TSTE25 Power Electronics

Lecture 1

Tomas Jonsson
ICS/ISY

LINKÖPING UNIVERSITY

Outline

- Course introduction
- Power electronic systems from nW to GW [Ch 1]
- Diode device characteristics
  - Semiconductor theory
  - Data sheet info
- Rectifiers
  - Single phase
  - Current commutation

Lars Eriksson

- Education
  - M. Sc. LiU Y-Program 1995
  - Lic. Vehicular Systems, 1997
  - PhD Vehicular Systems, 1999

- Work Experience
  - Post Doc ETH, Zürich, Switzerland 2000-2001
  - Engine and Vehicle propulsion research 1995-
  - Hybrid Electric Vehicle research 2008-
  - LiU representative in Swedish Electromobility Centre 2015-
  - Battery research 2016-
  - Power electronics research 2019-

Tomas Jonsson

- Education
  - M. Sc. degree in Electrical Engineering from the Lund Institute of Technology, 1987
- Work Experience
  - Master thesis work at ABB HVDC Ludvika
  - HVDC system development, Ludvika (1988 – 1998)
  - ABB Corporate Research HVDC & FACTS development projects, Västerås (1999 - 2009)
  - ABB Grid Systems, Senior Principal Engineer, R&D project manager, mentor of R&D group in Chennai India (2009 – 2016)
  - Teaching at Liu since 2015.
  - Research project on converter and battery system for heavy trucks
  - Research project on high current MOSFET for battery control
  - Employed by Scania since January -22.

Course Contents

- Course web page on ISY Server, Lisam course room
- 7 Lectures
  - Introduce and explain material
- 6+2 Tutorials
  - Problem solving
  - MATLAB/Simulink and Arduino Due tutorials
- 3 labs (Signup required)
  - Lab 1: DC/DC Buck & Boost conv in Simulink
  - Lab 2: AC/DC conv & MOSFET drive in Simulink and power circuit PCB
  - Lab 3: AC/DC conv harmonics & control on power circuit PCB
- Written exam

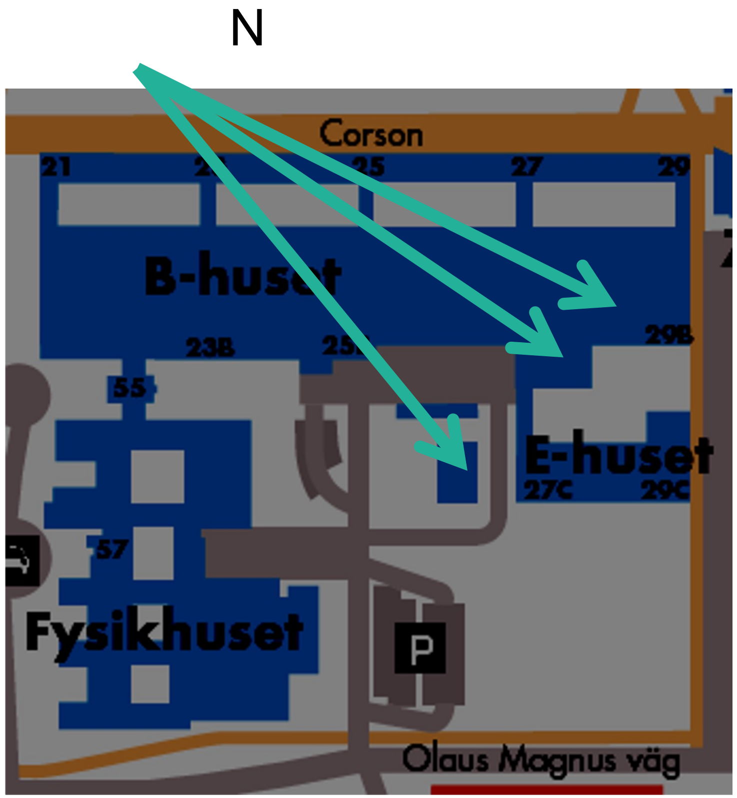
Course staff

Lectures, Tutorials

- Lars Eriksson
- 013 28 44 09
- lars.eriksson@liu.se
- Tomas Uno Jonsson

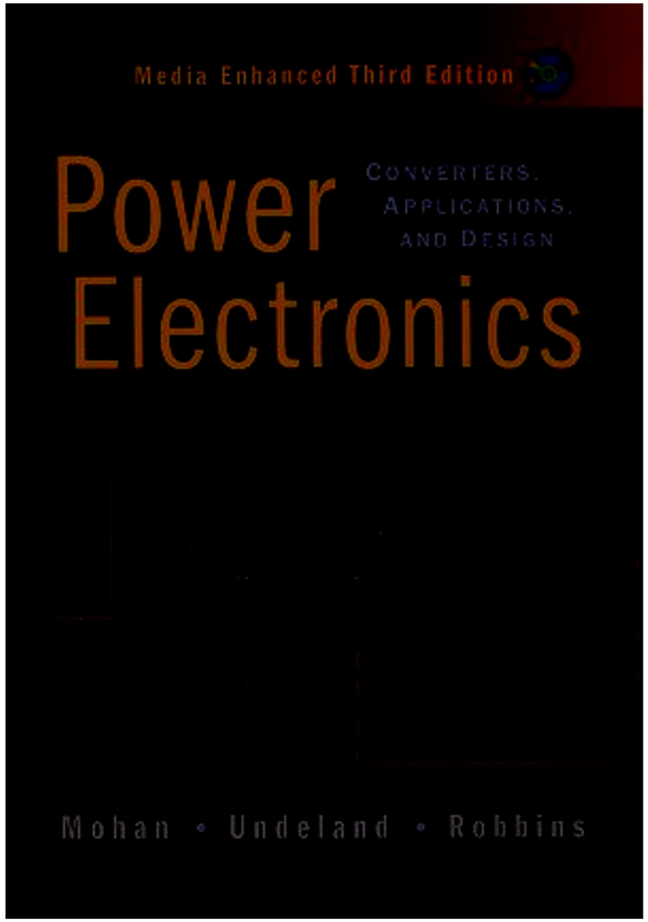
Assistant for Lab’s and Tutorials

- Arvind Balachandran



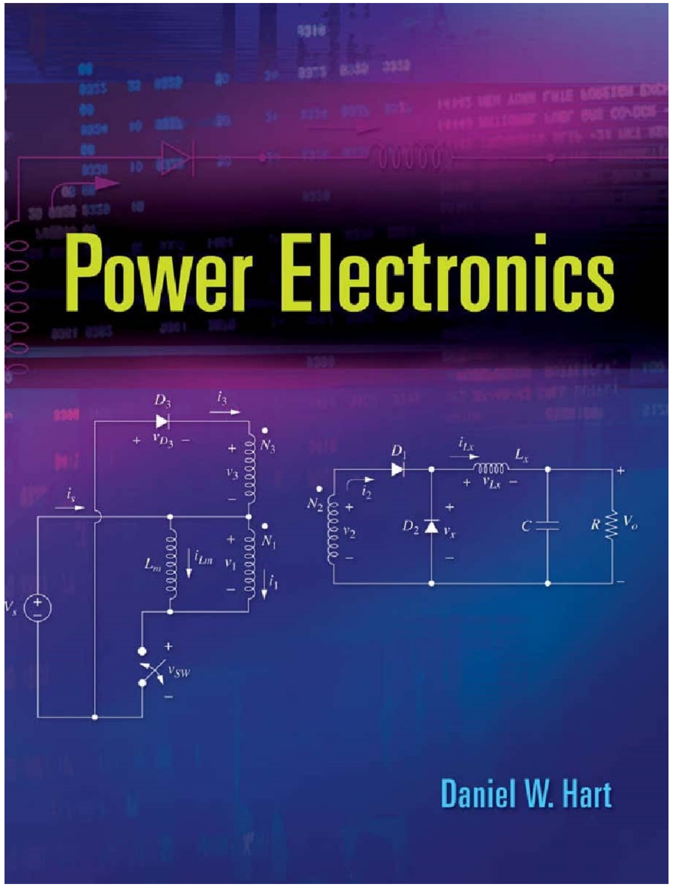
Literature

- Power Electronics:
  Converters, Applications, and Design,
  3rd Edition
- N. Mohan, T. M. Undeland, W. P. Robbins
- ISBN: 978-0-471-22693-2
- Wiley & sons., Inc. 2003
- Will sometimes indicate corresponding Swedish term in {}



Additional litterature

- Power Electronics
- Daniel W. Hart
- ISBN 978-0-07-338067-4
- McGraw-Hill
- Available as pdf at Academia.edu after personal registration at Academia
- No reference from the course is given



Course plan, part 1

	Date	Content	Course book
Lecture 1	28/8	Introduction, Diode rectifiers	Ch 1, 2.1-2.2, (20), 5.1-5.3
Tutorial 1	29/8	Circuit theory, diode rectifier	Ch 3.2
Lecture 2	31/8	DC/DC converters	Ch 7.1-7.4
Tutorial 2	11/9	Simulink introduction, DC/DC Buck & Boost converters	
Lecture 3	15/9	DC/AC inverter, PWM, half/full-bridge inverter	Ch 8.1-8.3
Lab 1	12-13/9	Buck & Boost DC/DC converter	
Tutorial 3	19/9	DC/AC inverter	
Lecture 4	18/9	Power transistors, MOSFET switching, thermal management	Ch 2.4, 22, 29

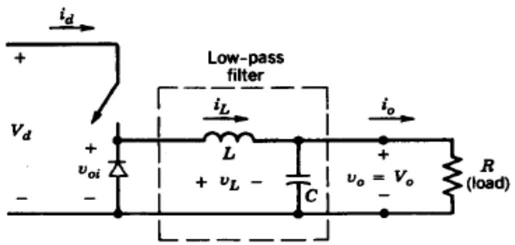
Dates are not updated

Course plan, part 2

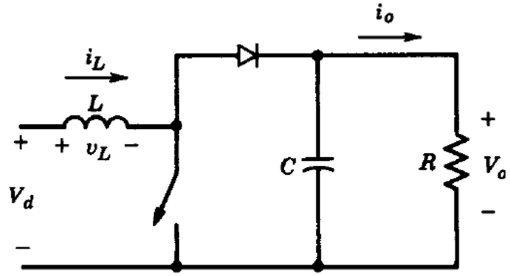
Dates are not updated

	Date	Content	Course book
Tutorial 4	1/9	MOSFET switching, thermal calculations, Simulink introduction for Lab 2	
Lab 2	13-14/9	DC/AC PWM, MOSFET gate control	
Lecture 5	15/9	DC/AC inverter 2, Harmonics	Ch 8.4, 8.5, 8.7
Tutorial 5	16/10	Harmonics	
Lecture 6	19/9	Converter control, Isolated DC/DC converters	Ch 28, 8.6, 27
Lab 3	20-21/9	DC/AC-converter operation and analysis	
Tutorial 6	26/9	Project introduction, Converter control	
Tutorial 7	27-28/9	Exercises	
Tutorial 8	4-5/10	Exercises	
Lecture 7	10/10	Thyristor converters, HVDC technology	Ch 2.3, 10.4, 17
Exam		Written exam	

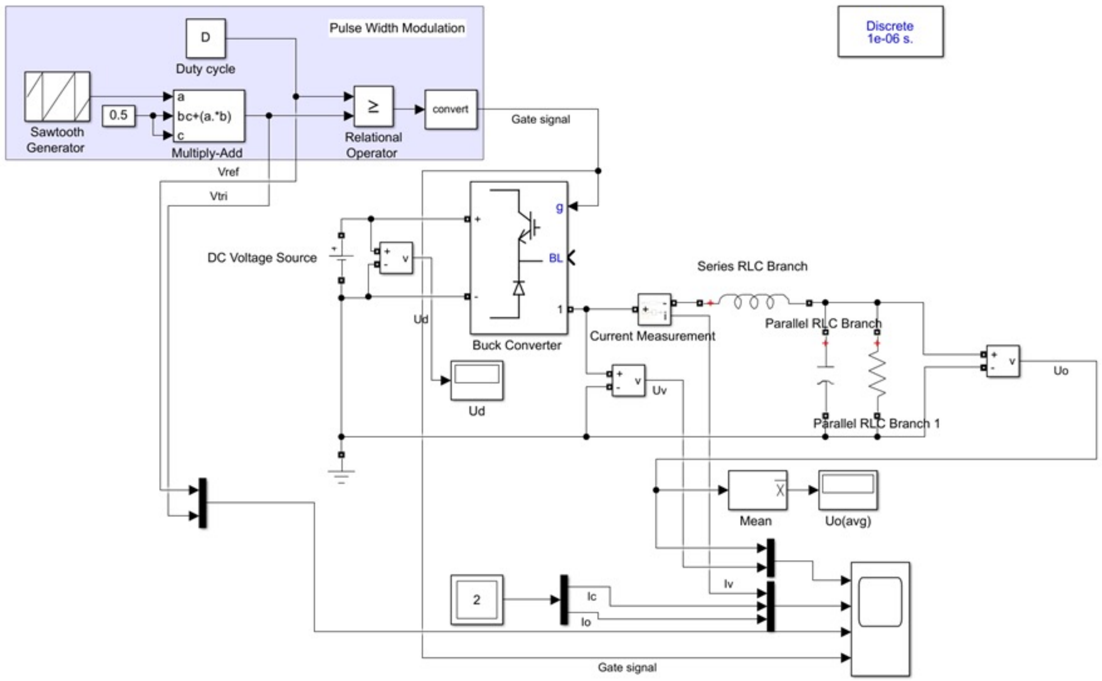
Lab1 DC/DC-conv simulation Matlab/Simulink



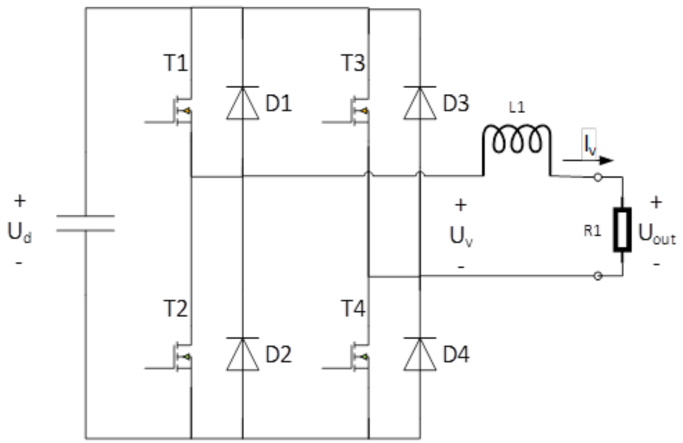
Step-down (Buck) DC/DC-converter



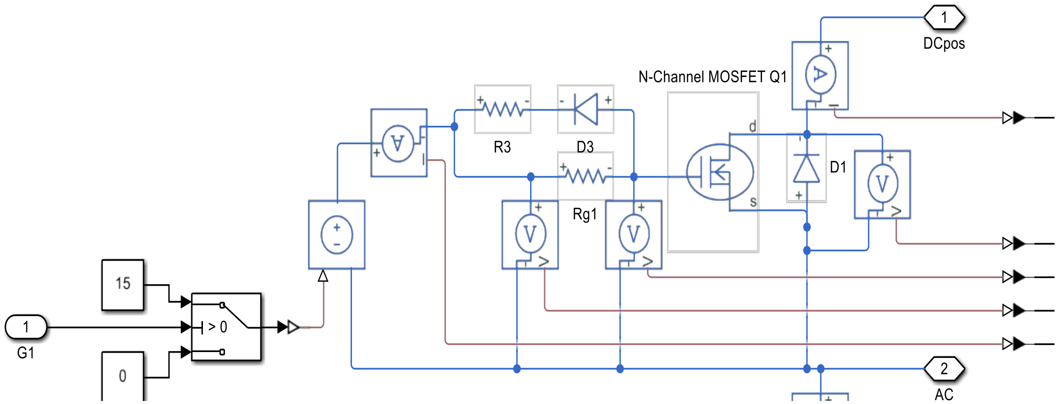
Step-up (Boost) DC/DC-converter



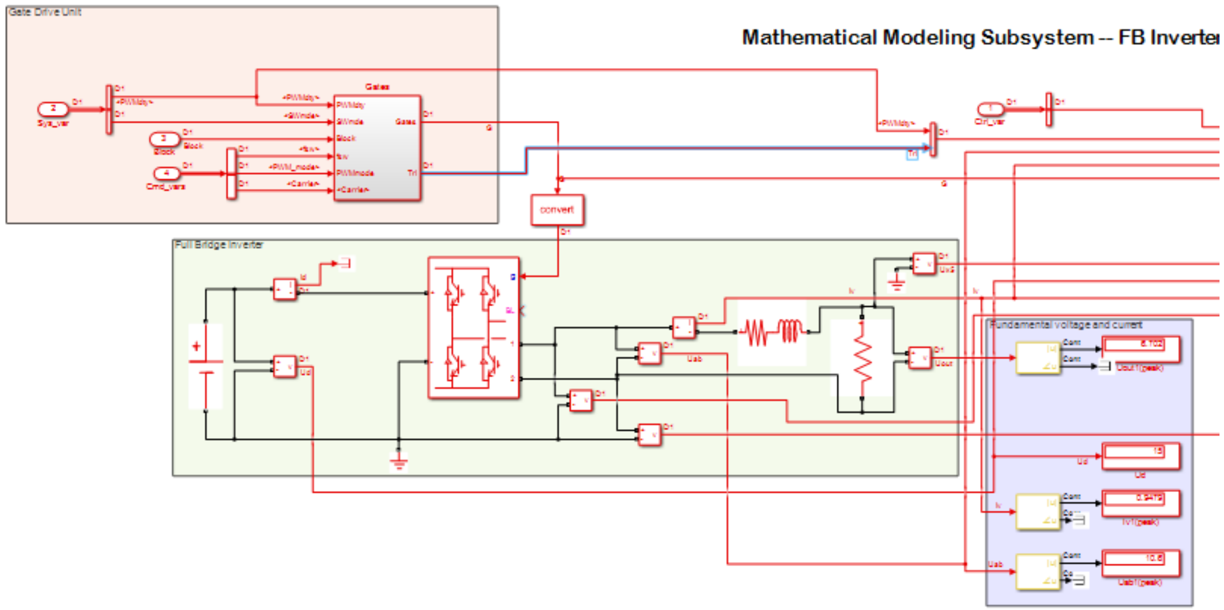
Lab2 MOSFET drive and PWM inverter



Full-bridge PWM inverter



MOSFET based full-bridge inverter with gate drive



Lab3: Harmonics & control of full-bridge inverter

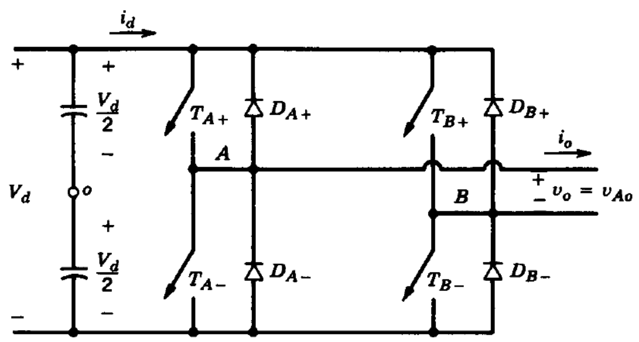
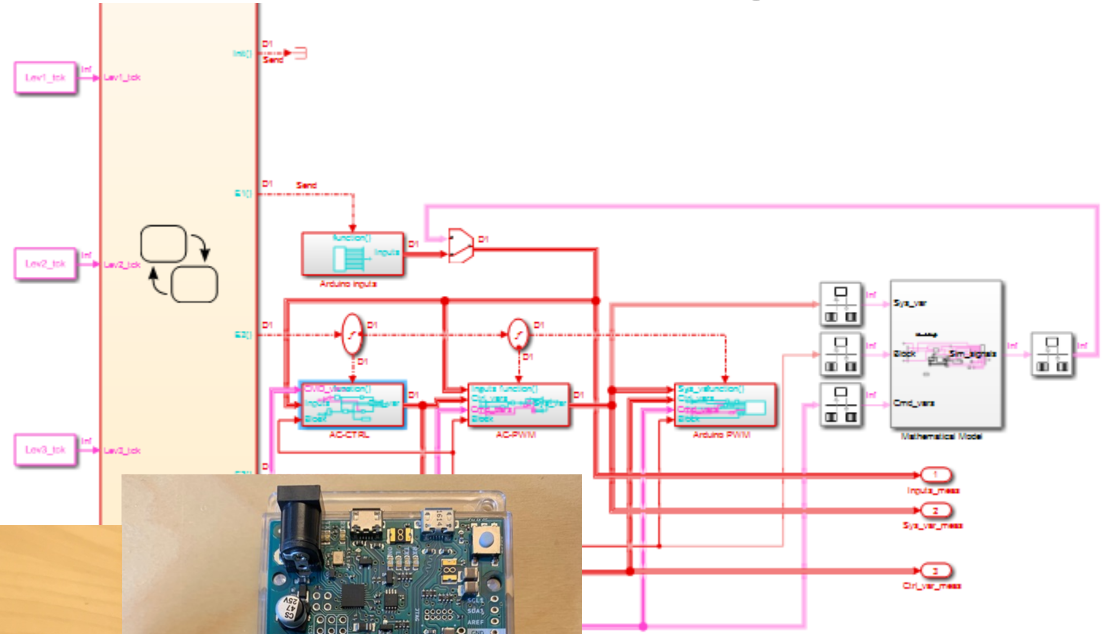
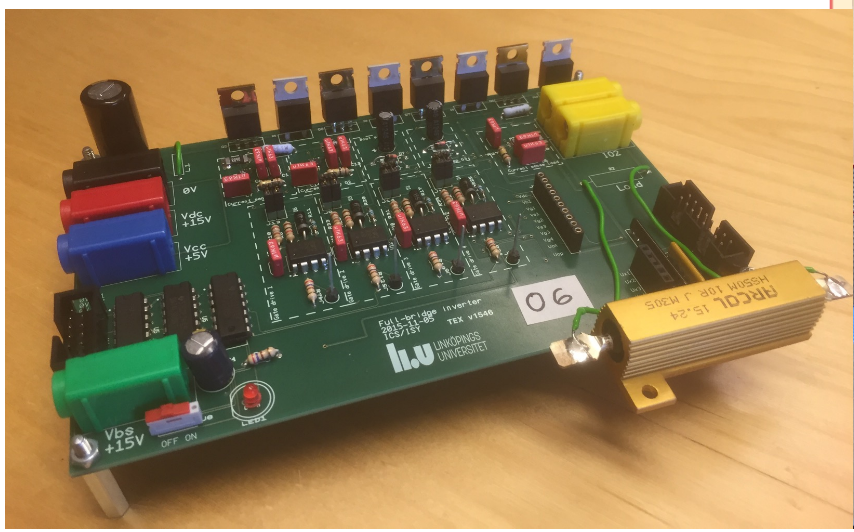
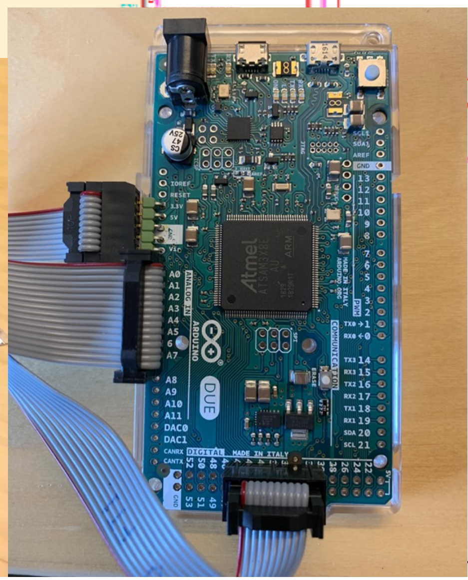


Figure 8-11 Single-phase full-bridge inverter.







MATLAB installation

- MATLAB 2021a
- Simulink
- Simscape
- Simscape Electrical
- Embedded Coder
- Simulink Coder

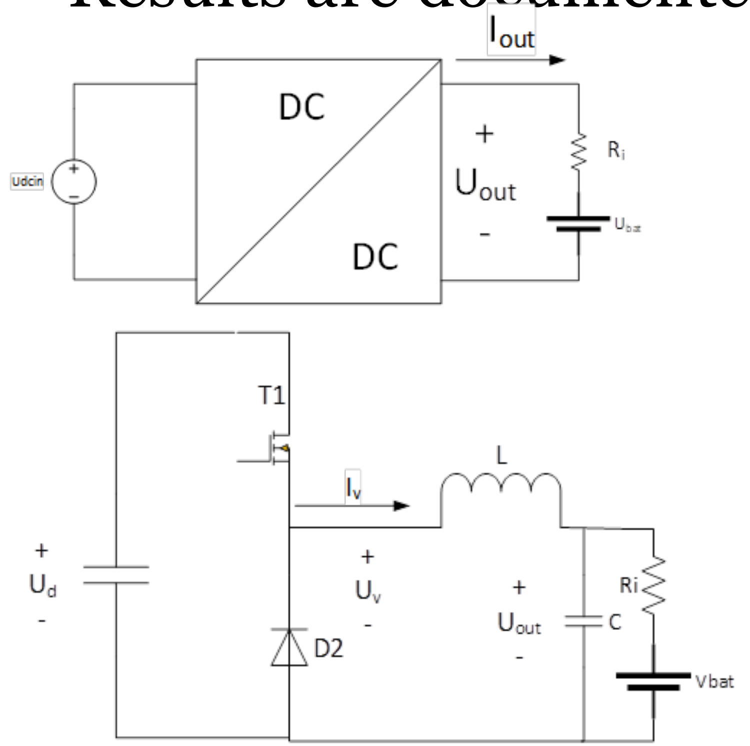
Add-ons

- Matlab support package for Arduino Hardware
- Simulink support package for Arduino Hardware
- MinGW-w64 C/C++ Compiler

Project task

Project task is done in groups of 2 students.
- Simulink simulation
- Hardware setup with Arduino

Results are documented in report.



Specification

Converter type			Buck
I_{out}	A	0.2	Average value
$\Delta I_{out\text{-}pp}$	A	0.02	Current ripple, peak-peak
U_{bat}	V	4.0-5.5	Battery voltage range
R_i	ohm	2.5	Internal resistance
U_{in}	V	12	DC input voltage
I_{qpk}	A	0.25	MOSFET peak current
P_{loss}	W	<0.1	Total MOSFET losses
Tc	C	<50	Max case temp
Tj	C	<100	Max junction temp

Examination

- 3 Lab tasks completed and presented
  - Simulation and measurement tasks
  - Reports submitted in Lisam by 17 Sep, 1 & 8 Oct.
- Written exam
  - Important principles of switching devices.
  - Problem solving as in the Tutorials.

Lecture 1

Power electronic systems [Ch 1]

Power electronics over 18 decades (10^{-8} W - 10^{10} W)

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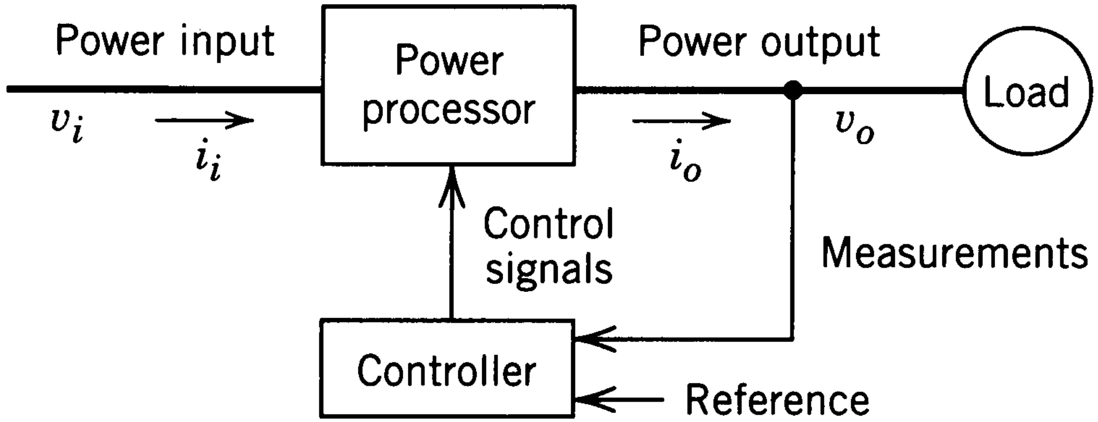
Power Electronic Systems

- Transfer electric power from source into load, controlling voltage/current applied to the load

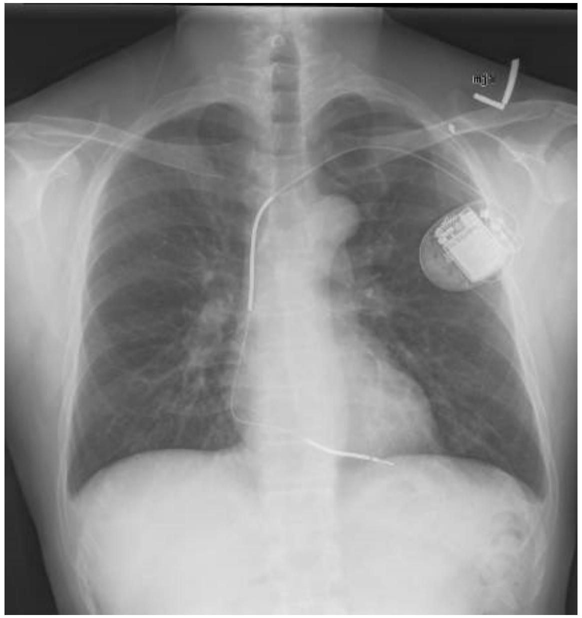


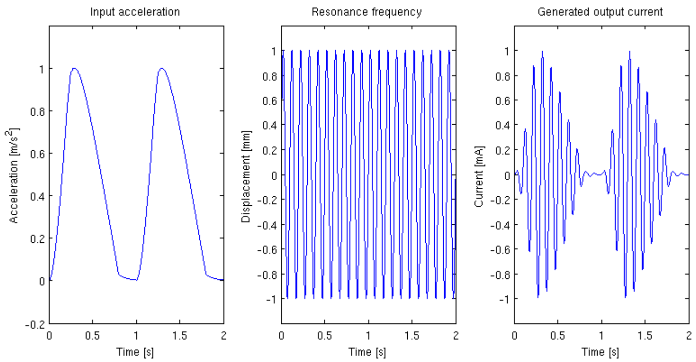
Power electronic systems

- Power conversion
  - Frequency transformation, e.g. AC to DC, DC to AC, AC 50Hz to AC X Hz
  - Voltage level transformation, 230V to 12V
  - Current control/limitation
  - Power flow control, charging v.s. discharging
  - Control related to load variations
  - Control related to source variations

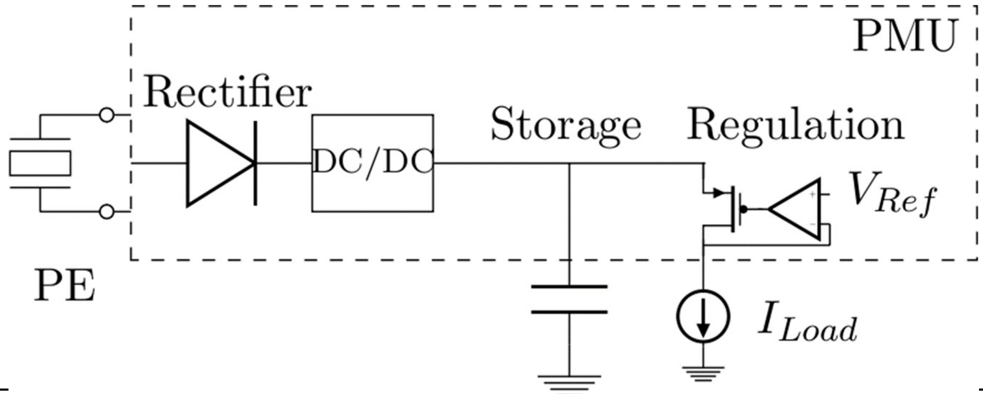
MEMS for pace maker power supply

- Energy harvesting from human heart vibrations for power supply of pacemaker implants.





Requirement	Value
Power	300 nW
Output voltage	300 mV



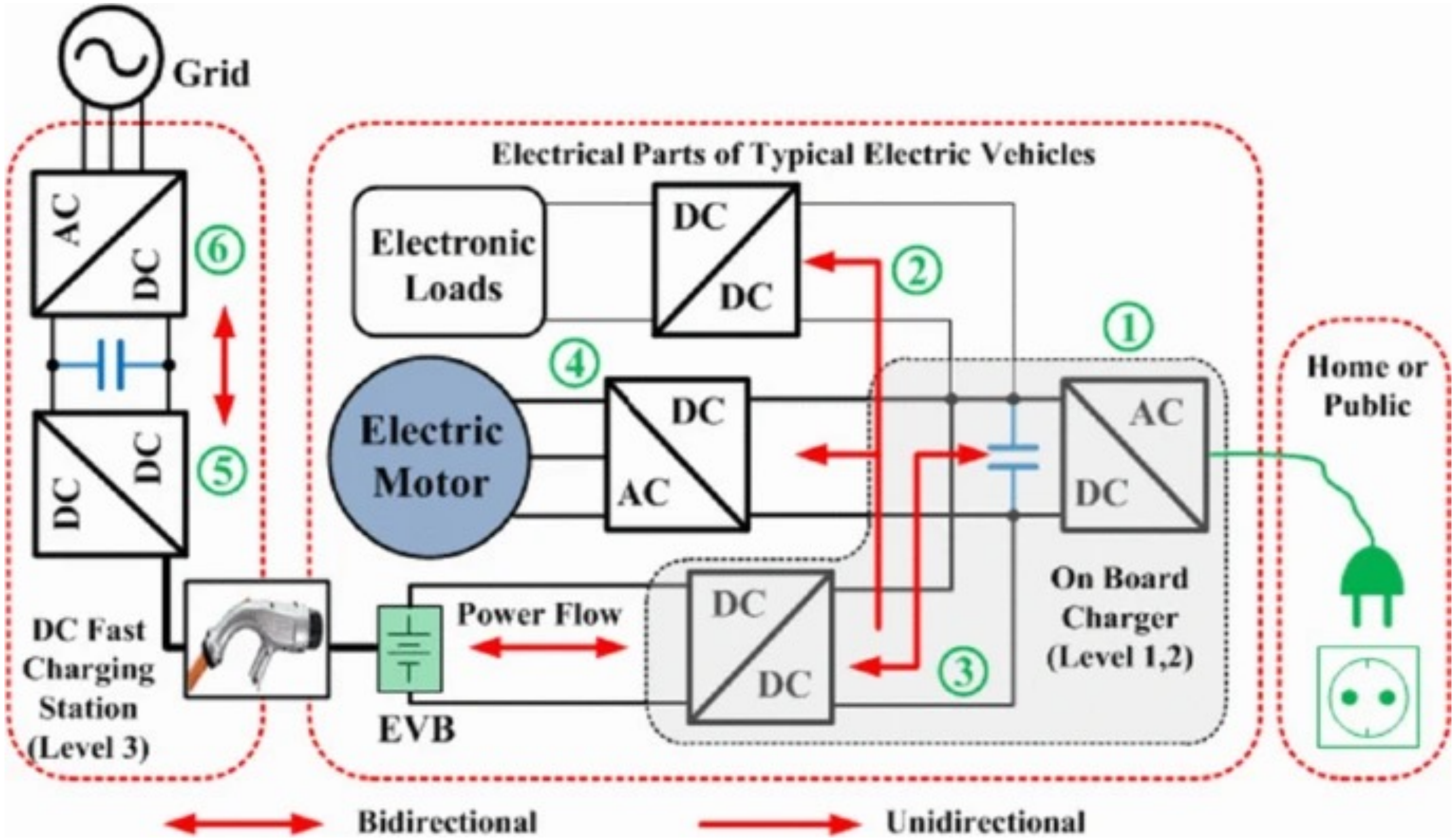
MEMS = Micro electro mechanical systems

Battery charging

- AC-DC converter
- Power conversion from AC power source to DC load
  - Battery
  - Mobile phone …

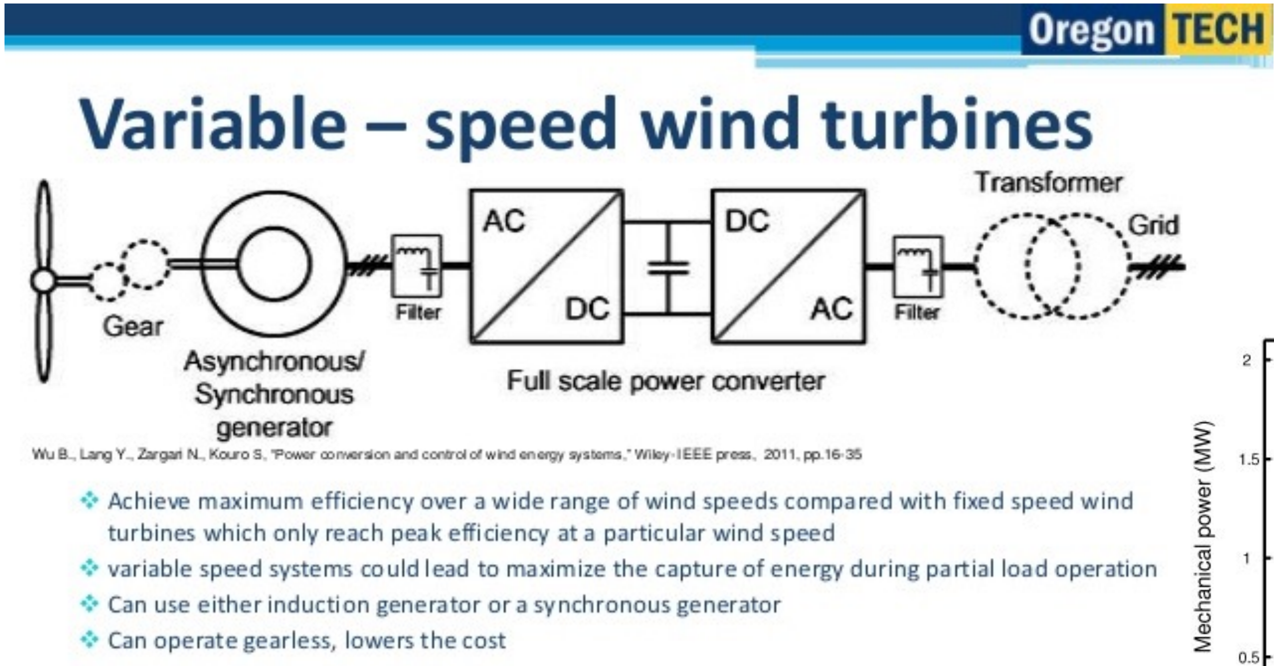
Electric Vehicle battery charger

P = 2 kW – 150 kW



Brenna, M., Foiadelli, F., Leone, C. *et al.* Electric Vehicles Charging Technology Review and Optimal Size Estimation. *J. Electr. Eng. Technol.* **15**, 2539–2552 (2020).

Wind turbine converter control



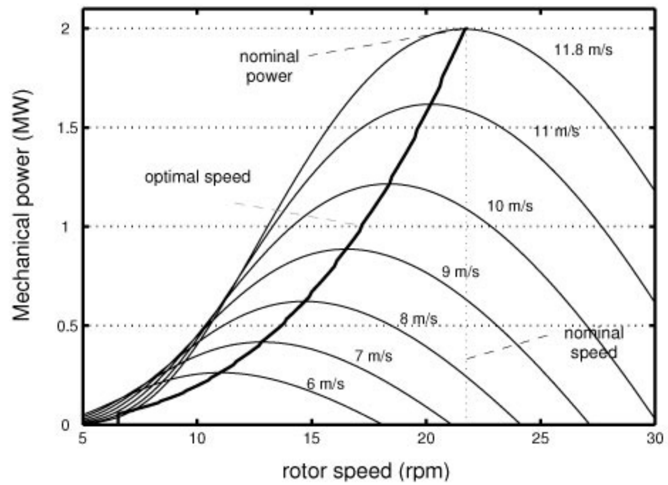
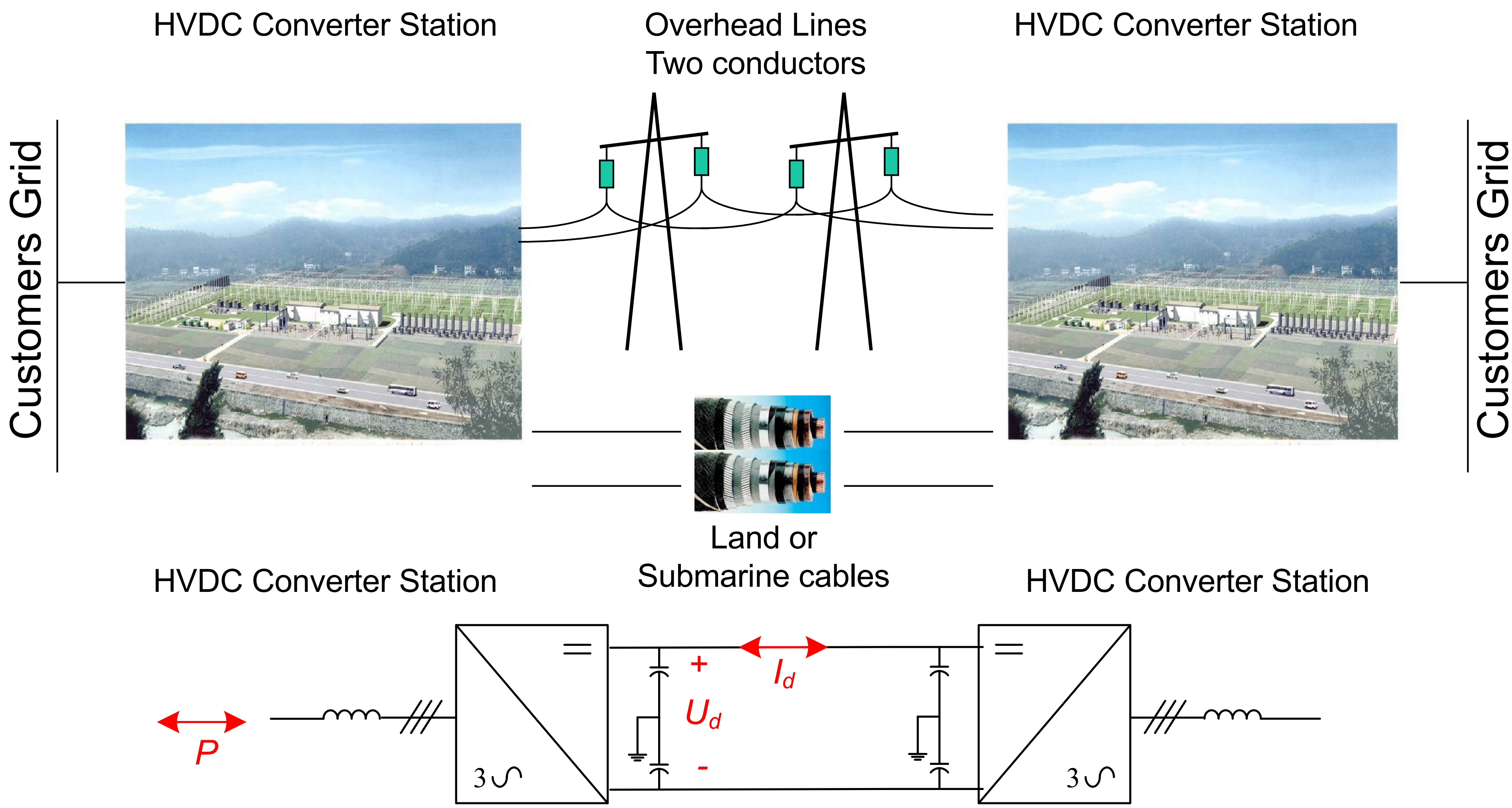


Fig. 8 Output power for different values of wind speed (m/s).

Wind turbine speed/power control P=5 MW

HVDC Transmission System



HVDC power transmission P = 10^{10} = 10 GW
(±800 kV, 6 kA)

Goals of the power transformation

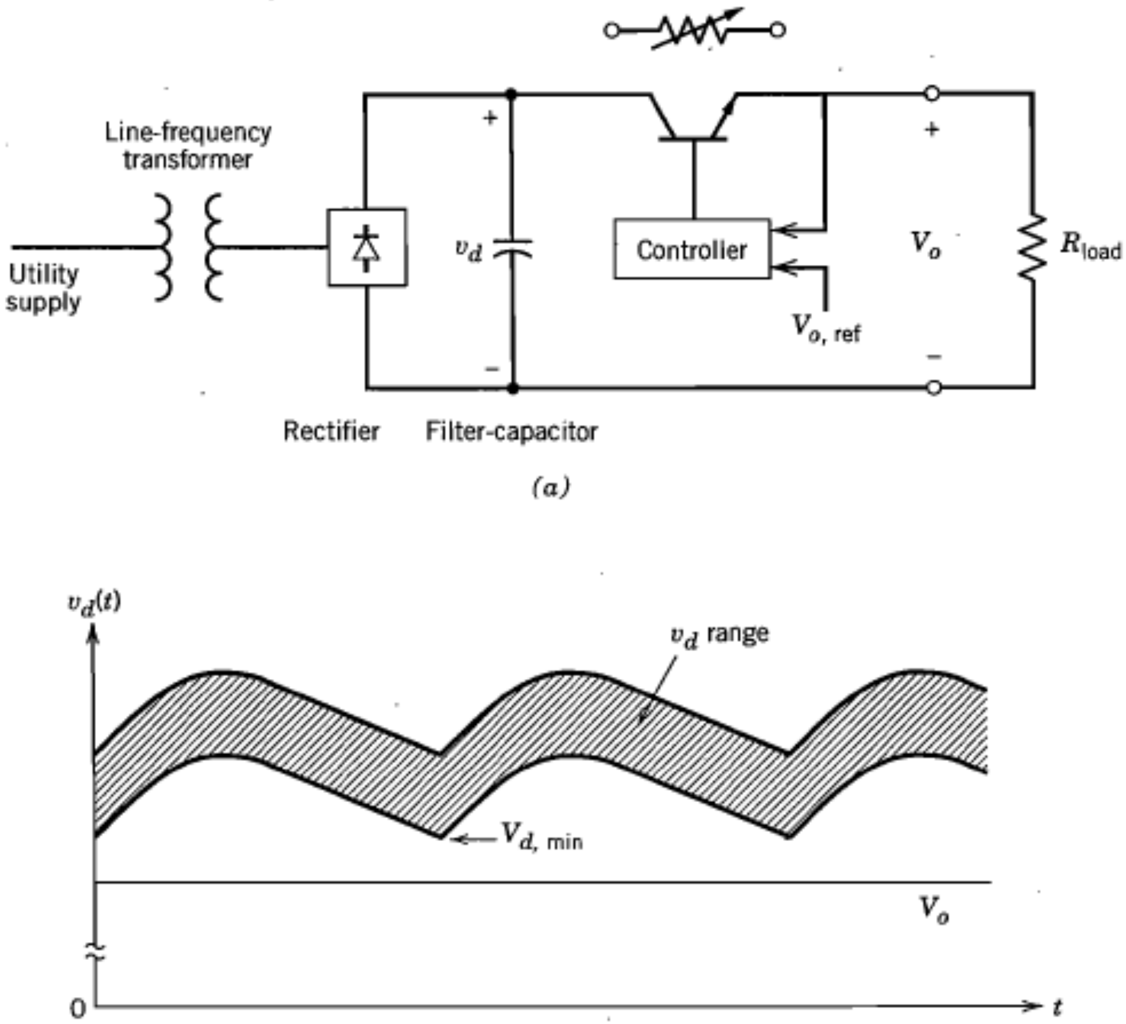
- High efficiency

$$\eta = \frac{P_{out}}{P_{in}} \approx 1$$

- Accurate output voltages/currents
  - Voltage/current ripple
  - Correct for varying load impedance
- Small size
- Low cost
- :

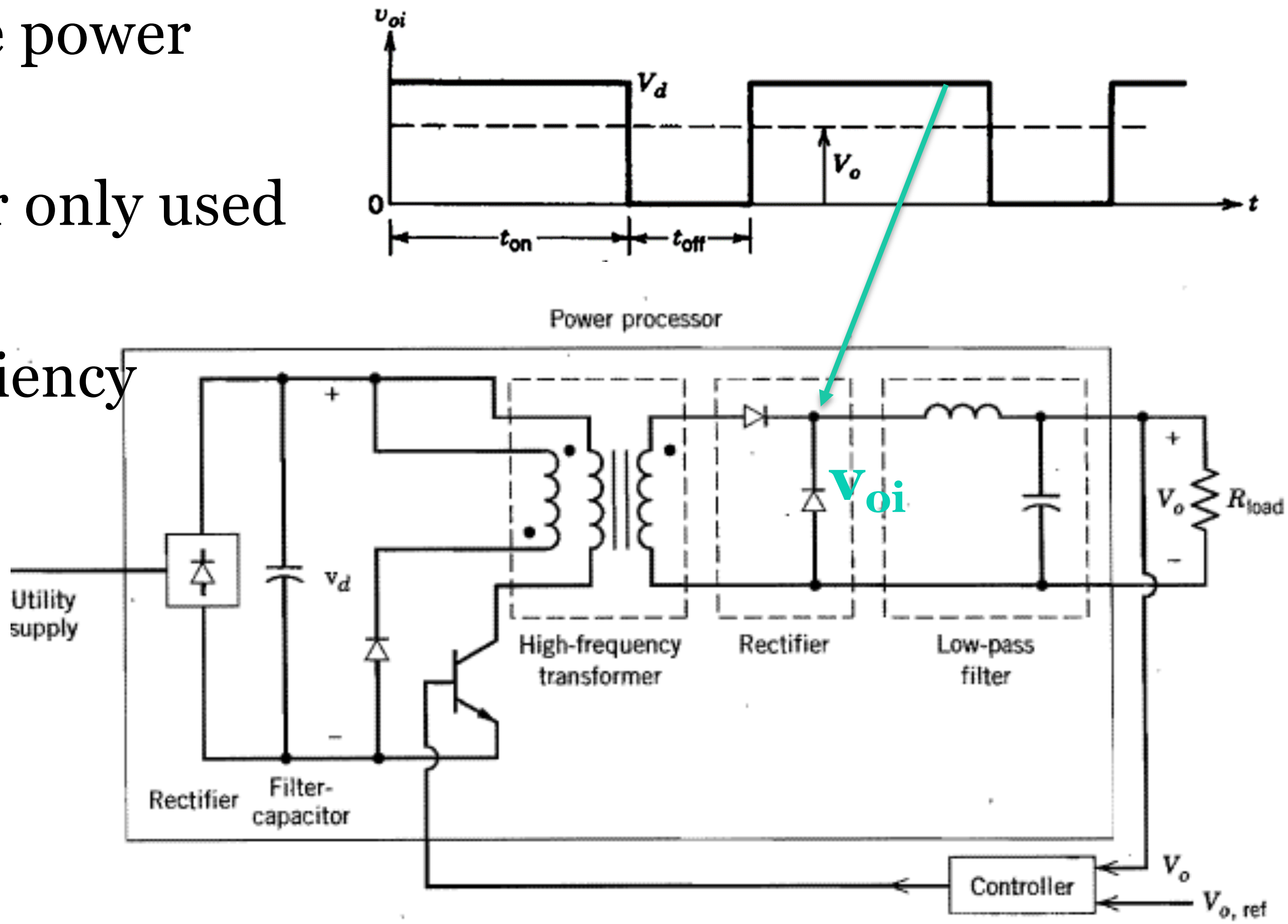
Example 1: Linear Power Supply

- Goal
  - Fixed DC voltage
  - Accept variation on input voltage
- Linear power supply
  - Adjustable resistor implemented using a transistor
  - Low efficiency, lot of power dissipated in transistor
  - Bulky line-frequency transformer



Example 2: Switched Power Supply

- Switch-mode power supply
  - Transistor only used as switch
  - High efficiency
  - Small size



Goal of power conversion

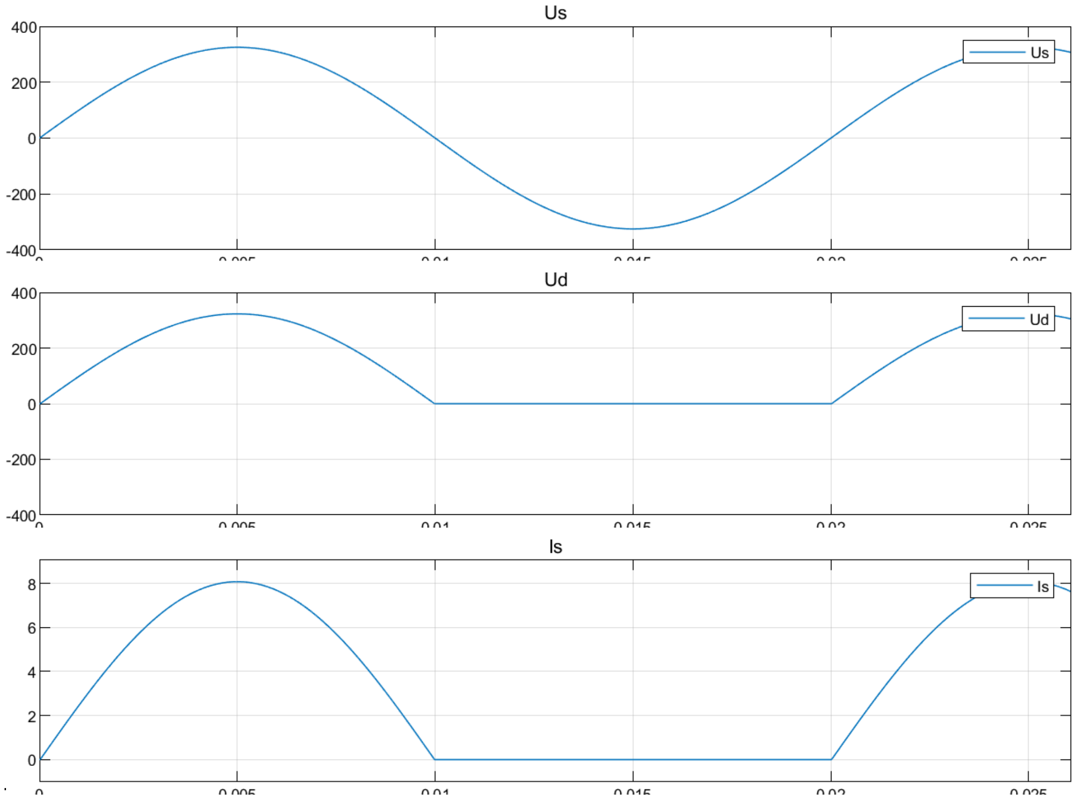
- Translate input voltage into expected waveform of output voltage
- Dissipate little/no power
- Technology: semiconductors, inductors, capacitors, (resistors)
- Should not use semiconductors as resistances

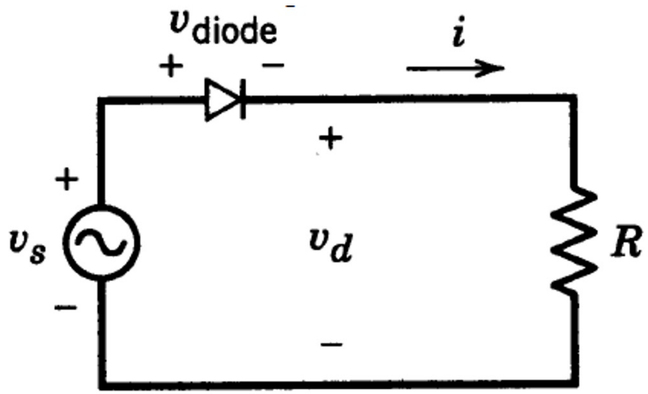
Lecture 1

- Diode device characteristics
  - Semiconductor theory
  - Data sheet info
- Rectifiers
  - Half-wave
  - Full-wave

Half-wave rectifier, resistive load

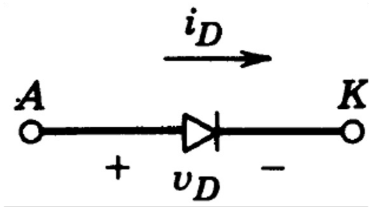
- Large ripple on i and v_d
- Half-wave rectifier

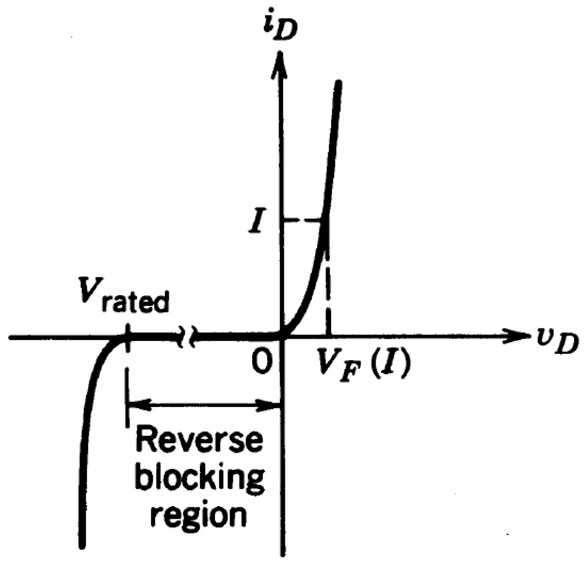




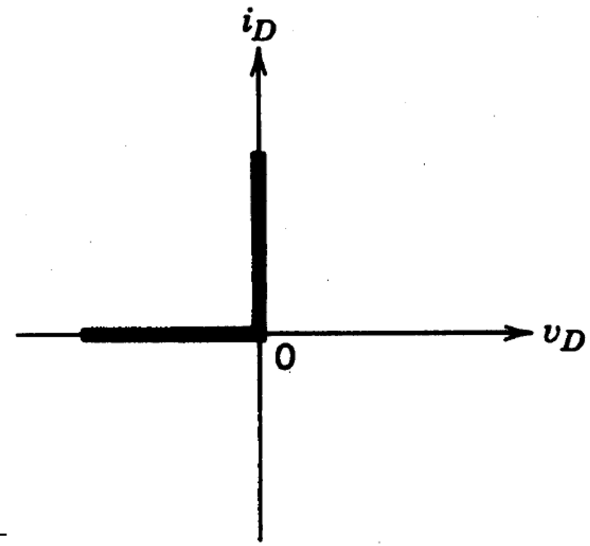
Diodes

- Characteristic



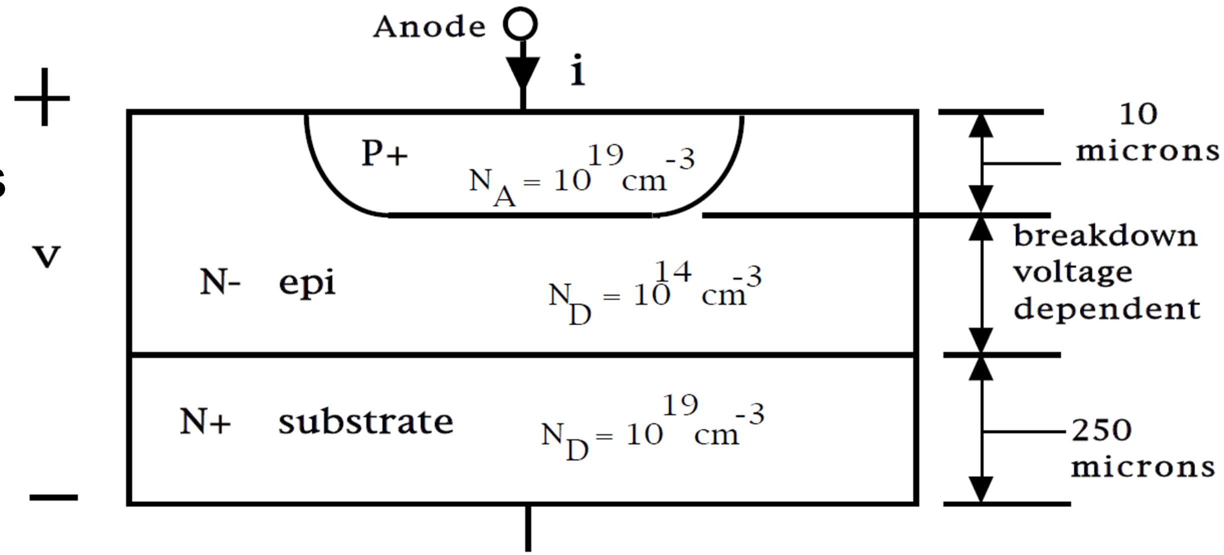


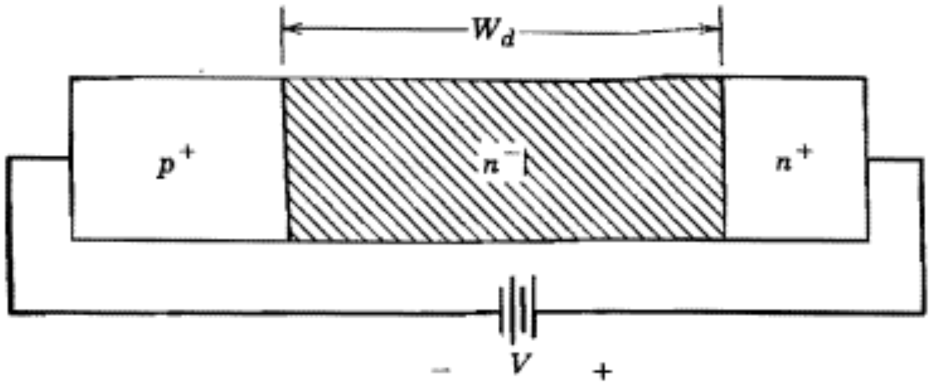
- Idealized characteristic
  - Neglect forward voltage drop
  - Neglect breakdown voltage
  - Turns off only if current drops to 0



Diodes, physical implementation

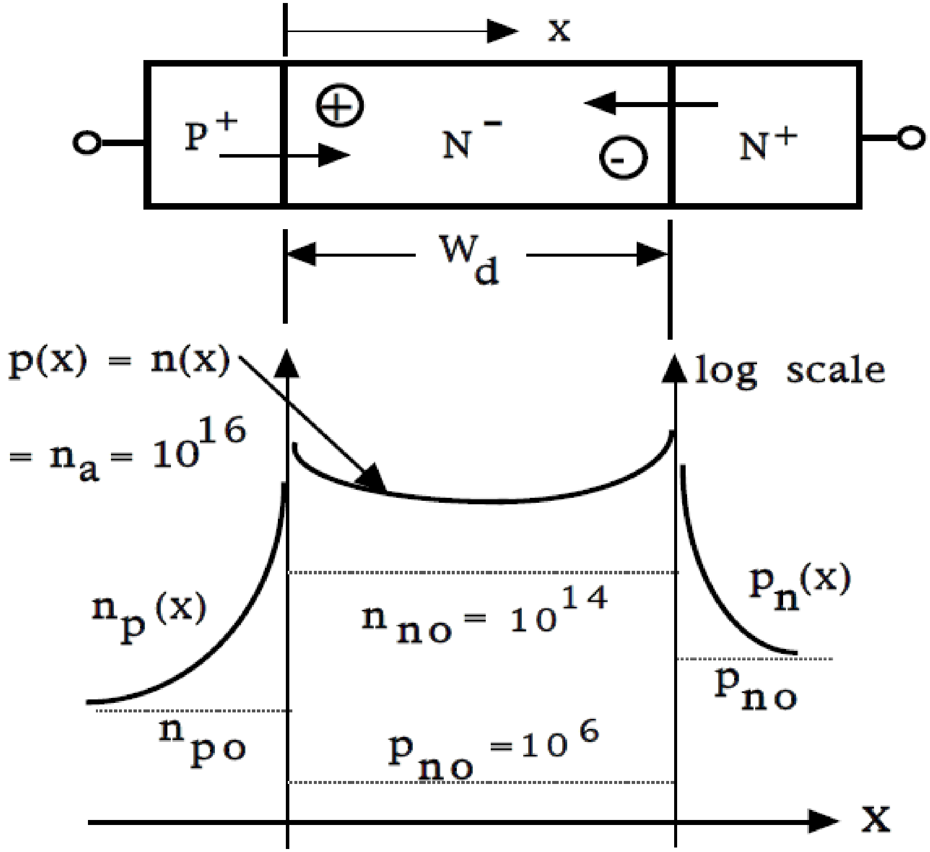
- P-N junction
- Cross-section defines the current capability
- N- epi thickness related to breakdown voltage capability
- Negative bias
  - Depleted (carrier free) N- epi





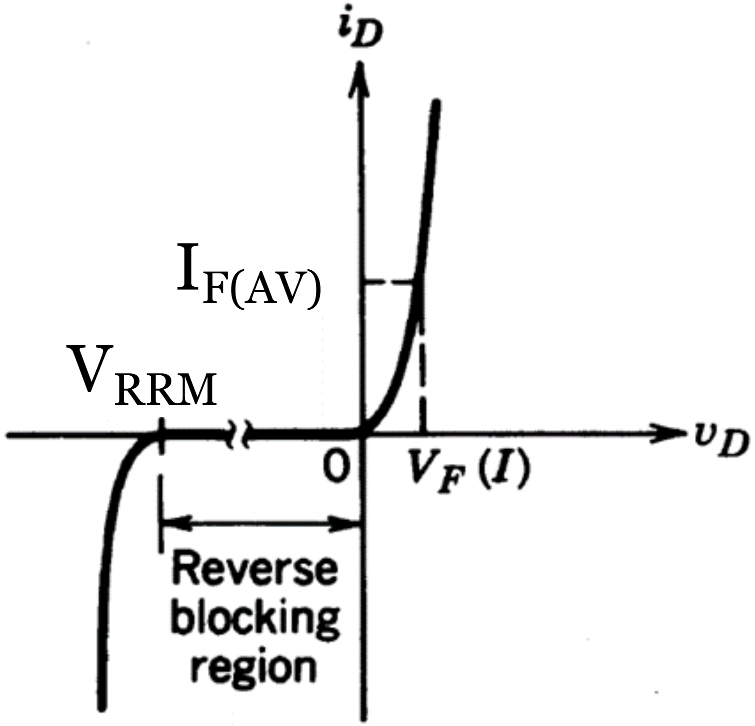
On-state: Carrier injection

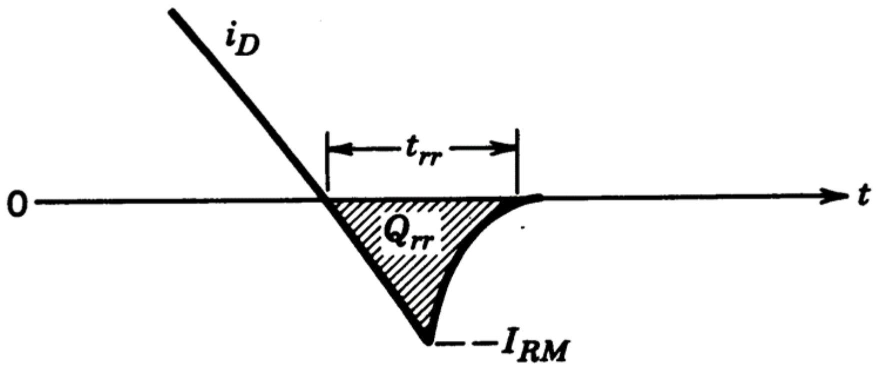
- Forward bias (U>0.6 V)
  - Holes from P^+
  - Electrons from N^+
- Drift region (N^-)
  - High carrier concentration
  - Low on-state resistance (losses)



Diode data sheet

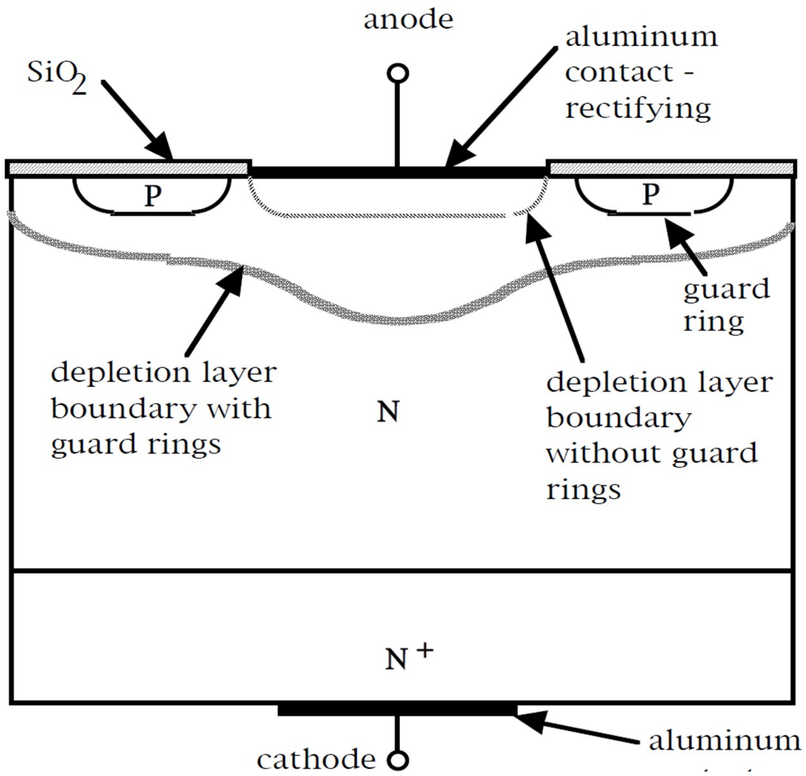
- $I_{F(AV)}$ = Max average forward current
- V_F = Voltage at $I_{F(AV)}$
- V_{RRM} = Repetitive peak reverse voltage
- t_{rr} = Reverse recovery time (turn-off delay)
- Q_{rr} = Recovered charge, $Q_{rr} = \int_0^{t_{rr}} i_D dt$





Schottky diode

- Metal on N-doping
- Low forward voltage ~ 0.3 V
- Blocking voltage range 50 - 100V



Lecture 1

Rectifiers

Half-wave

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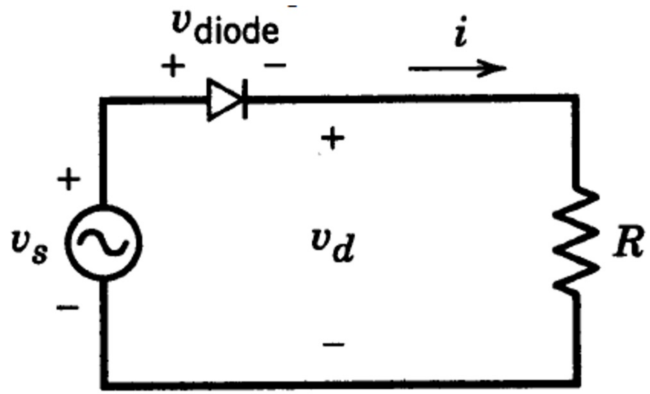
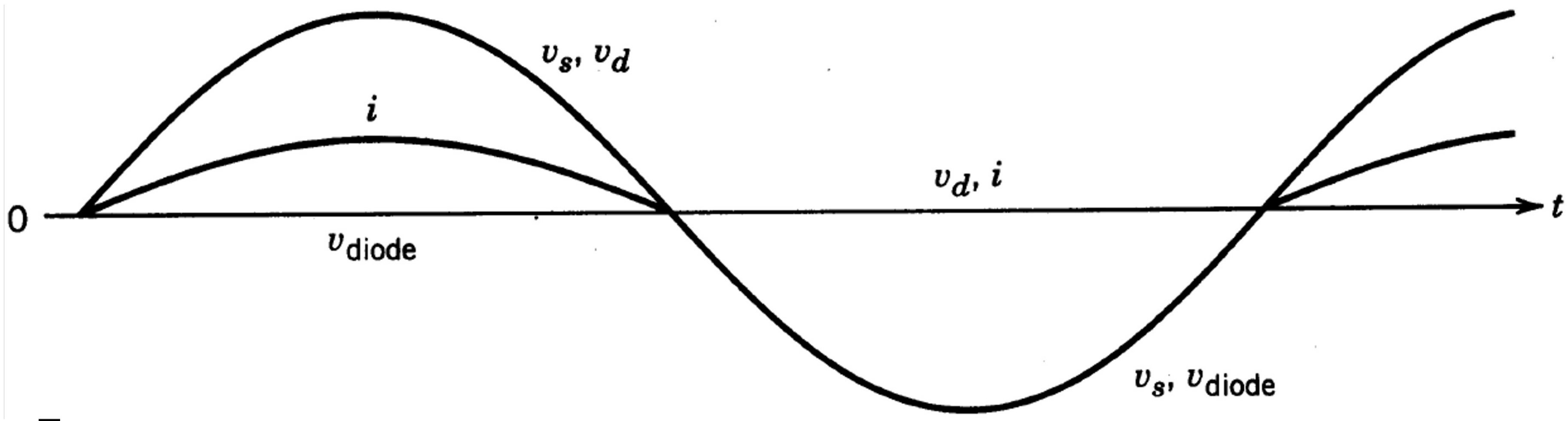
Half-wave rectifier, resistive load

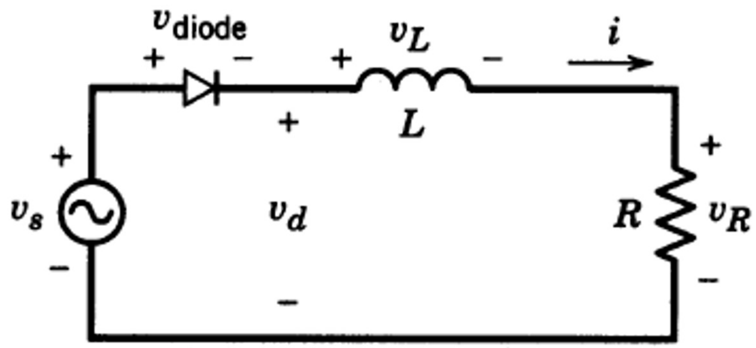
- Large ripple on i and v_d
- Half-wave rectifier

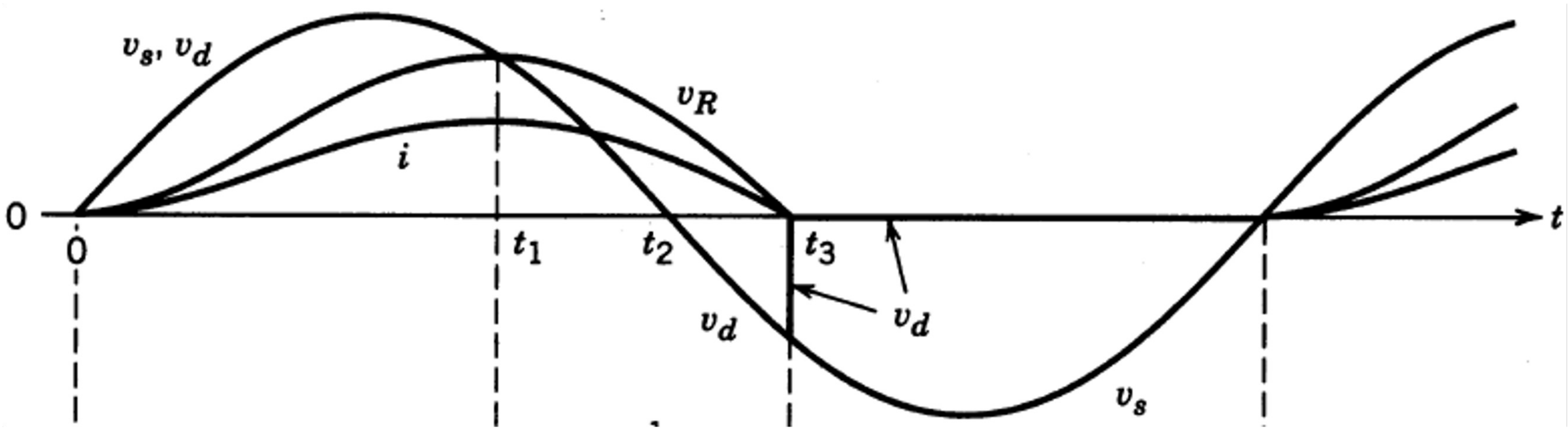




Inductive load

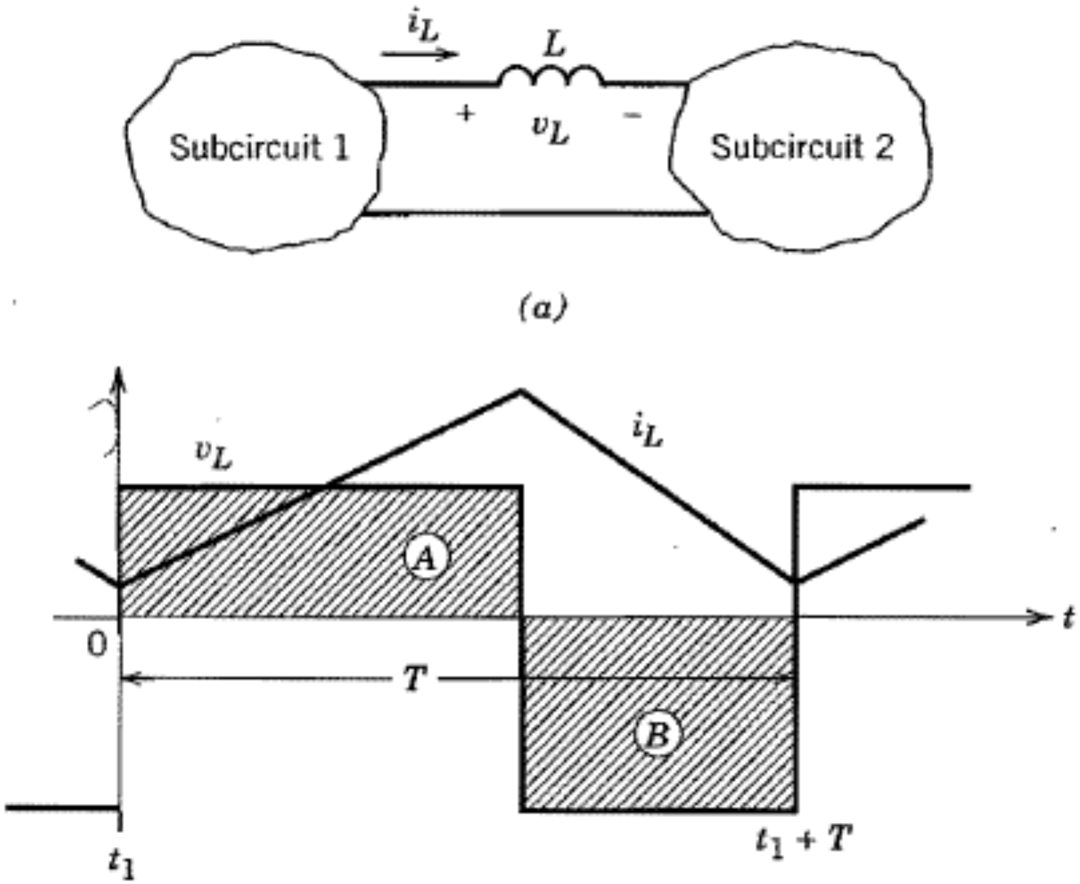
- Inductor causes delay of the current change
- Diode turn-off at $t=t_3$





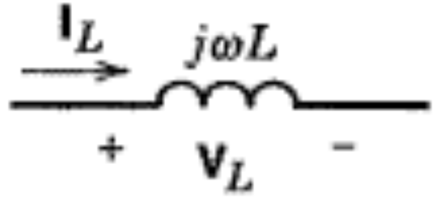
Inductor a current storage

- Voltage is required to change the current
- $v_L>0$: i_L increase
- $v_L<0$: i_L decrease
- Steady state:
  - Voltage-time area A=B
  - Repetitive waveform

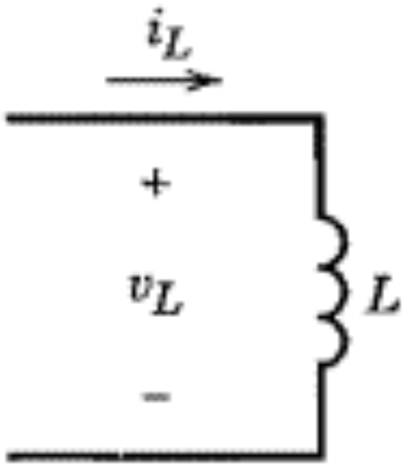


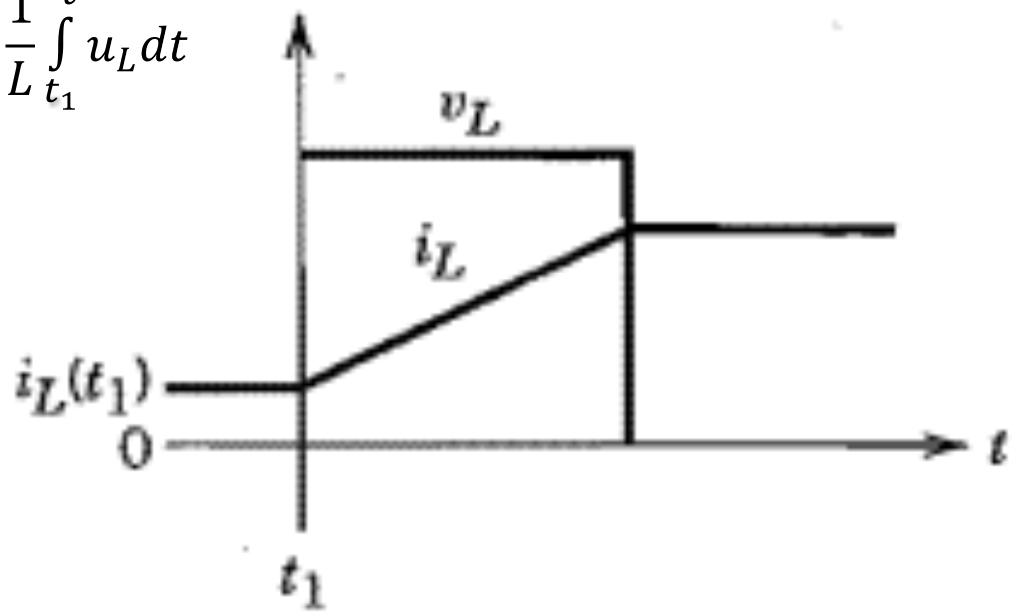
Inductor model

- Time and frequency domain
- $u_L = L\frac{di_L}{dt}$ $\bar{U}_L = j\omega L\bar{I}_L$

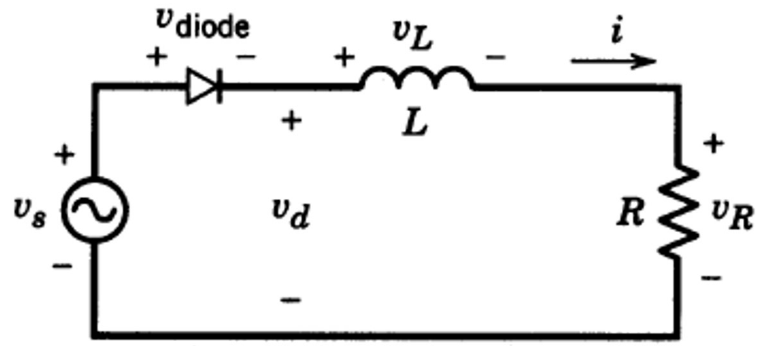


$$i_L(t) = i_L(t_1) + \frac{1}{L}\int_{t_1}^{t} u_L dt$$

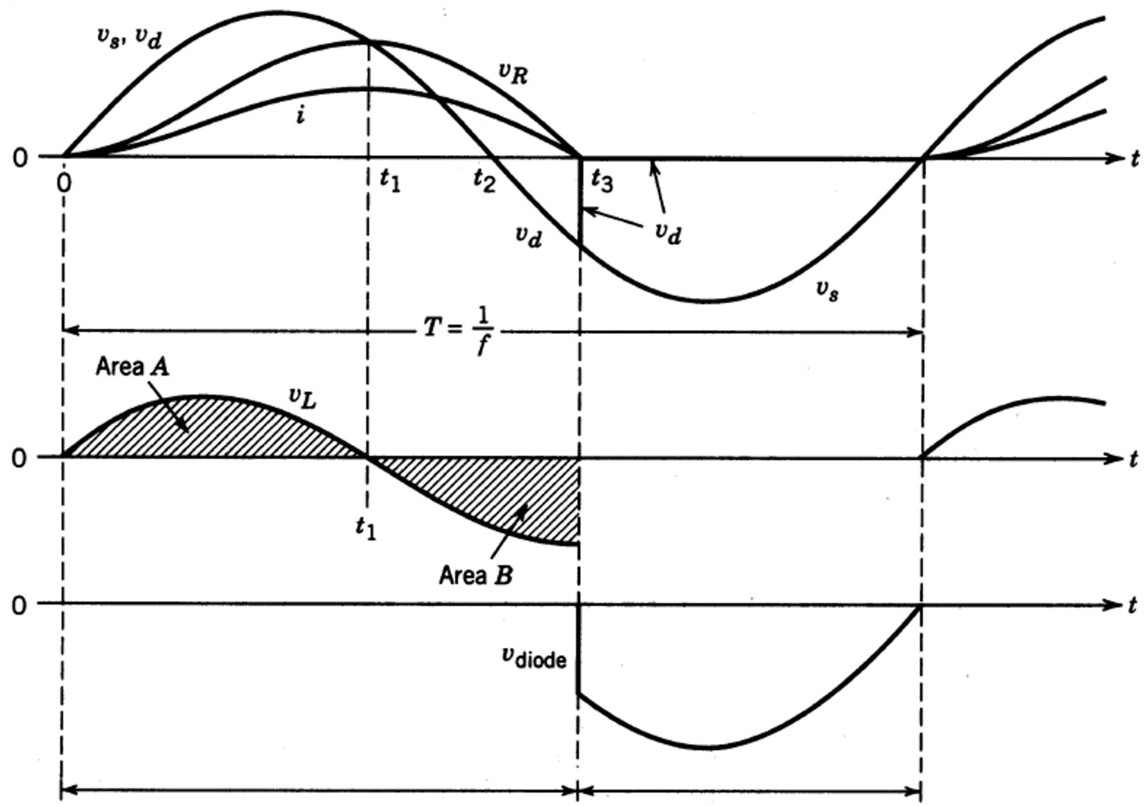




Inductive load, cont



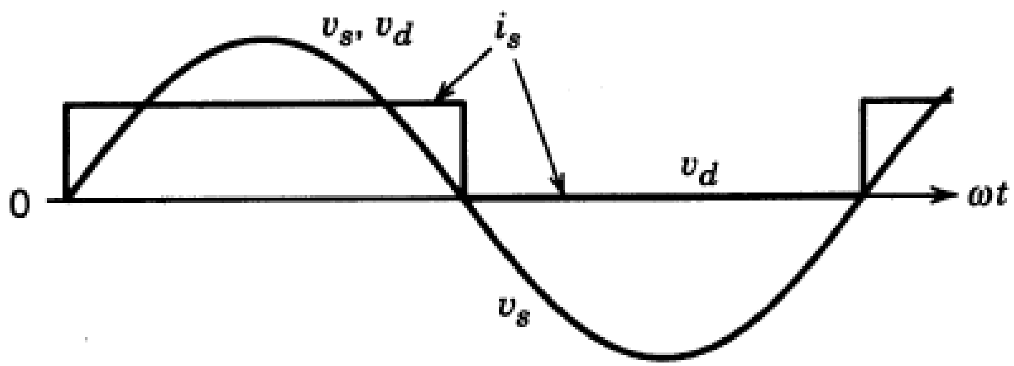
- From t_0 to t_1
  - Inductor is storing energy
- At t_1: $v_d = v_R$
  - Inductor starts to output energy
- At t_2: negative input voltage, but still non-zero current
- At t_3: zero current, diode switch off
- Current even when v_s negative

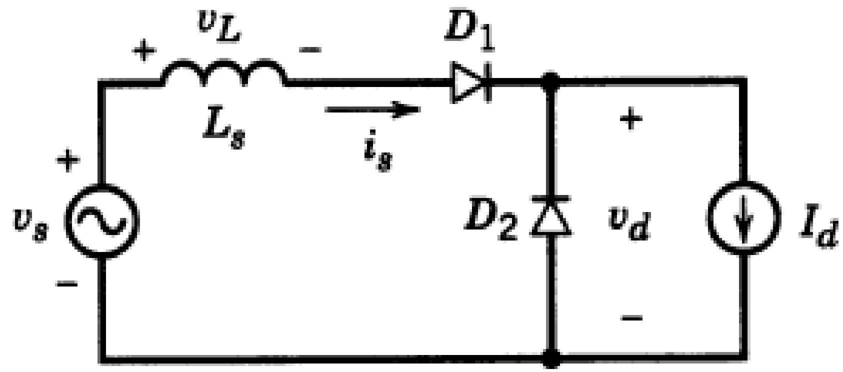


Constant current load

In a current source, the current has to flow somewhere at all times!!

- Waveform if $L_s=0$

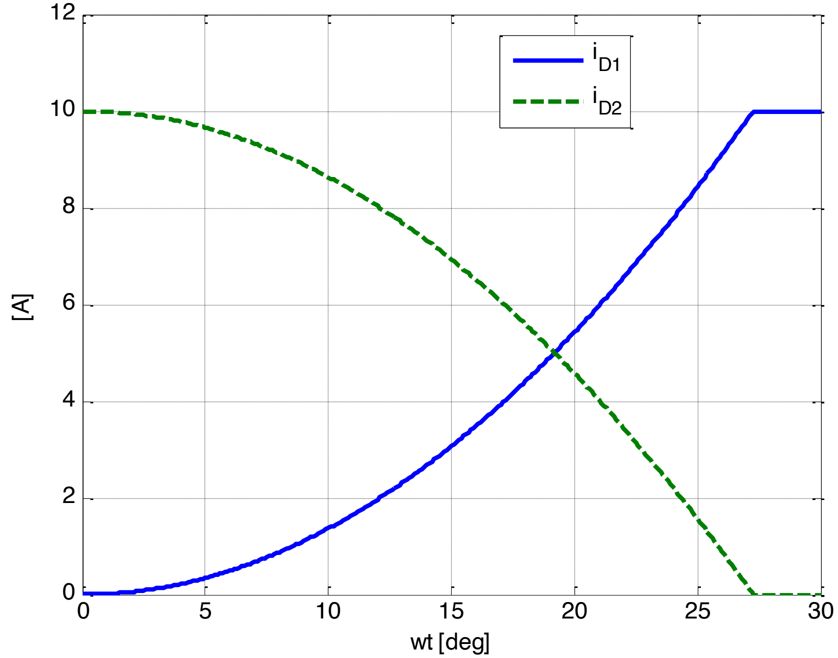


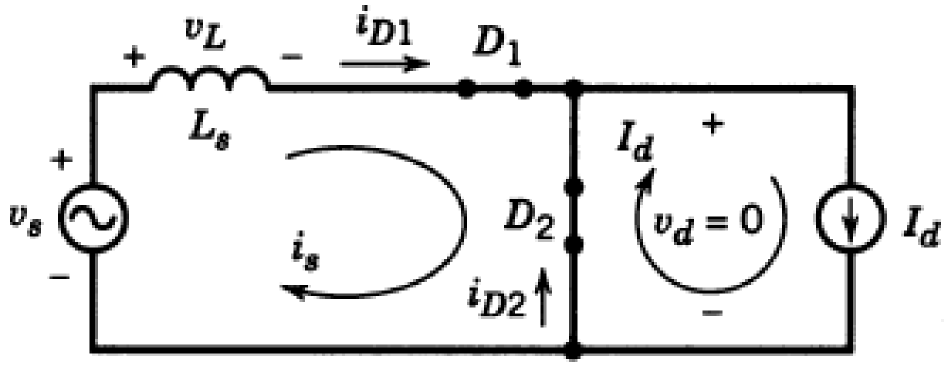


- Prior to $\omega t = 0$, v_s is negative, current flow through D2
  - $v_d = 0$, $i_s = 0$
- After $\omega t = 0$, v_s is positive, current flow through D1
  - $v_d = v_s$, $i_s = I_d$

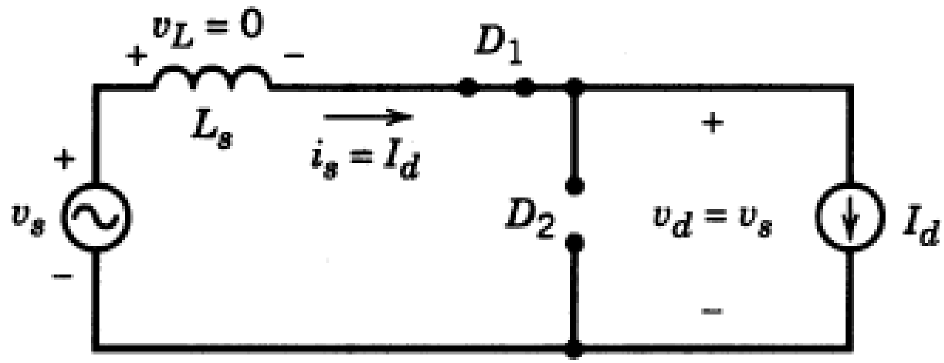
Current commutation

- During commutation ($\omega t > 0$)
  - v_s positive, D1 turns on
  - $i_{D1} = i_s$
  - $i_{D2} = I_d - i_s$
  - $i_{D1} + i_{D2} = I_d$
  - D2 stops conducting when $i_{D2} = 0$





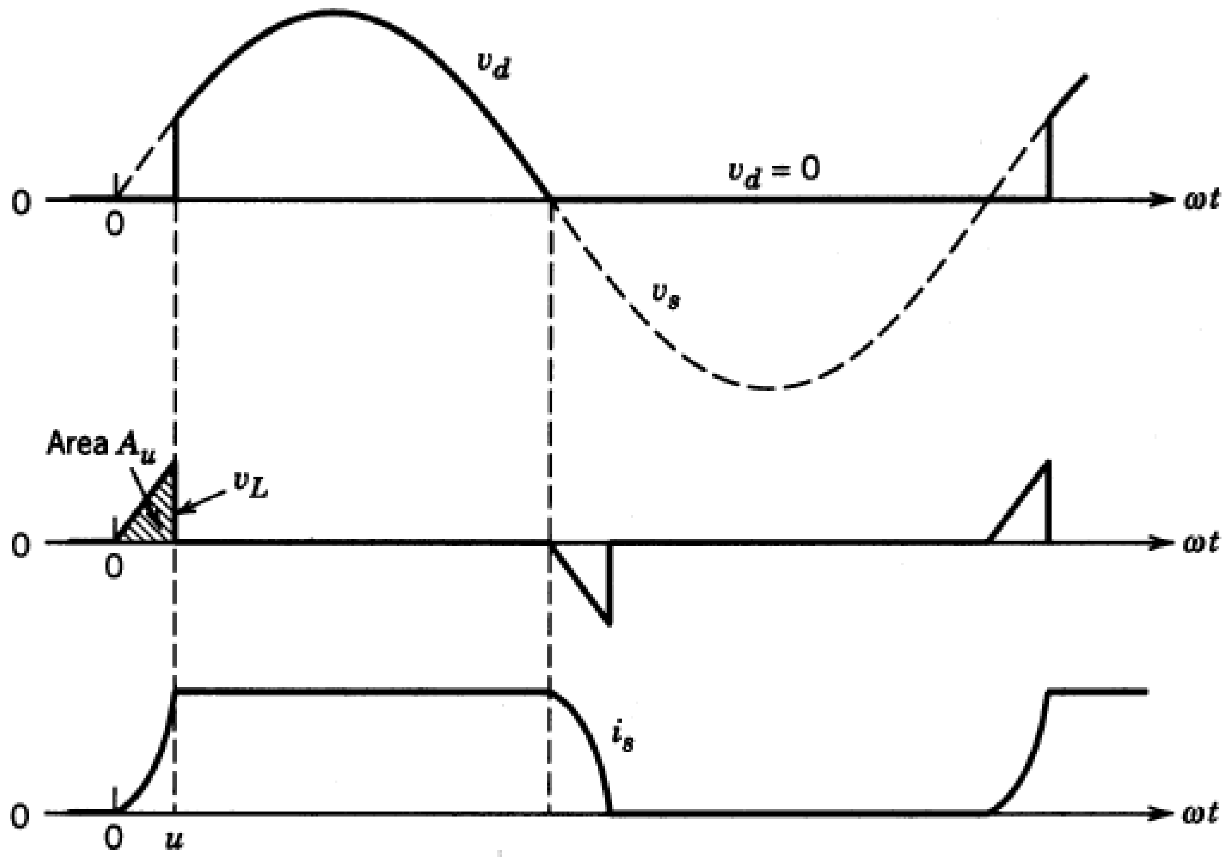
Valid for $0 < i_s < I_d$



After commutation completed

Current commutation waveforms

- Large L_s used to clearly show effect
- Time for commutation depend on L_s size and current change in L_s



Commutation conclusions

- **Conduction**:
  - Magnetic energy is stored related to the inductance of the conduction path
- **Commutation**
  - Transfer of current between two paths:
  - ⇒**Stored magnetic energy needs to be transfered!**
  - **Output voltage reduction proportional to I_d and L_s**

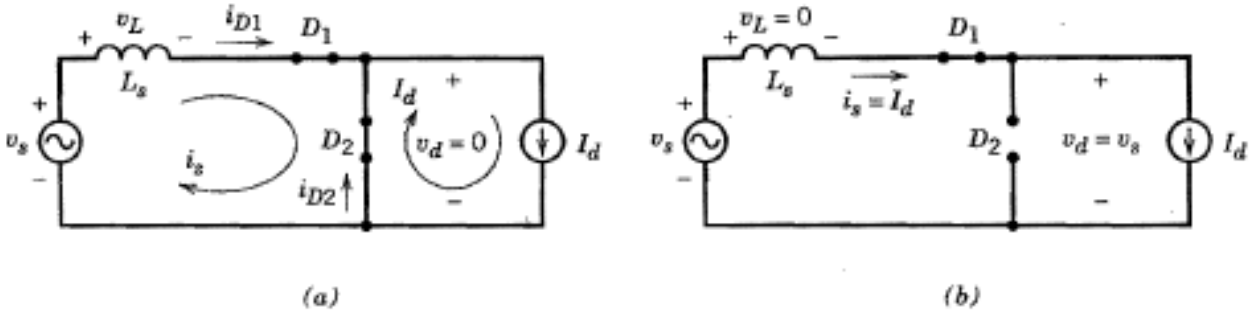


Figure 5-12 (*a*) Circuit during the commutation. (*b*) Circuit after the current commutation is completed.

Lecture 1

Rectifiers

Full-wave

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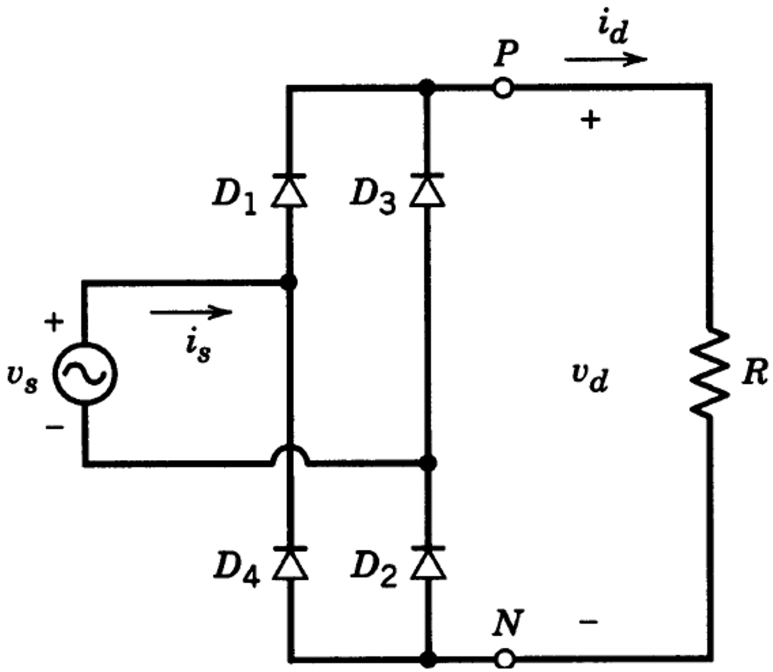
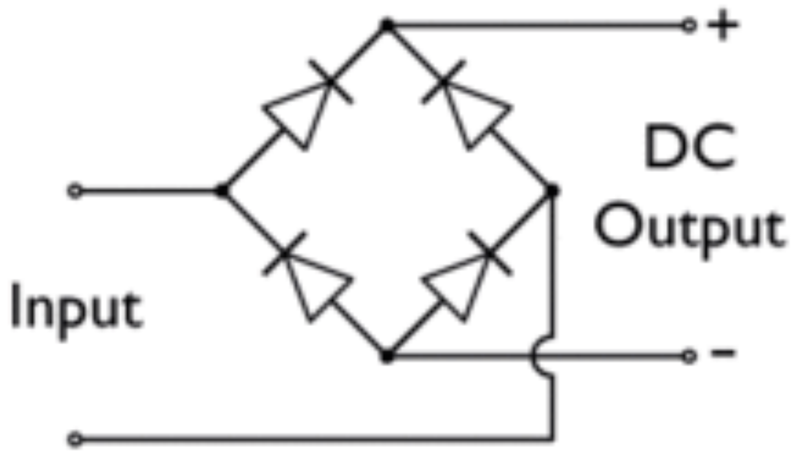
Full-wave diode bridge rectifier

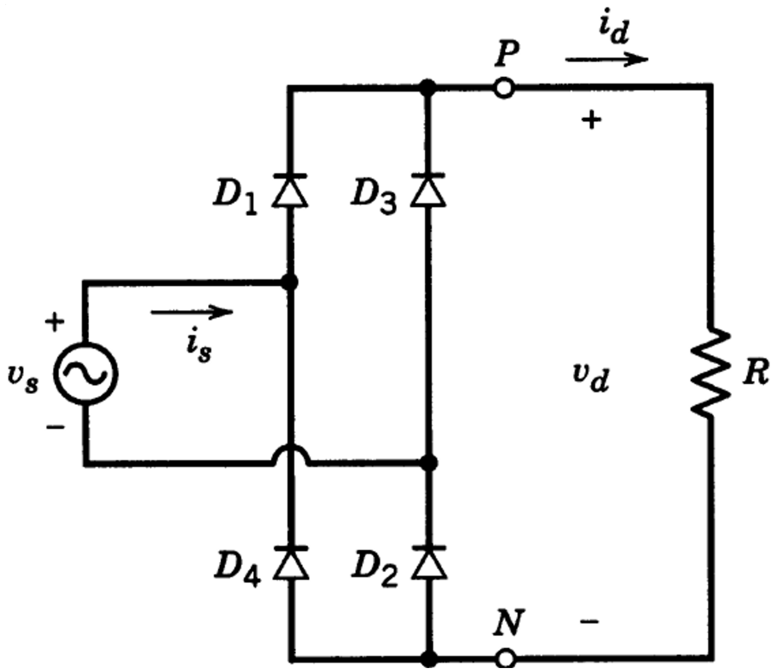
- Single phase, full-wave, full-bridge, Graetz-bridge
- Two separate circuits defined related to the polarity of v_s

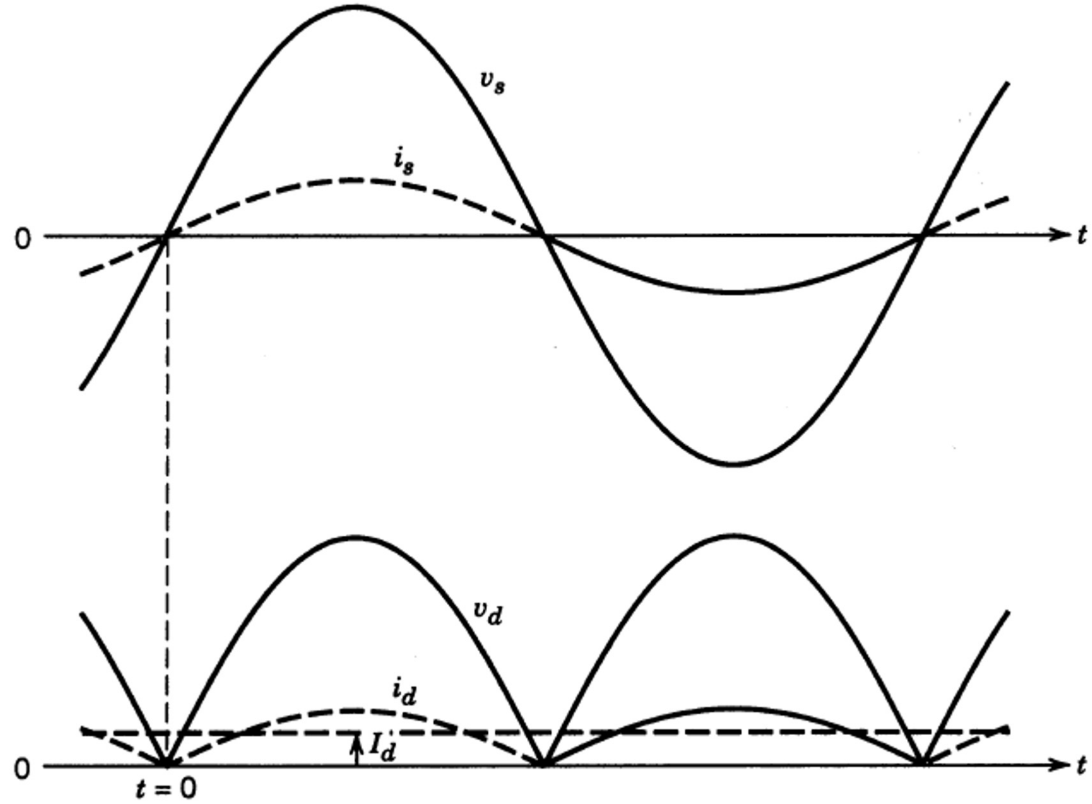




Idealized circuit, L_s = 0, resistive load

- No inductance L_s considered on ac-source side

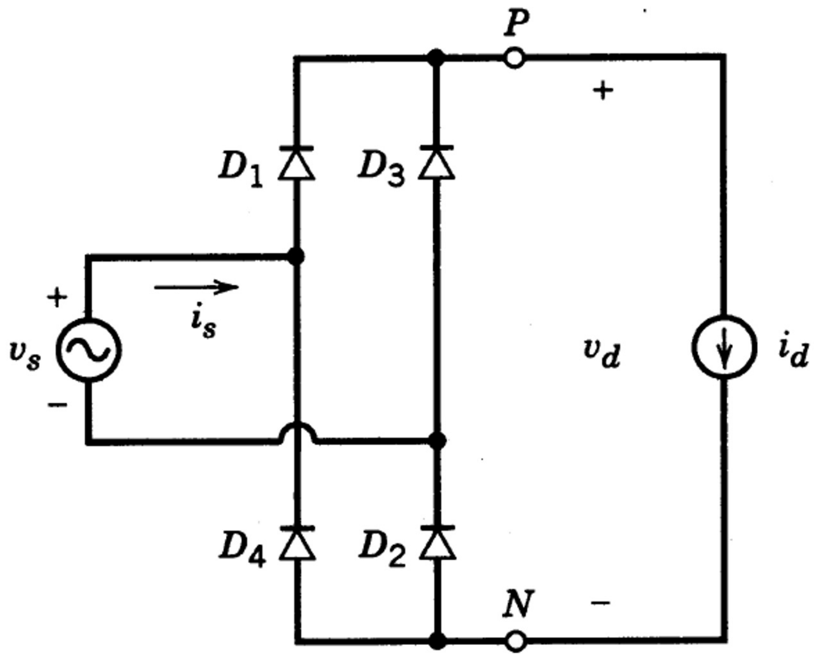


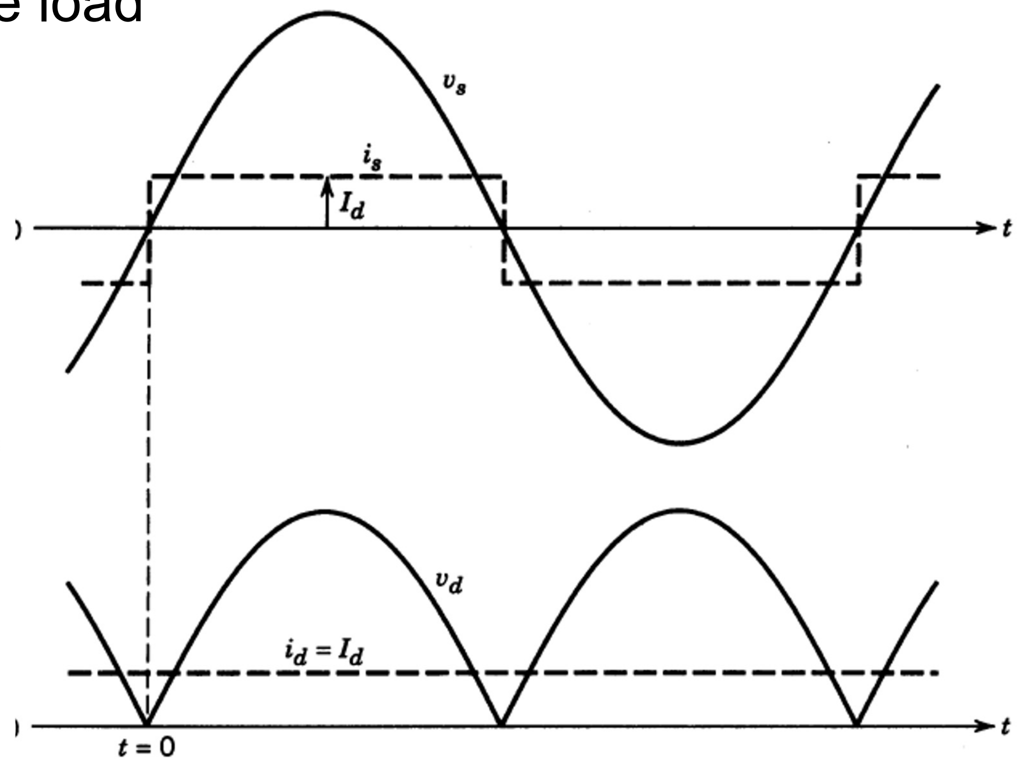


$$Average: U_d = \frac{2}{\pi}\sqrt{2}V_s = 0.9V_s$$

Idealized circuit, Ls = 0, current load

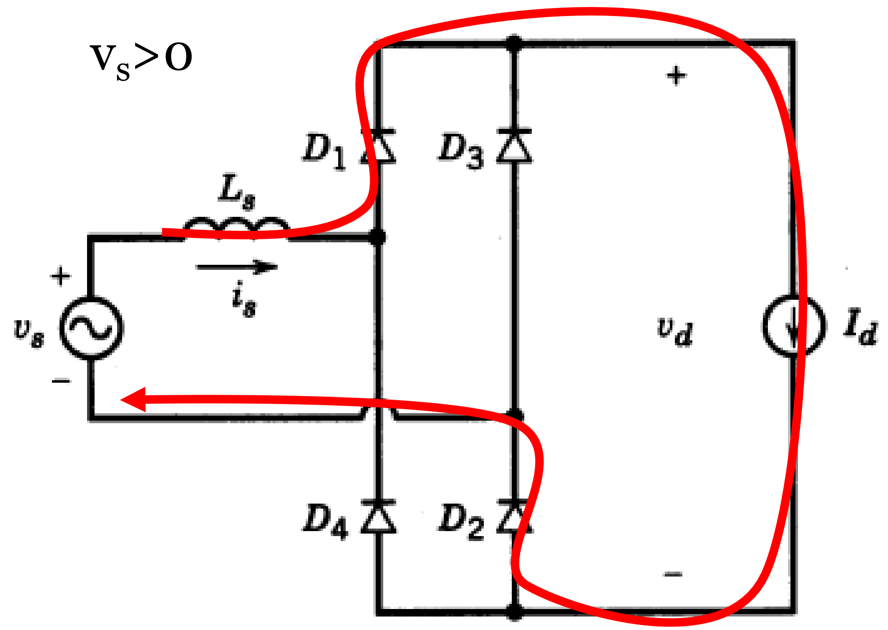
- Current source can be same as large inductance in series on the dc-side
- Same average U_d as resistive load

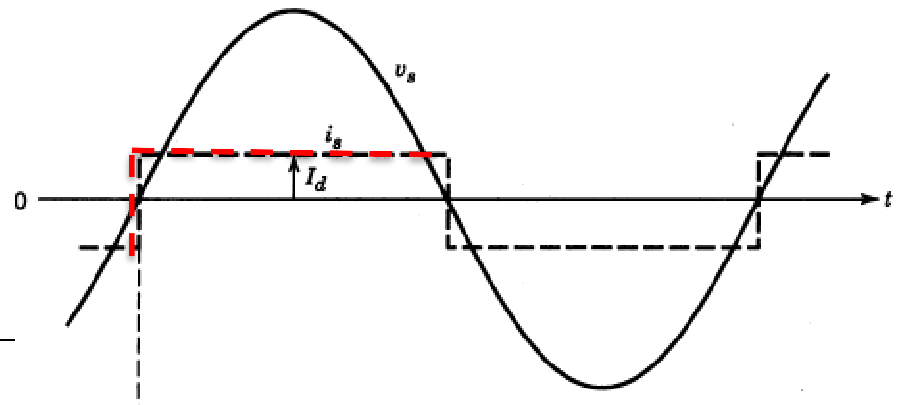




Effect of L_s on current commutation

- Current commutation = current path changed from one diode to another
  - Commutation not instantaneous when L_s nonzero
  - Stored magnetic energy change
- Use simplified example
  - Output represented by constant dc current source





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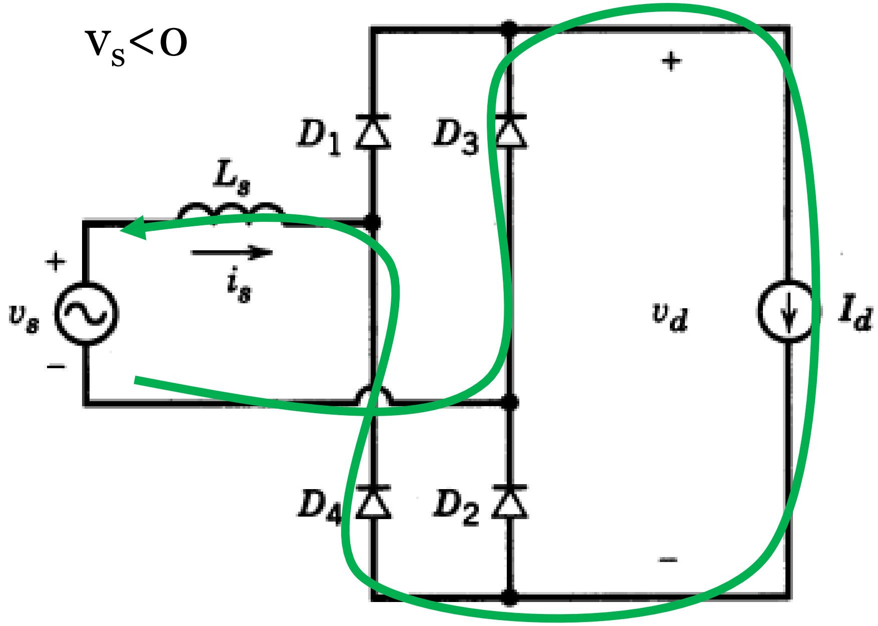
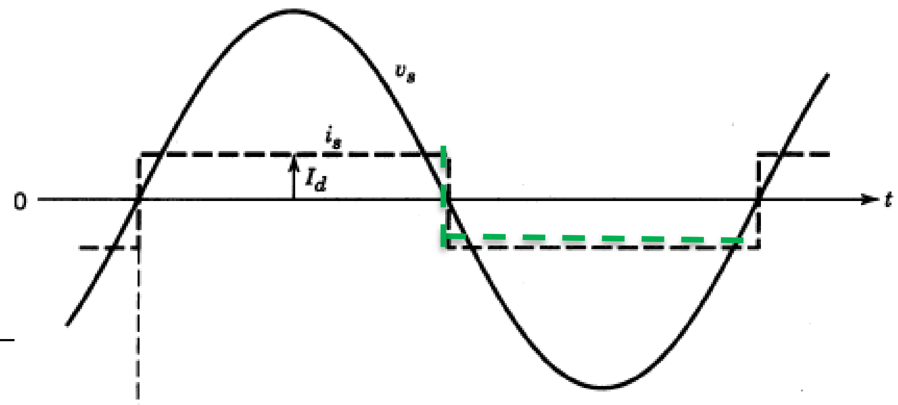
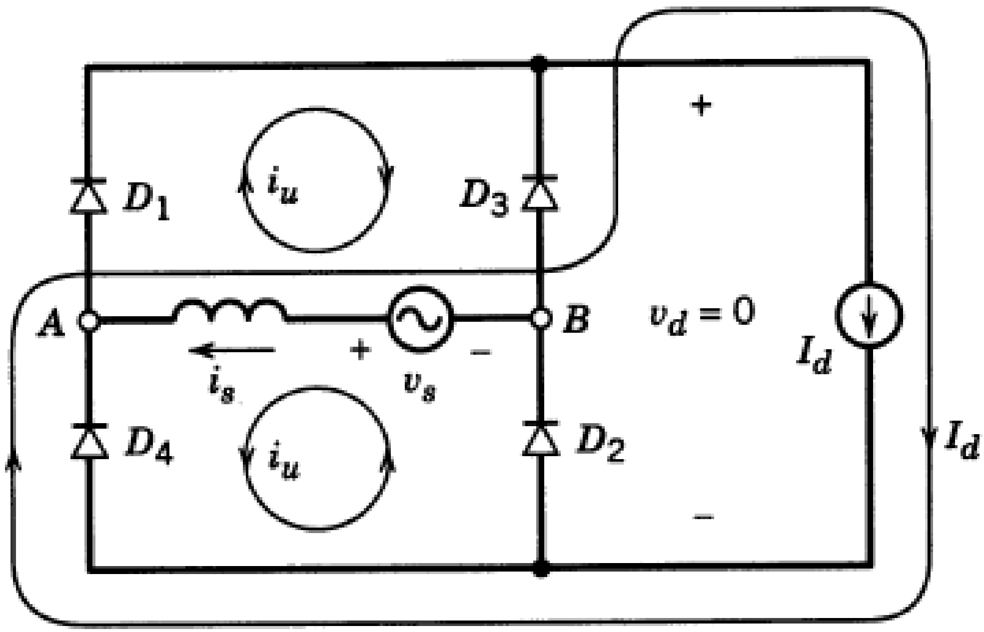




Full-bridge during current commutation

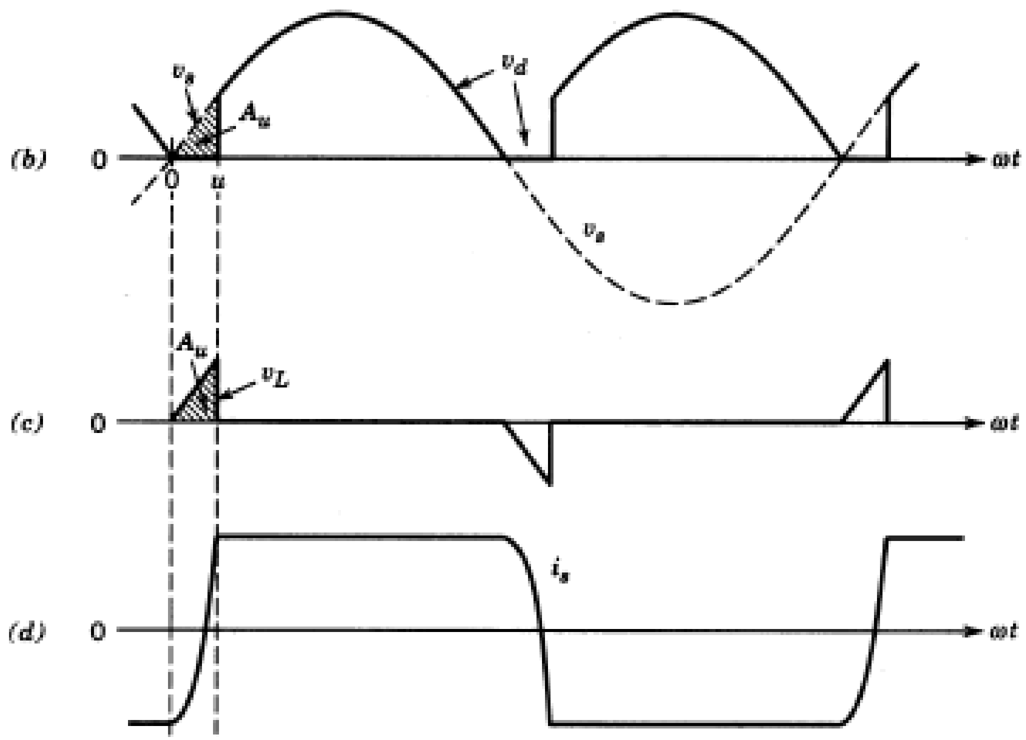
- v_s negative before t = 0
  - D3 and D4 conducting
  - $i_s = -I_d$
- v_s positive
  - D1 and D2 starts conducting (Short circuit path through D3 and D4)
- i_u are commutation currents
- v_d = 0 during commutation

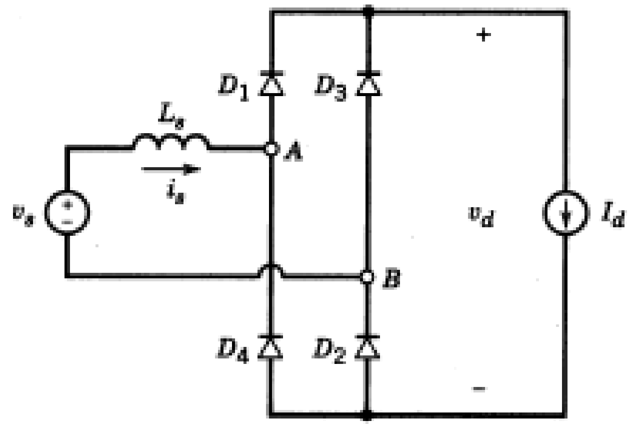


Valid for $-I_d < i_s < I_d$

Current commutation in full-bridge

- Same principle for area A_u due to L_s





Average output voltage:

$V_d = V_{d0} - \Delta V_d =$

$= V_{d0} - \frac{A_u}{\pi} = 0.9V_s - \frac{2\omega L_s}{\pi} I_d$

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