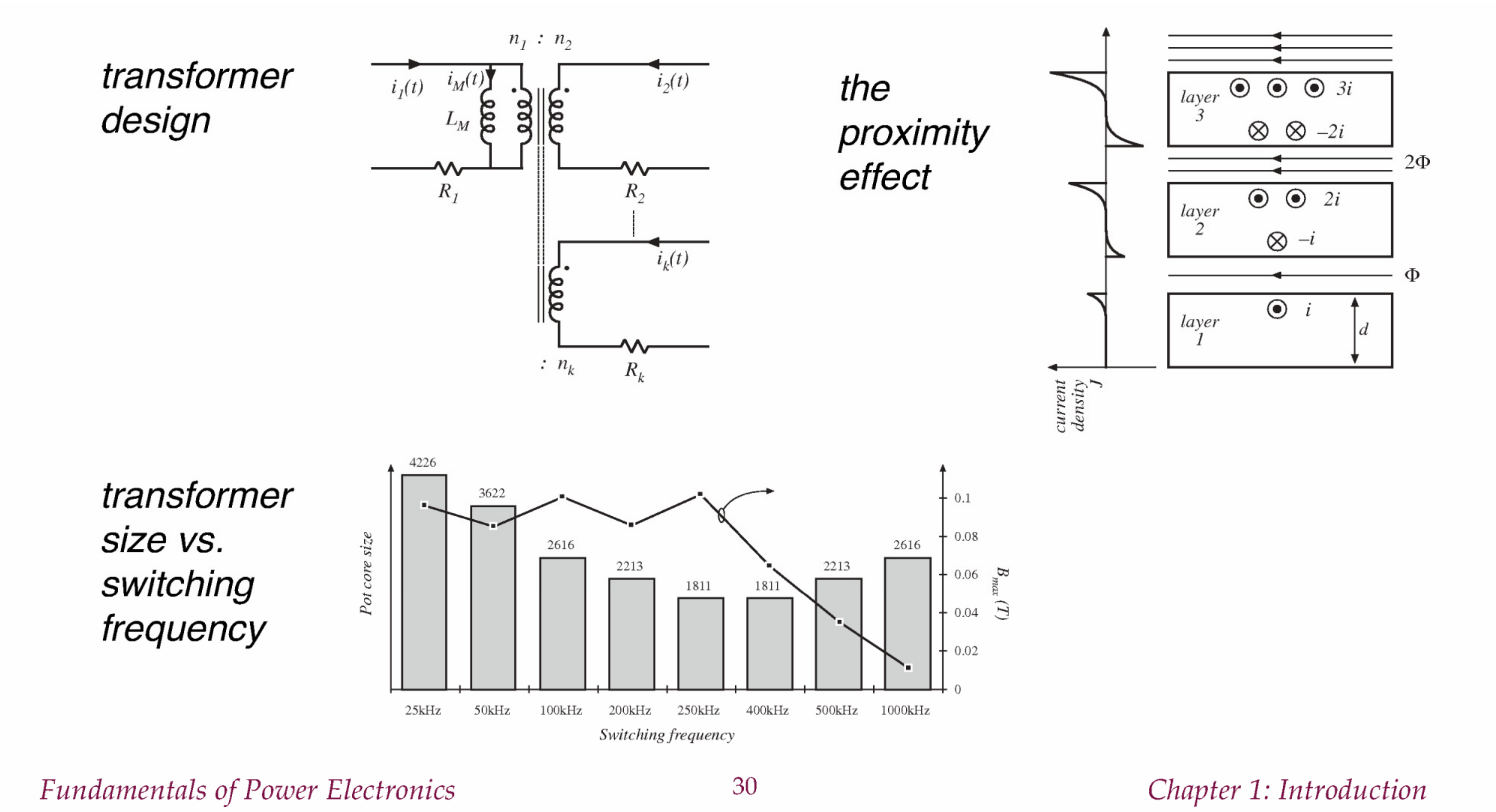
Small-signal averaged equivalent circuit

Fundamentals of Power Electronics 28 Chapter 1: Introduction

Part III: Magnetics

10. Basic Magnetics Theory
11. Inductor Design
12. Transformer Design

Part III: Magnetics



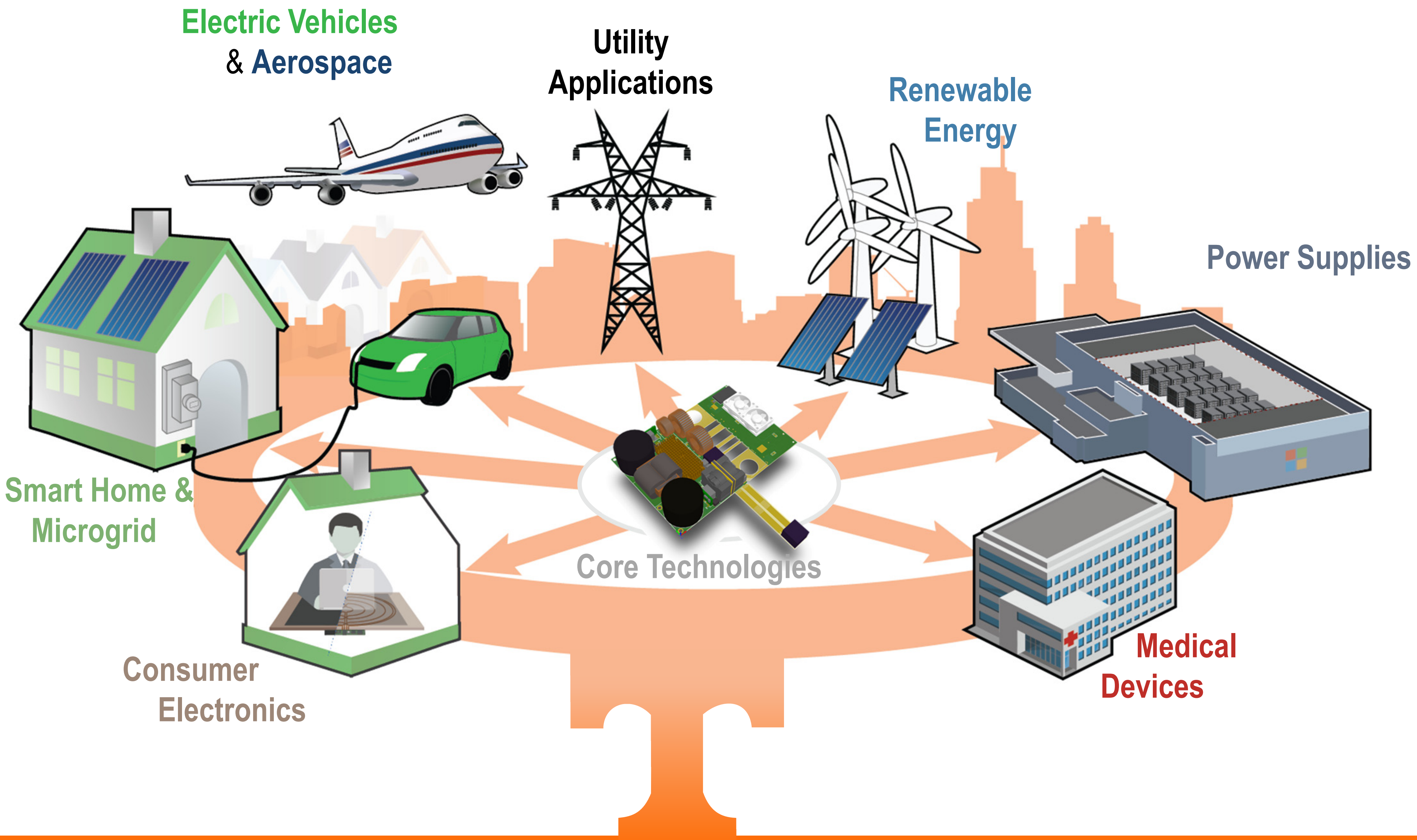
transformer design

the proximity effect

transformer size vs. switching frequency

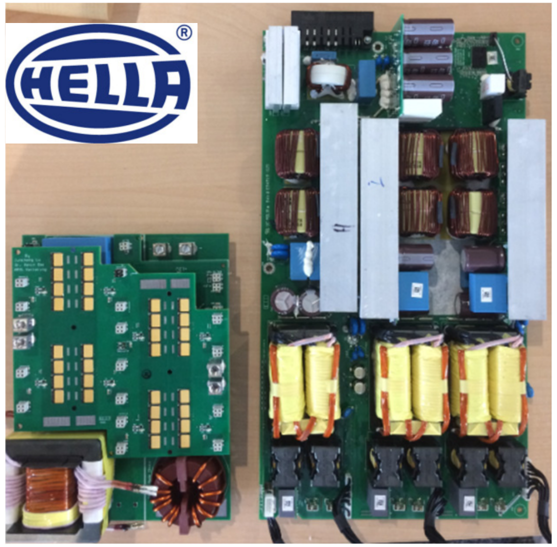
Fundamentals of Power Electronics 30 Chapter 1: Introduction

Power Electronics Research Applications

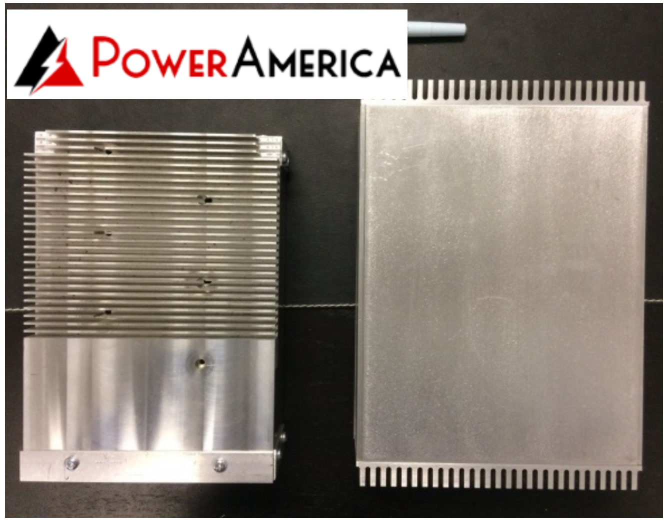


EV Battery Chargers

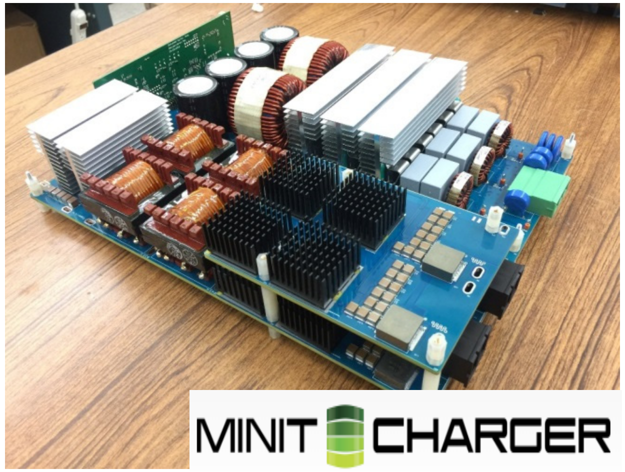
11kW charger (Si IGBT)



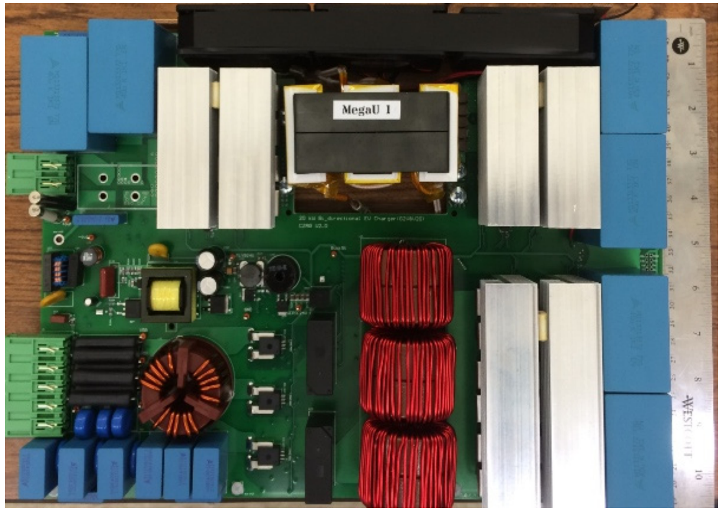
6.6kW charger (GaN vs Si)



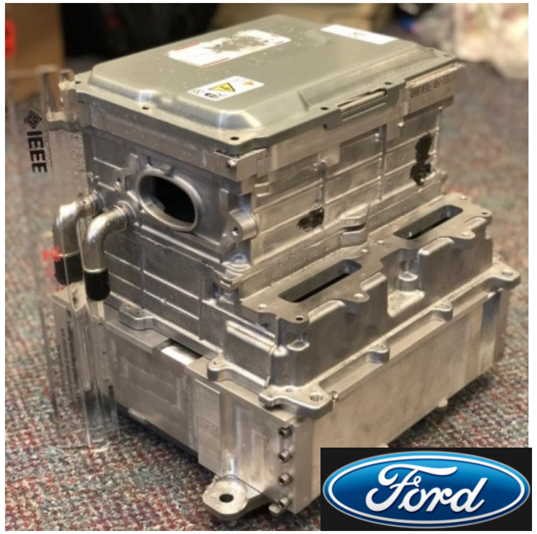
6.6kW charger (GaN vs SiC)



48V/11kW charger



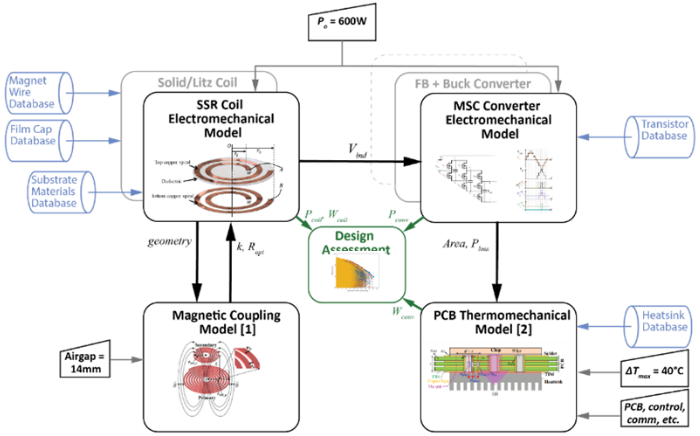
20kW SiC charger

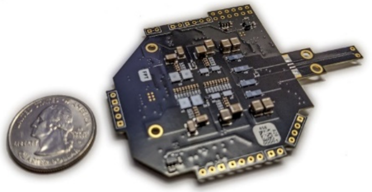


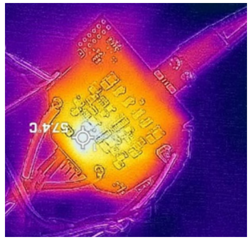
20kW V2L Charger

Wireless Power Transfer

Ultralightweight Wireless Chargers for UAVs

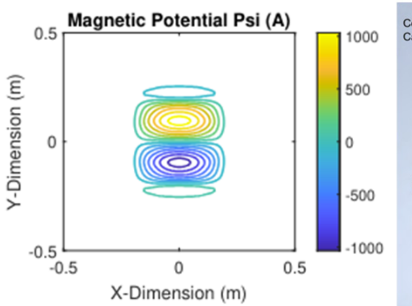


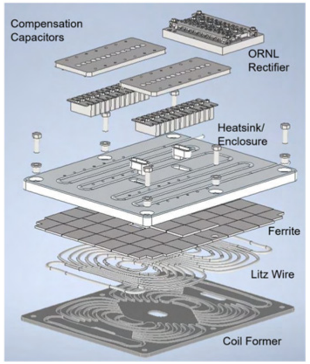


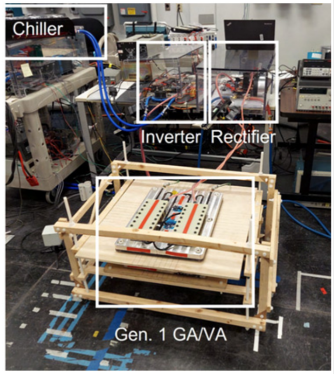


High gravimetric power density wireless receiver design optimization

High Power Wireless EV Charger



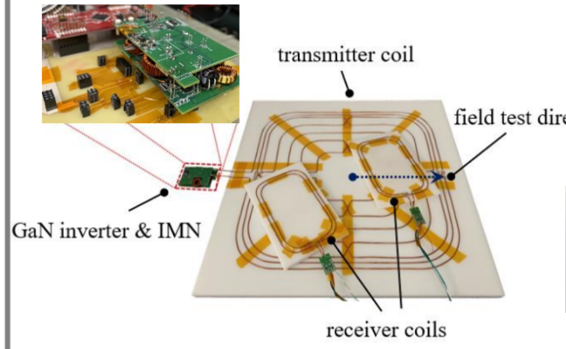




Low stray-field

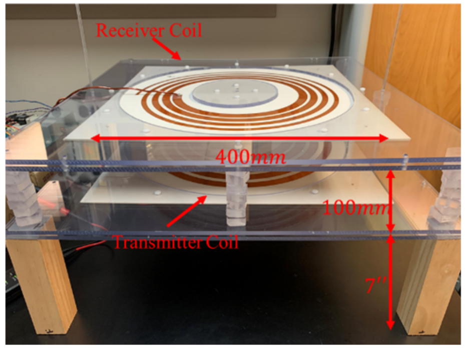
120kW coil model and prototype

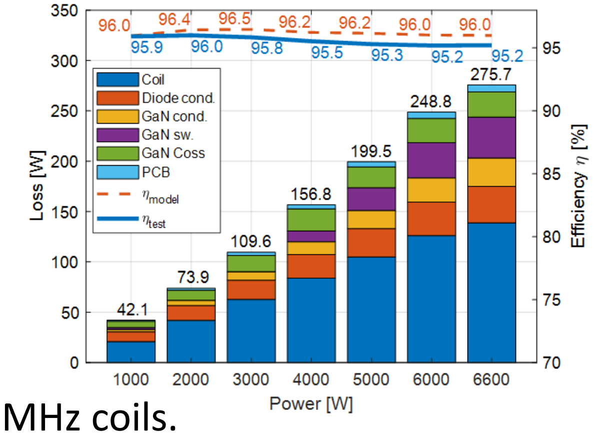
Multi-Receiver Wireless Workstation



Multi-receiver 100 W workstation with 92% end-to-end efficiency

High Frequency Wireless EV Charger





Low-profile, self-resonant 3 MHz coils.

95.2% efficiency at 6.6kW

Cryogenically-Cooled 1 MW Ultralight Inverter

❑ **Partners**

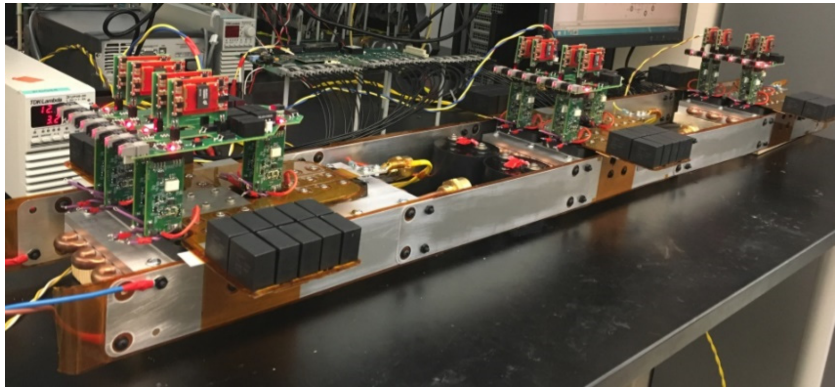
- ➢ NASA, Boeing

❑**Technical Objectives**

- ➢ 99.3% efficiency
- ➢ 26 kW/kg specific power
- ➢ Inverter technologies to be scalable and reliable
- ➢ Cooled at -200°C with LN_2
- ➢ Input DC voltage level of 1000 V and AC output frequency range of 200-3000 Hz
- ➢Meet stringent PQ and EMI requirements

❑ **Faculty**

- ➢F. Wang, L. Tolbert, B. Blalock, D. Costinett, K. Bai



1 MW prototype with LN_2 cooling

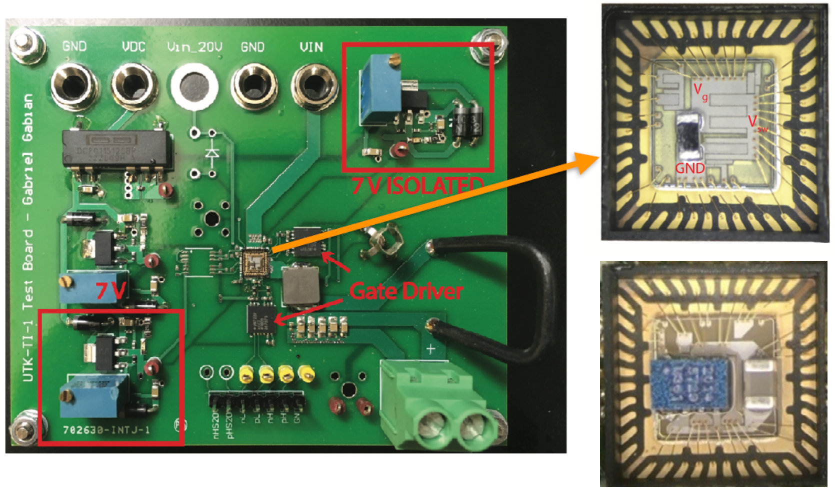
High Current Battery Charger Integrated Circuits

Project Objectives

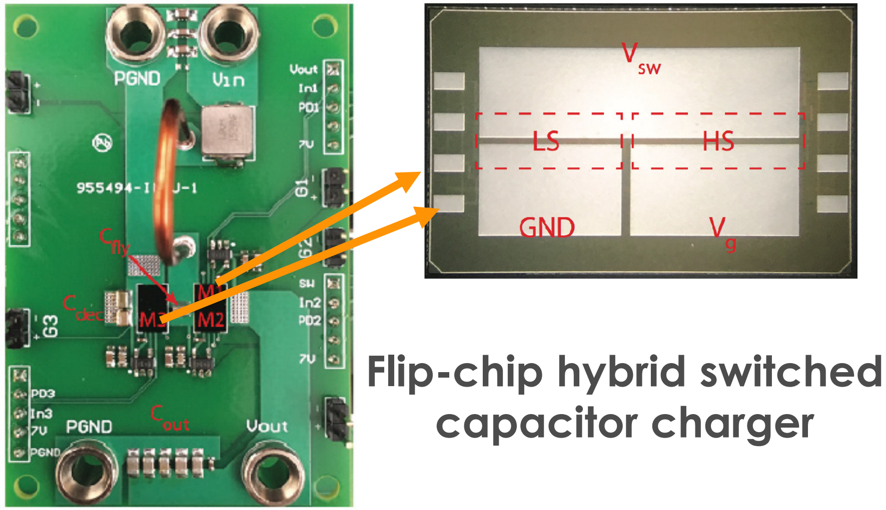
- Increase continuous charging power of monolithic solution to 40W (2x increase over existing parts)
- Develop integrated charging and balancing for multi-cell packs

Achievements

- Optimized novel hybrid switched capacitor topology for high-current charging
- Demonstrated 40W charging using silicon integrated circuit
- Demonstrated new topology with independent control of charging and balancing currents for multi-cell packs



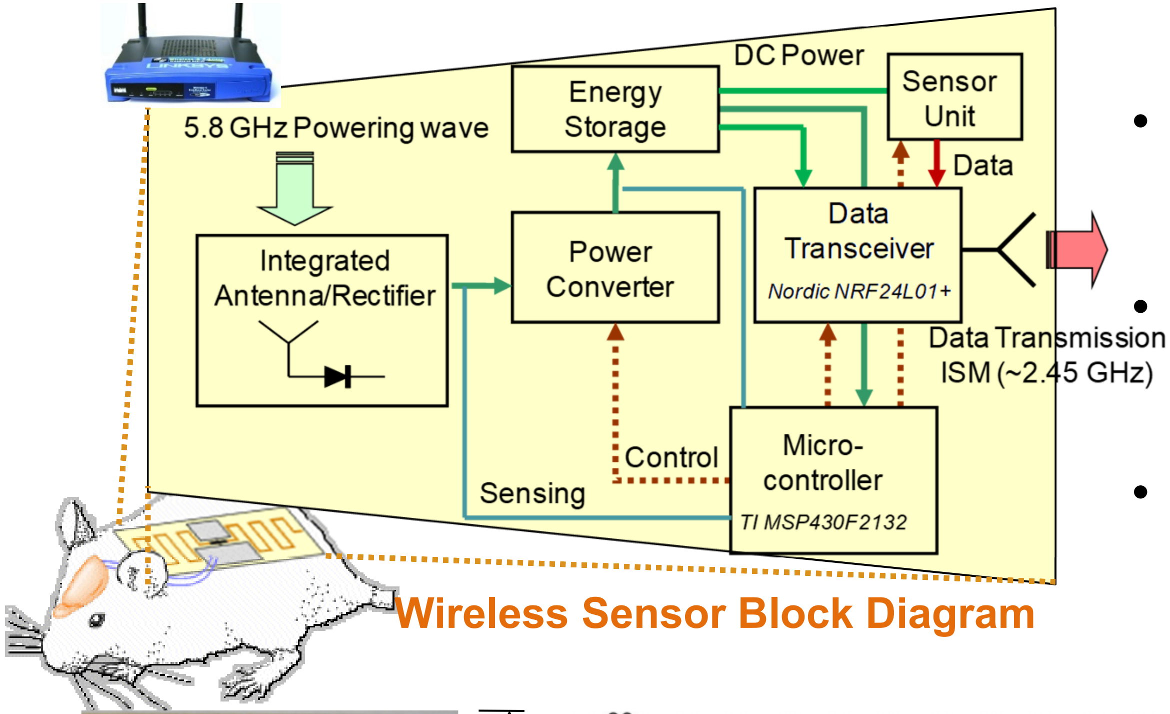
Co-packaged high-current chargers



Flip-chip hybrid switched capacitor charger

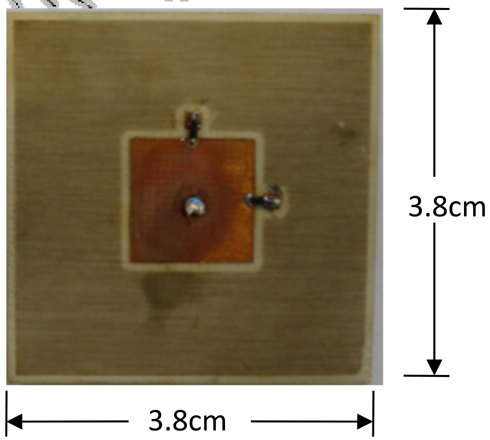
G. Gabian, J. Gamble, B. Blalock and D. Costinett, "Hybrid buck converter optimization and comparison for smart phone integrated battery chargers," 2018 IEEE Applied Power Electronics Conference and Exposition (APEC), 2018

Medical Devices: RF Energy Harvesting

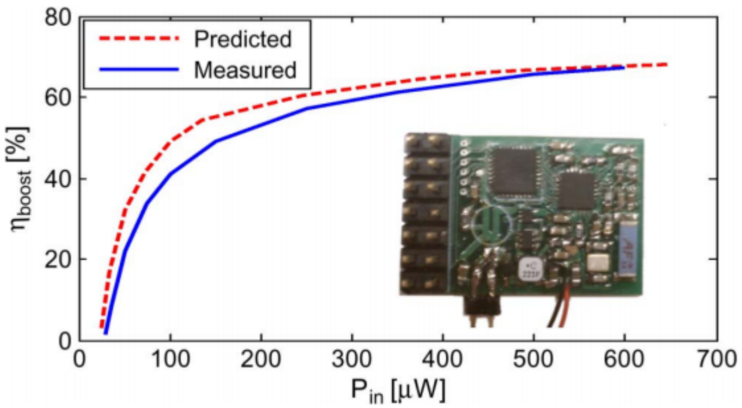


Wireless Sensor Block Diagram

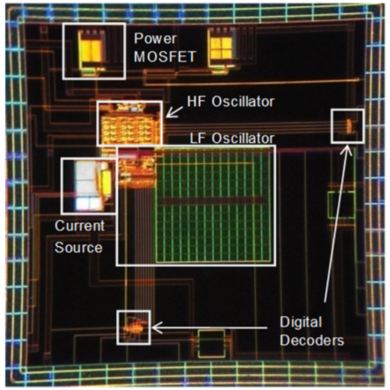
- Powered entirely by commercial 5.8GHz WiFi adapter
- Able to operate with ~5µW power using only off-the-shelf components
- Able to operate down to 100nW using a custom IC



5.8 GHz patch rectenna



OTS Power Converter Design



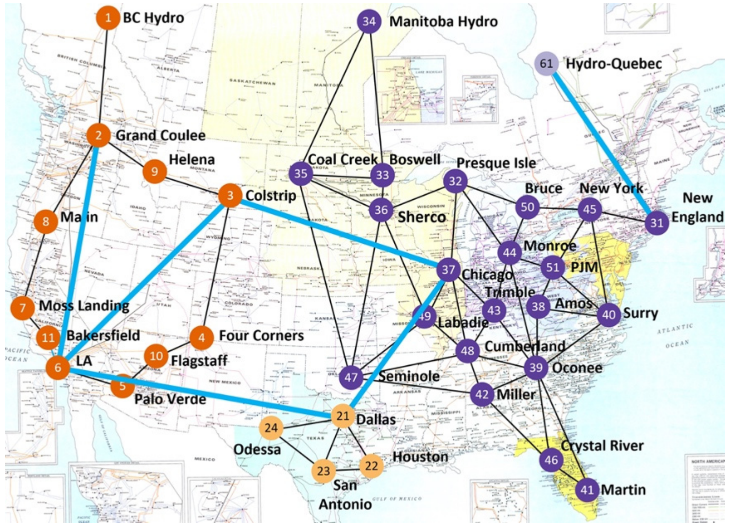
P_{out} (µW)	η_{boost} (%)
0.16	18.05
0.52	35.13
1.29	47.36
2.57	53.58
8.81	65.16
23.86	71.14
60.66	75.70
123.6	79.06

Custom harvester IC implementation

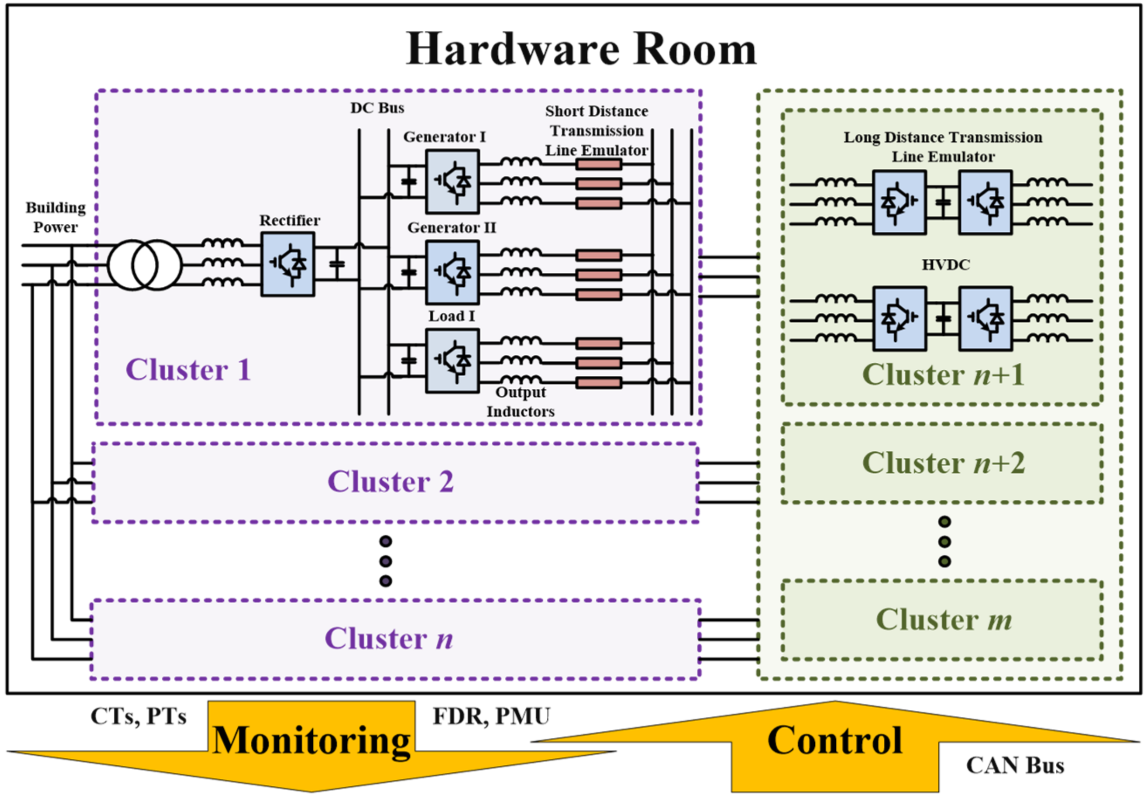
Popovic, Z.; Falkenstein, E.A.; Costinett, D.; Zane, R., "Low-Power Far-Field Wireless Powering for Wireless Sensors," *Proceedings of the IEEE* , vol.101, no.6, pp.1397,1409, June 2013

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

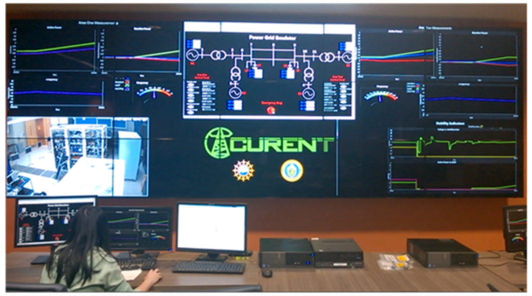
Grid Emulation with Power Electronics Hardware Testbed

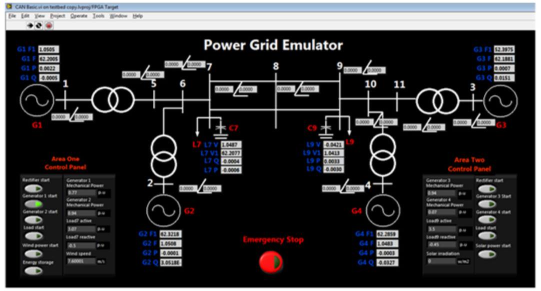


North American CURENT system with WECC, EI, and ERCOT systems connected via multi-terminal HVDC overlay, and high penetration (>80%) of renewable energy sources

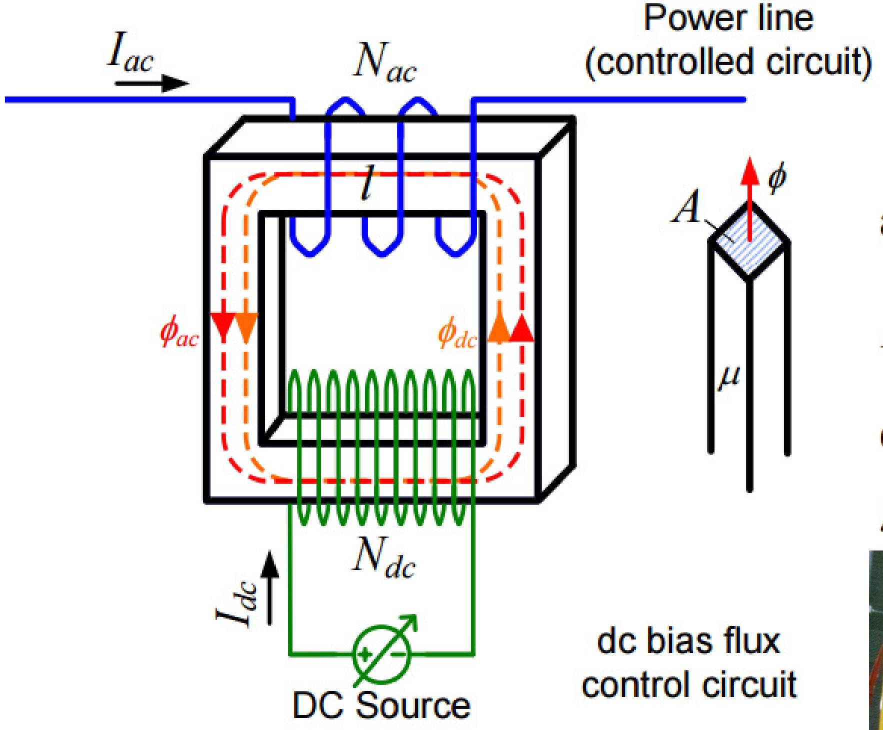


Visualization and Control Room





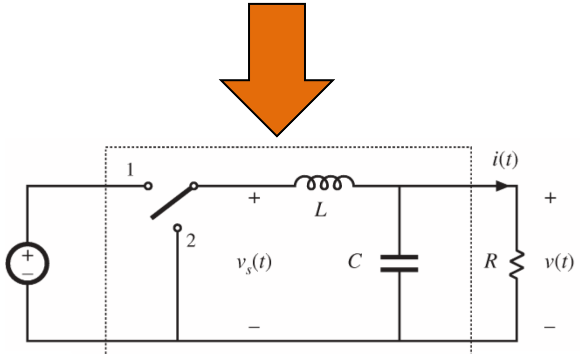
Power Transmission: Saturable Reactor



Power line
(controlled circuit)

dc bias flux
control circuit

DC Source



ac circuit inductance :

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

controlled by dc circuit current :

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