TSTE19 Power Electronics

Lecture 1

Tomas Jonsson

ICS/ISY

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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
  - ABB AB, Sweden since 1988.
  - HVDC control system design, Ludvika (1988 – 1992)
  - HVDC commissioning engineer, New Zealand HVDC project (1992-1993)
  - HVDC system development engineer, Ludvika (1993 – 1996)
  - HVDC system development manager, Ludvika (1997 – 1998)
  - Brazil-Argentina HVDC interconnection project (1998)
  - ABB Corporate Research HVDC & FACTS development projects, Västerås (1999-2009)
  - ABB Grid Systems, R&D project manager, including mentoring of R&D group in Chennai India
  - Since 2013, Senior Principal Engineer in the area of high power converters for power transmission at ABB Grid Systems.

HVDC Transmission Technologies

HVDC Classic, line commutated converters

- Power control
- Terminals demand reactive power
- Reactive power balance by shunt bank switching
- Minimum system short circuit capacity of twice rated power

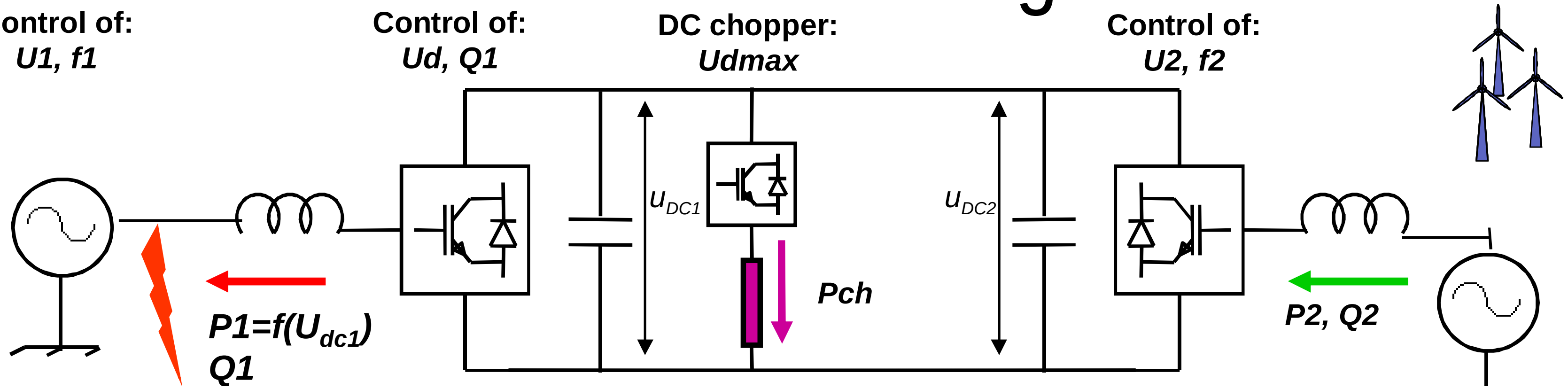
Capacitor Commutated Conveters (CCC)

- Power control
- Weak systems, long cables
- Reactive power from series capacitor
- Minimum system short circuit capacity of rated power

HVDC Light® *, forced commutated converters (VSC)*

- Real and Reactive Power control
- Dynamic voltage regulation
- Modular and expandable
- Black start capability
- No short circuit restriction

Example of HVDC control task: Fault ride through



Control of:
U1, f1

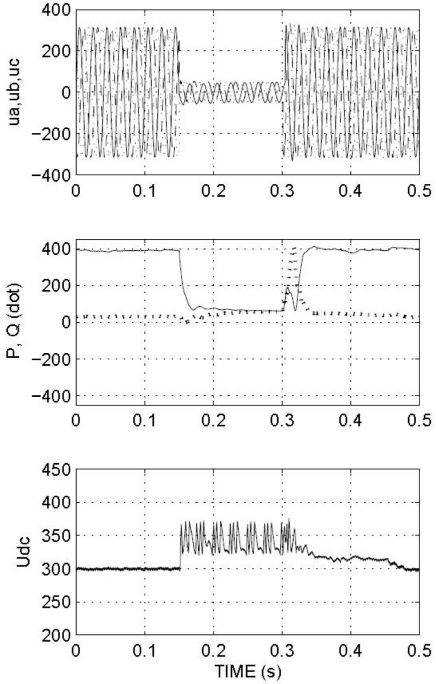
Control of:
Ud, Q1

DC chopper:
Udmax

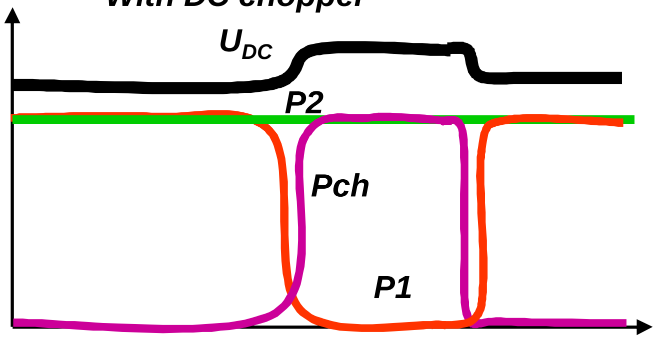
Control of:
U2, f2

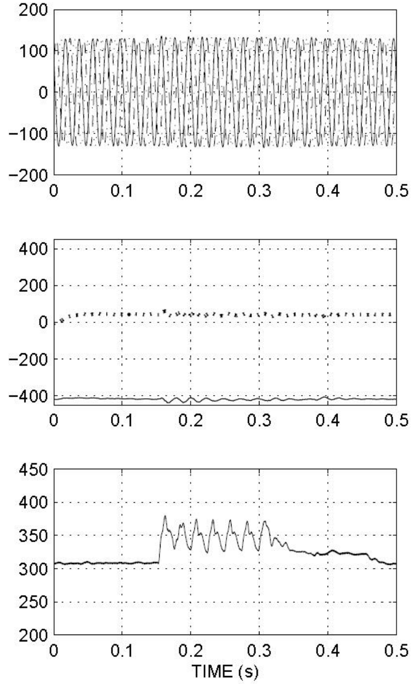
On-shore

Off-shore



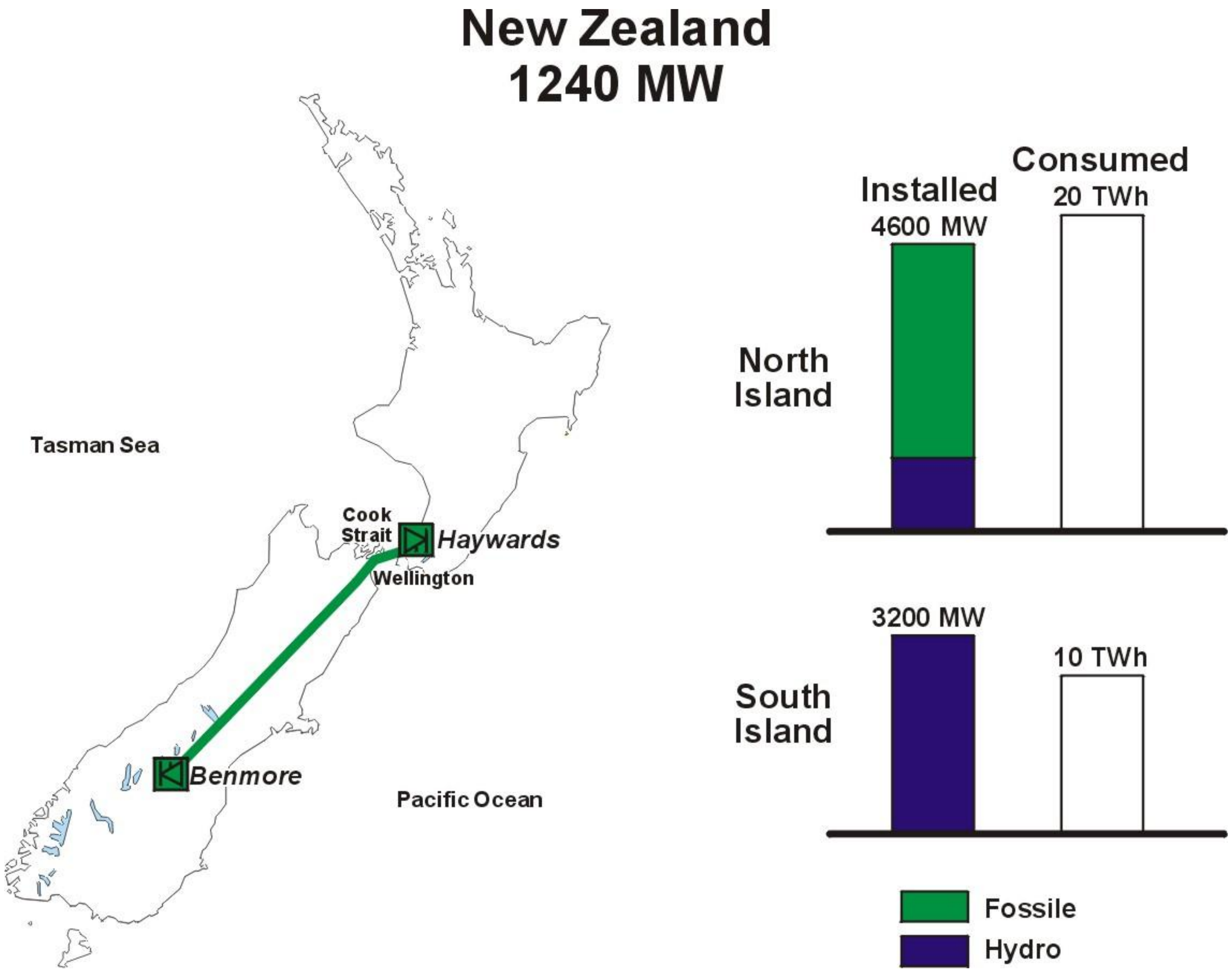
With DC chopper





- DC-chopper decouples windpark from on-shore grid
- Minimum impact on wind production during on-shore grid faults

DC hybrid link, New Zealand, 1240 MW



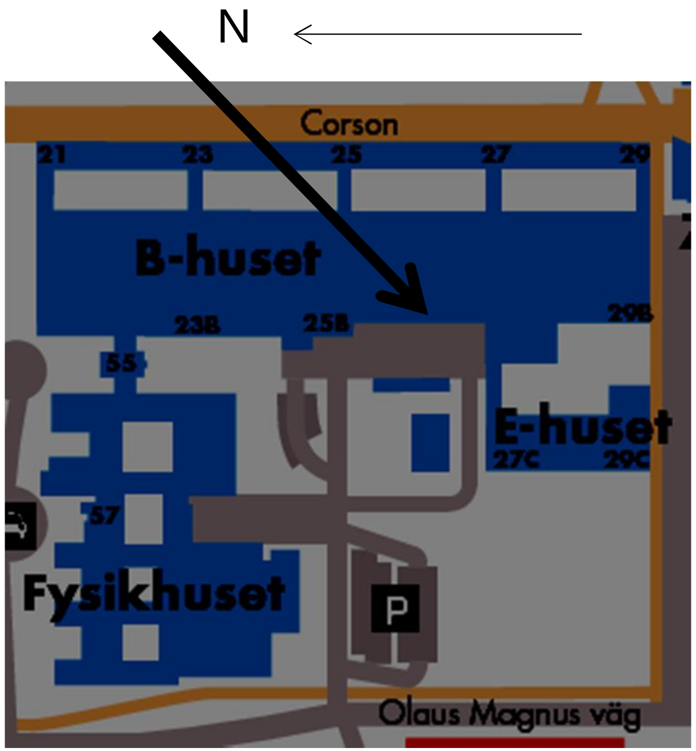
Course staff

Lectures

- Tomas Jonsson
- 013 28 17 21
- tomas.u.jonsson@liu.se
- Office 3D:513
  (2nd floor, between entrance 25 & 27)

Lab's

- Martin Nielsen Lönn

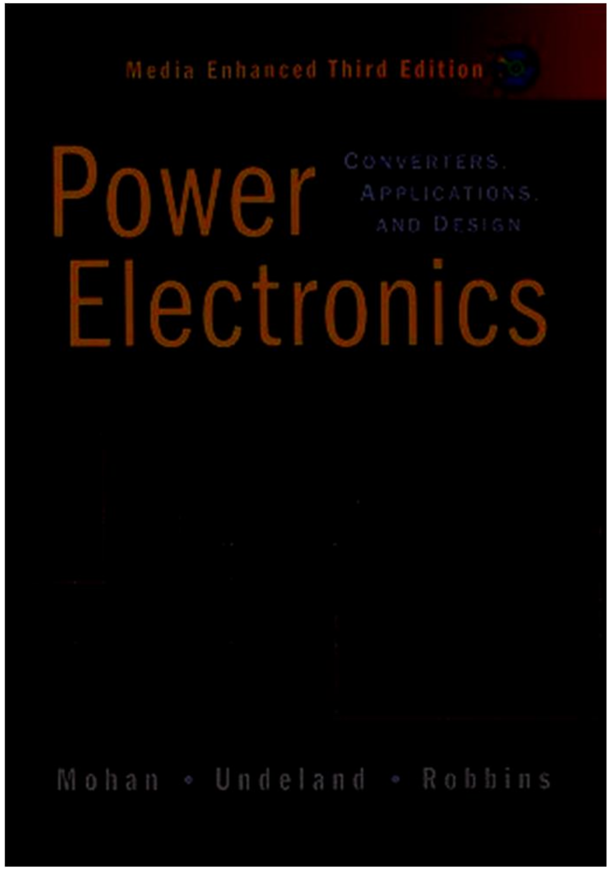


Course Contents

- Course web page
  http://www.isy.liu.se/edu/kurs/TSTE19/
- 16 Lectures (incl exercises)
  - Introduce and explain material
  - Problem solving
  - Lab preparation
- 3 labs
  - Lab 1 & 2: Multisim simulation of power circuits
  - Lab 3: Control & measurements on power circuit
  - Lab notes will be available on course web page

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 {}



Lecture plan part 1

Date	Room	Number	Content
Tue 3/11 13-15	R34	1	Course introduction "Energy conversion through power electronics" an overview of applications. Power electronic systems [1], Circuit theory [3-2]
Wed 4/11 10-12	R35	2	Diode rectifier, part 1: Diode semiconductor theory [19,20], operation [5.2], harmonics
Tue 10/11 13-15	R26	3	Diode rectifier, part 2: Commutation [5.3], reactive power [3.2], circuit simulation [4]
Wed 11/11 10-12	R42	4	Phase controlled converter: Thyristor semiconductor theory [23], thyristor converter operation [6.2 – 6.4]
Mon 16/11 8-10	R18	5	Power semiconductor devices and rating: Semiconductor switches (MOSFET, IGBT, GTO) [21-22, 24-26], data sheet, rating, cooling [29]
Wed 18/11 10-12	R35	6	DC/DC converter, part 1: Switch-mode power supply [10], step-down [7.3], step-up [7.4]
Tue 24/11 13-15	R35	7	DC/AC inverter, part 1: Half-bridge [8.3], commutation, PWM [8.2]
Wed 25/11 10-12	R34	8	DC/AC inverter, part 2: Full-bridge [8.3], harmonics

Lecture plan part 2

Date	Room	Number	Content
Tue 1/12 13-15	R36	9	DC/AC inverter, part 3: Blanking time [8.5], gate control [28]
Wed 2/12 10-12	R37	10	Design review of full-bridge circuit for Lab3: Principles, component selection, control
Tue 8/12 13-15	R18	11	Control & protection: Current control modes [8-6], snubbers [27], short circuit
Wed 9/12 10-12	R23	12	DC/AC – AC/DC: Rectifier vs. inverter operation [8.7], 3-phase converter [8.4]
Tue 15/12 13-15	R19	13	Switch-mode DC/DC converter, part 2: Buck-boost, converters with isolation [10-4], resonant converters
Wed 16/12 10-12	R22	14	Utility applications [17]: HVDC, TCR, TSC, STATCOM
Mon 21/12 8-12	P30	15	Motor drive applications [12-13]: Induction motors [14]
Tue 22/12 13-15	P18	16	Preparation for exam

Lab schedule

Date	Room	Number	Content
Thu 19/11 17-21	Freja	1	Computer lab on diode bridge rectifier, phase controlled converter
Thu 3/12 17-21	Freja	2	Computer lab on VSC full-bridge Inverter, dc/dc buck
Thu 10/12 17-21	Transistorn	3	Measurement lab on VSC full-bridge inverter
Tue 15/12 17-21	Transistorn	1-3	Spare. Opportunity to complete any of Labs 1-3

Lab3: Full-bridge PWM inverter

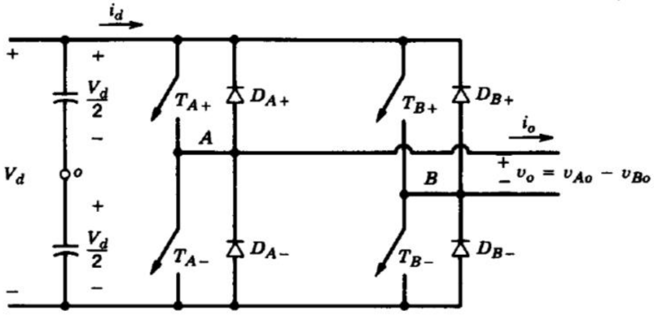
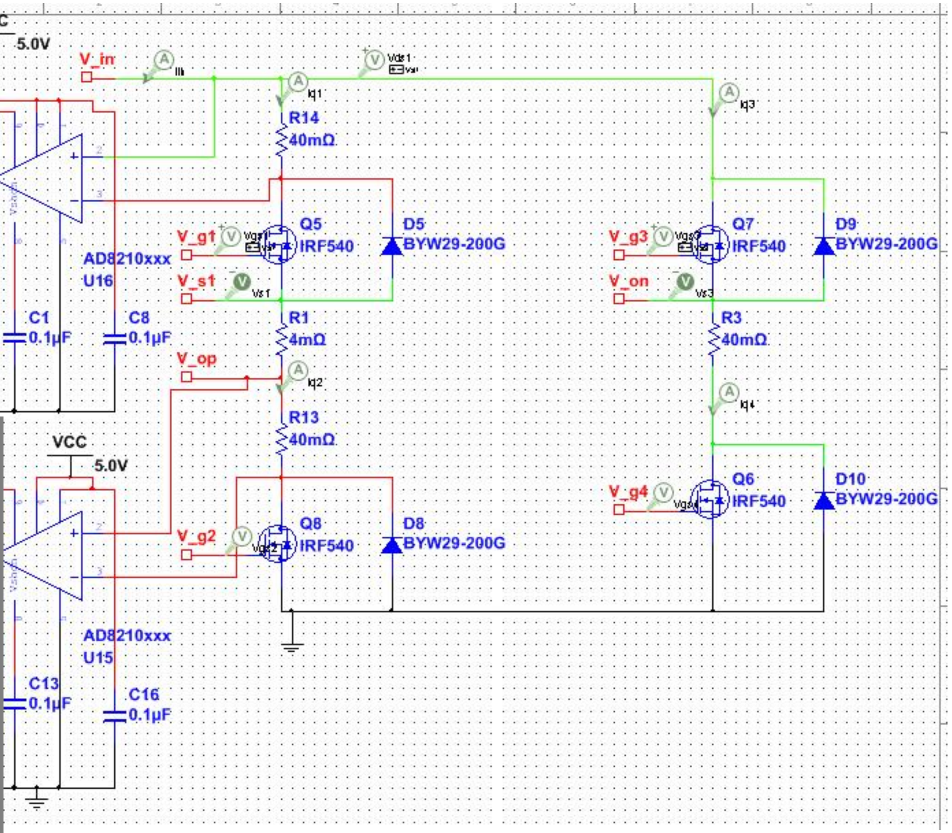
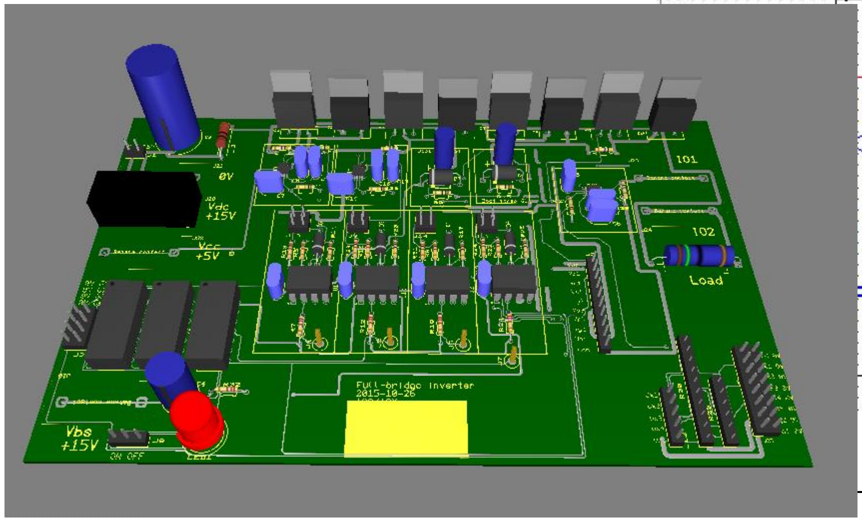


Figure 8-11 Single-phase full-bridge inverter.





Examination

- 3 Lab tasks completed and presented (during the lab)
  - Simulation and measurement tasks
- Written exam

Lecture 1

Power electronic systems from nW to GW
Power electronic systems [Ch 1]
Circuit theory [Ch 3-2]
Exercises [1-1 – 1-5, 3-3 – 3-5]

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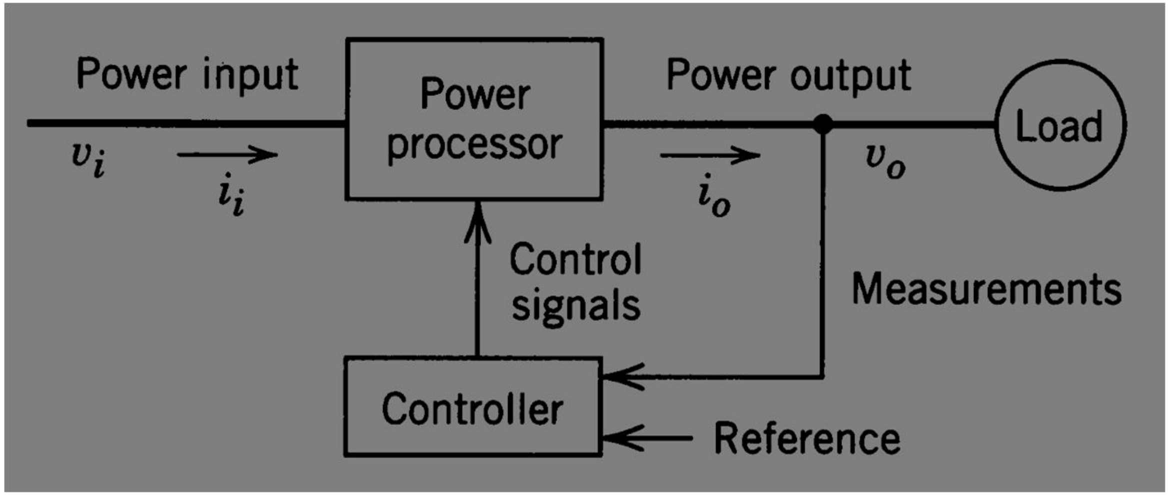
Power Electronic Systems

- 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
  - Voltage level transformation, 230V to 12V
  - Current control/limitation
  - Power control, charging v.s. discharging
  - Control related to load variations
  - Control related to source variations

Goals of the power transformation

- High efficiency

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

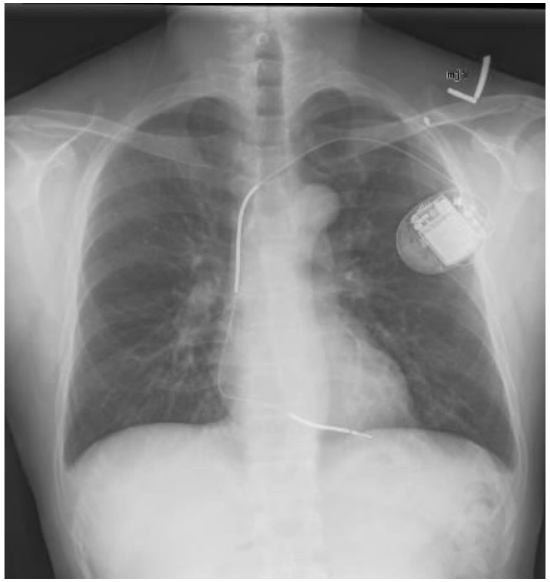
- Accurate output voltages/currents
  - Voltage/current ripple
  - Correct for varying load impedance
- Small size
- Low cost
- :

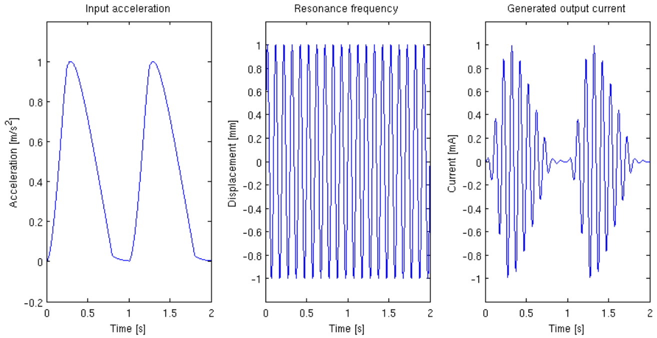
Lecture 1,
Power electronics over 18 decades
(10^{-8} W - 10^{10} W)

MEMS P = 10^{-8} = 10 nW (200 mV, 50 nA)
Electric Vehicle battery charger P = 1 kW – 50 kW
Wind turbine speed/power control P=5 MW
HVDC power transmission P = 10^{10} = 10 GW (±800 kV, 6 kA)

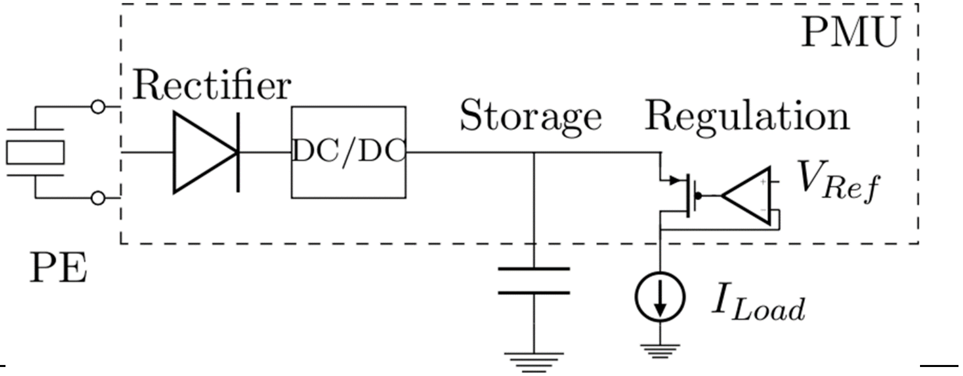
MEMS for pace maker power supply

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



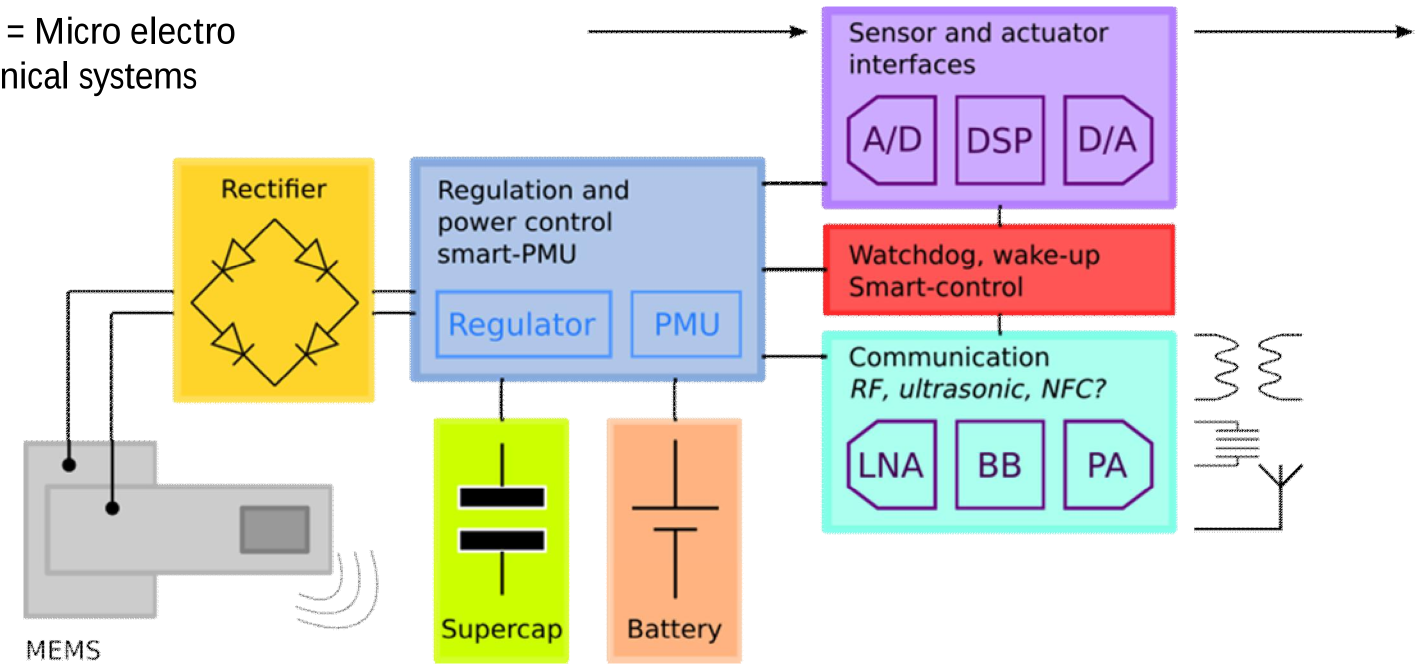


Requirement	Value
Power	300 nW
Output voltage	300 mV



Soil moisture sensor node

MEMS = Micro electro
mechanical systems



Only wakes up every hour to measure soil moisture

Requirement	Value
Power	25 nW
Output voltage	400 mV

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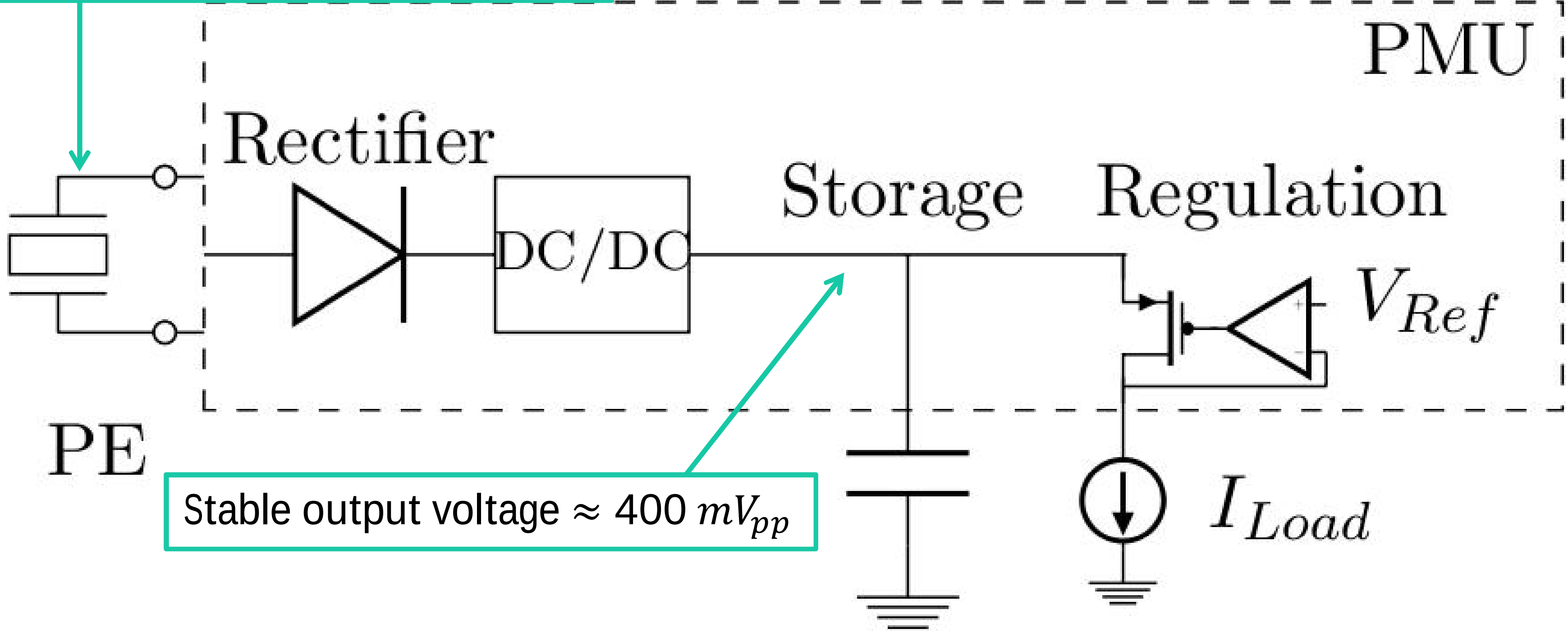
Soil moisture sensor PMU

Varying input, ≈ 150 – 250 mV_{pp}



Stable output voltage ≈ 400 mV_{pp}

Picks up vibration in the ground or the human body, rectifies and boost the voltage to store it in a supercapacitor

Battery charging

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

IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 28, NO. 5, MAY 2013 2151

Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles

Murat Yilmaz, *Member, IEEE*, and Philip T. Krein, *Fellow, IEEE*

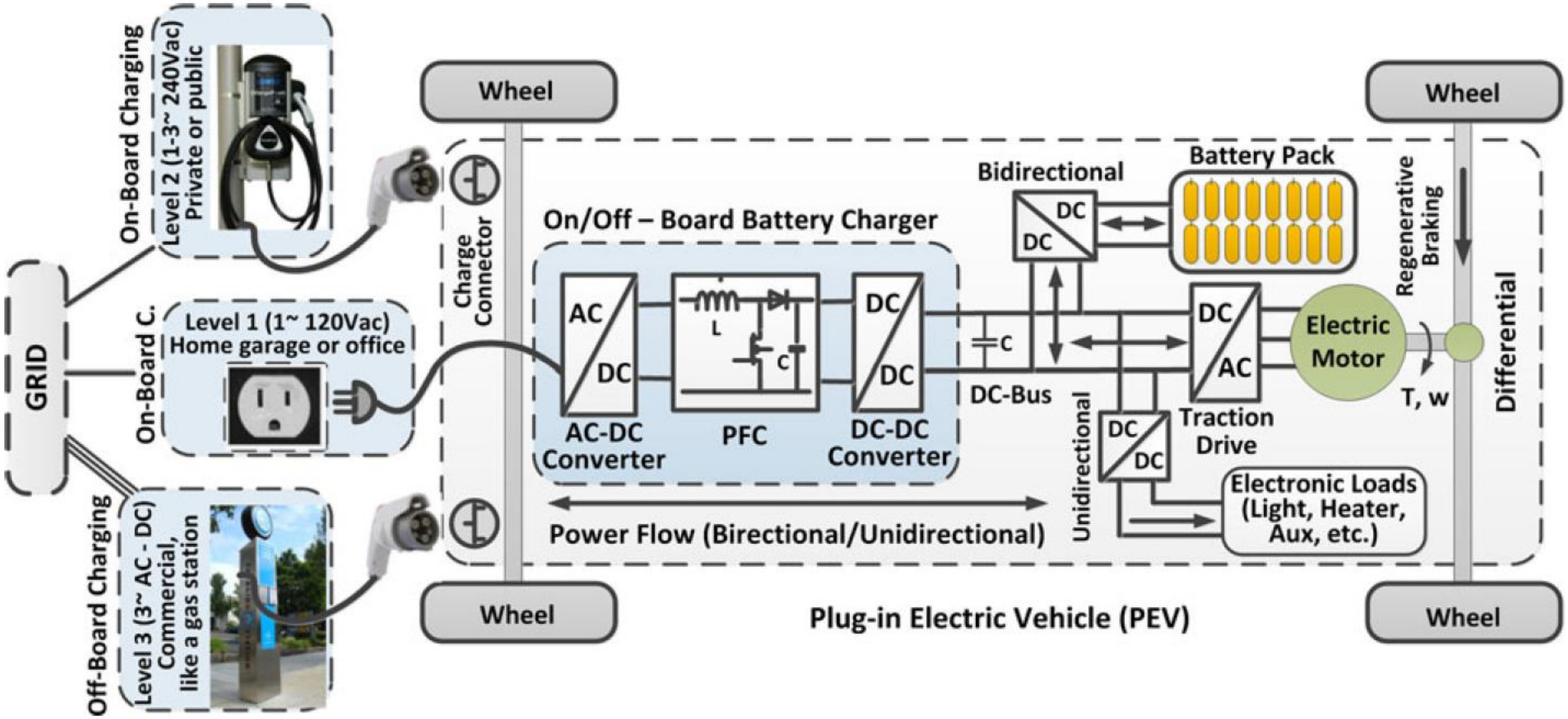
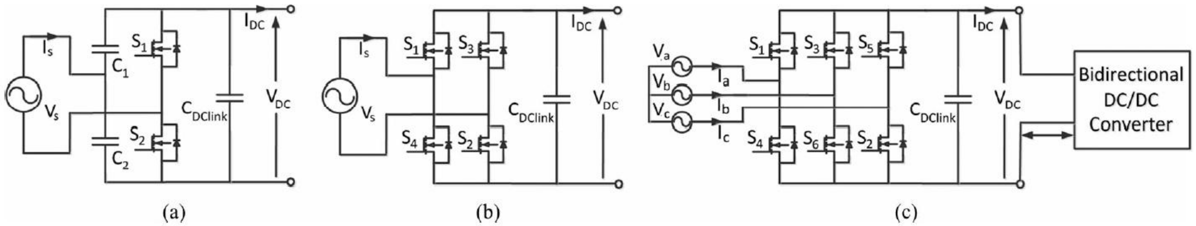


Fig. 6. On/off board charging system and power levels for EVs.

Fig. 5. SAE's J1772 *combo connector* for ac or dc Level 1 and Level 2 charging [65].



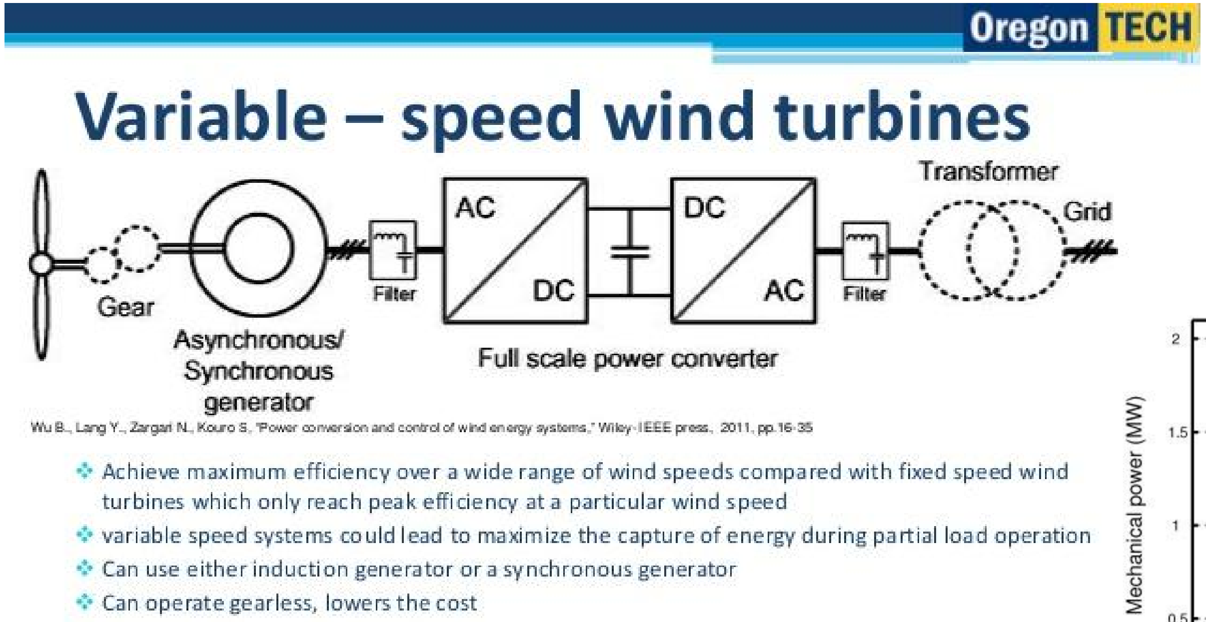
(a) (b) (c)

Fig. 4. Bidirectional chargers: (a) single-phase half-bridge, (b) single-phase full-bridge, and (c) three-phase full-bridge.

TABLE II
CHARGING CHARACTERISTICS AND INFRASTRUCTURES OF SOME MANUFACTURED PHEVS AND EVS

	Battery Type and Energy	All-Electric Range	Connector Type	Level 1 Charging		Level 2 Charging		DC Fast Charging	
				Demand	Charge Time	Demand	Charge Time	Demand	Charge Time
Toyota Prius PHEV(2012)	Li-Ion 4.4kWh	14 miles	SAE J1772	1.4kW (120V)	3 hours	3.8kW (240V)	2.5 hours	N/A	N/A
Chevrolet Volt PHEV	Li-Ion 16kWh	40 miles	SAE J1772	0.96–1.4 kW	5–8 hours	3.8kW	2–3 hours	N/A	N/A
Mitsubishi i-MiEV EV	Li-Ion 16kWh	96 miles	SAE J1772 JARI/TEPCO	1.5kW	7 hours	3kW	14 hours	50kW	30 minutes
Nissan Leaf EV	Li-Ion 24kWh	100 miles	SAE J1772 JARI/TEPCO	1.8kW	12–16 hours	3.3kW	6–8 hours	50 + kW	15-30 minutes
Tesla Roadster EV	Li-Ion 53kWh	245 miles	SAE J1772	1.8kW	30 + hours	9.6–16.8 kW	4–12 hours	N/A	N/A

Wind turbine converter control



Variable – speed wind turbines

Wu B., Lang Y., Zargari N., Kouro S., "Power conversion and control of wind energy systems," Wiley-IEEE press, 2011, pp.16-35

- Achieve maximum efficiency over a wide range of wind speeds compared with fixed speed wind turbines which only reach peak efficiency at a particular wind speed
- variable speed systems could lead to maximize the capture of energy during partial load operation
- Can use either induction generator or a synchronous generator
- Can operate gearless, lowers the cost

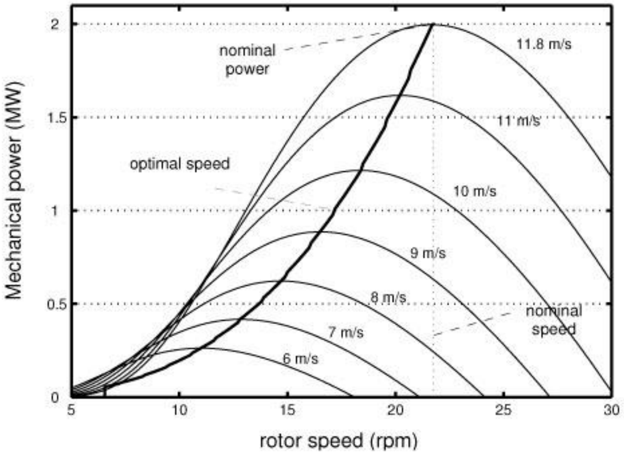


Fig. 8 Output power for different values of wind speed (m/s).

Lecture 1, Power electronics of 20 decades (10^{-10} W - 10^{10} W)

HVDC

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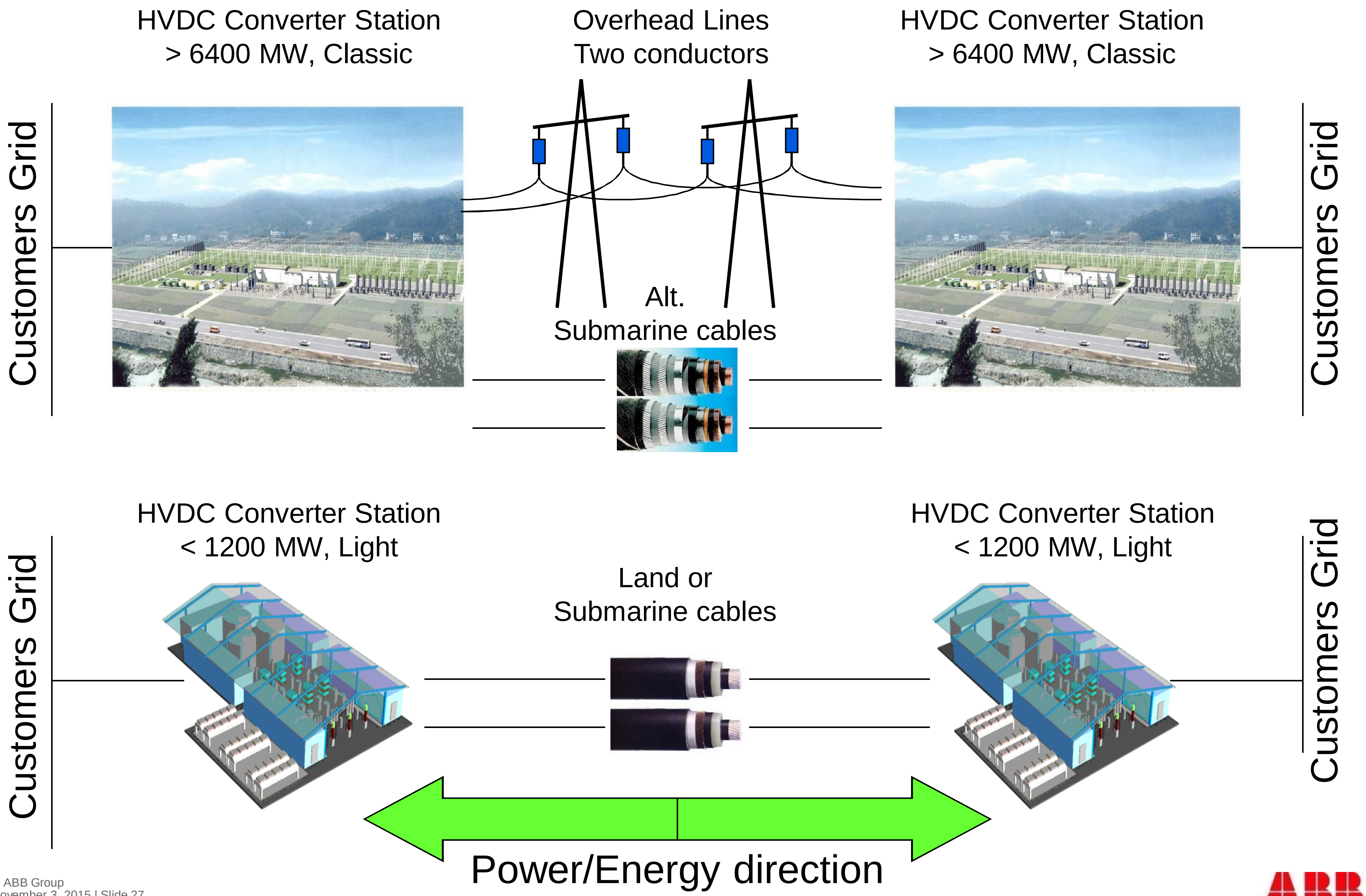
What is an HVDC Transmission System?



HVDC Converter Station
> 6400 MW, Classic

Overhead Lines
Two conductors

HVDC Converter Station
> 6400 MW, Classic

Customers Grid

Alt.
Submarine cables

Customers Grid

HVDC Converter Station
< 1200 MW, Light

Land or
Submarine cables

HVDC Converter Station
< 1200 MW, Light

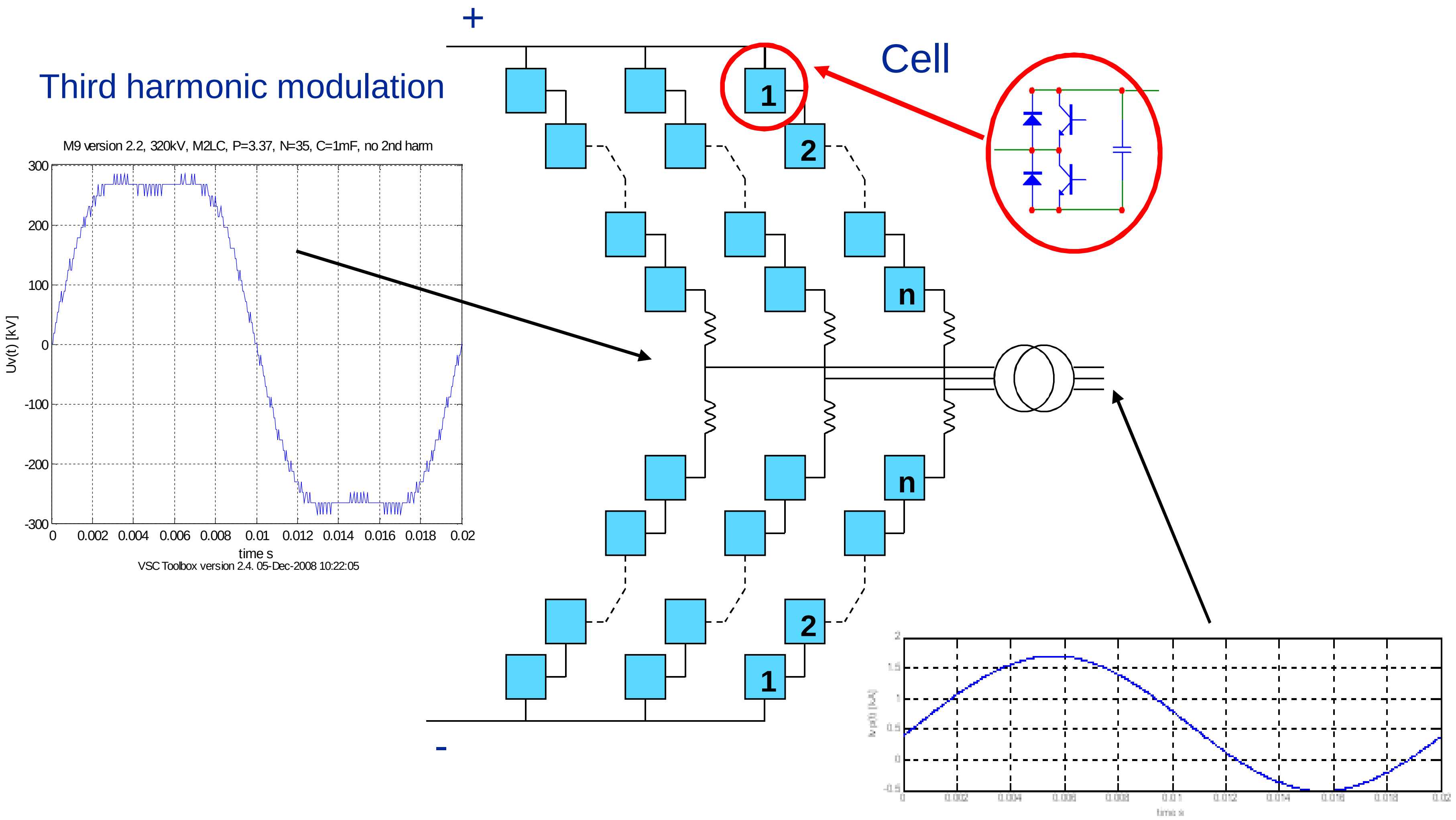
Customers Grid

Customers Grid

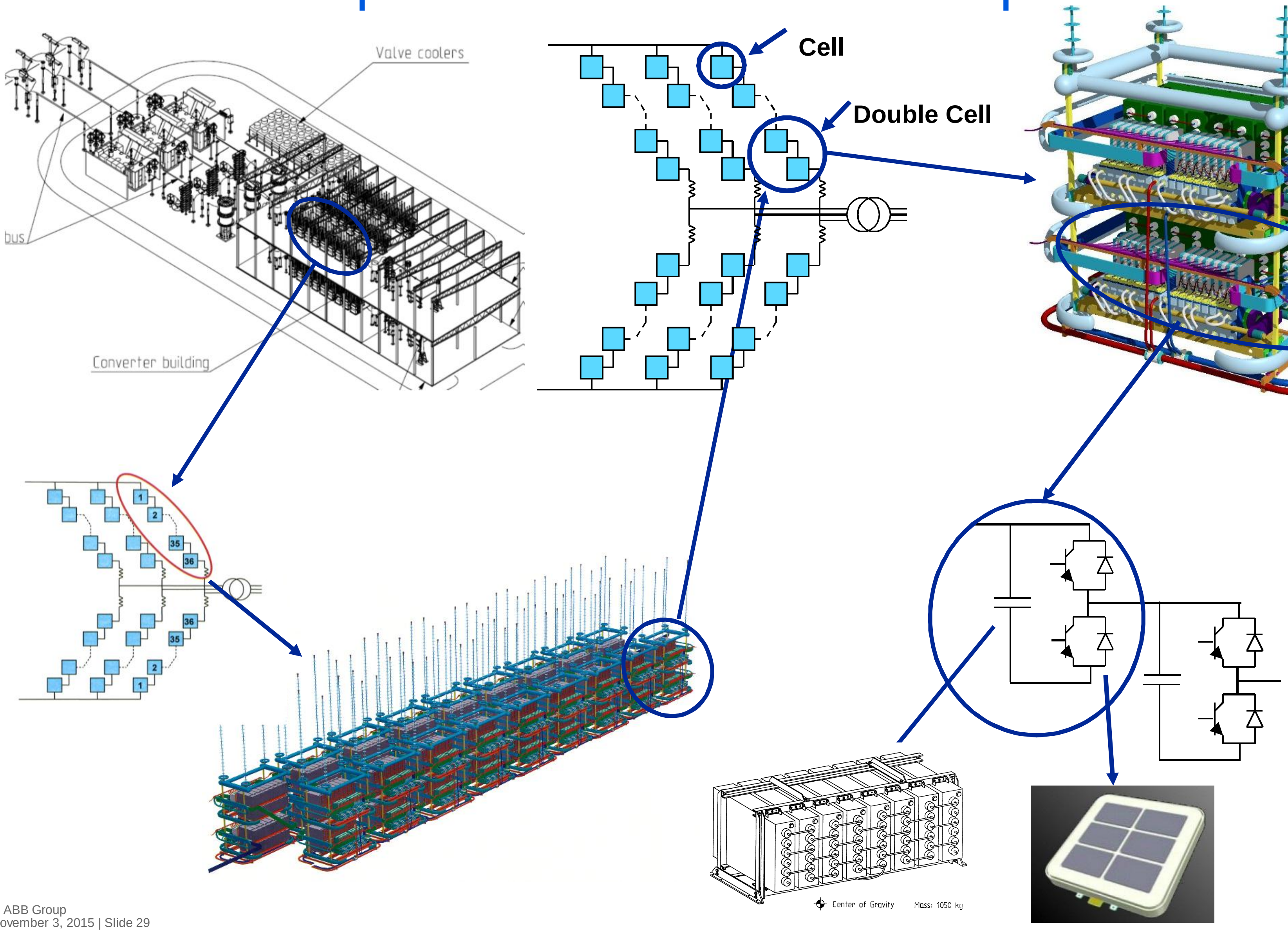
Power/Energy direction

Today's converter design

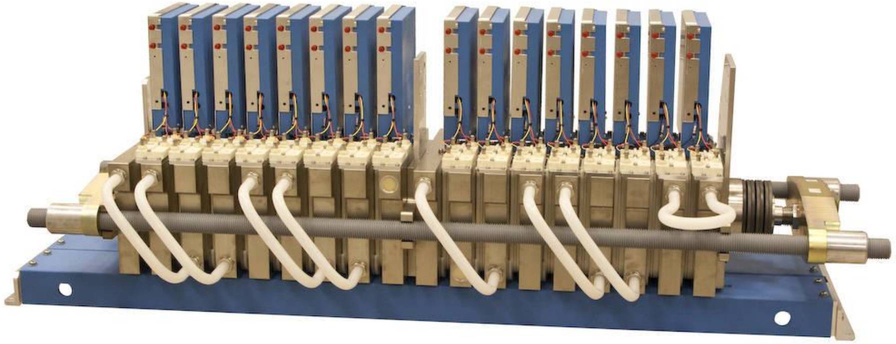
Converter output voltage

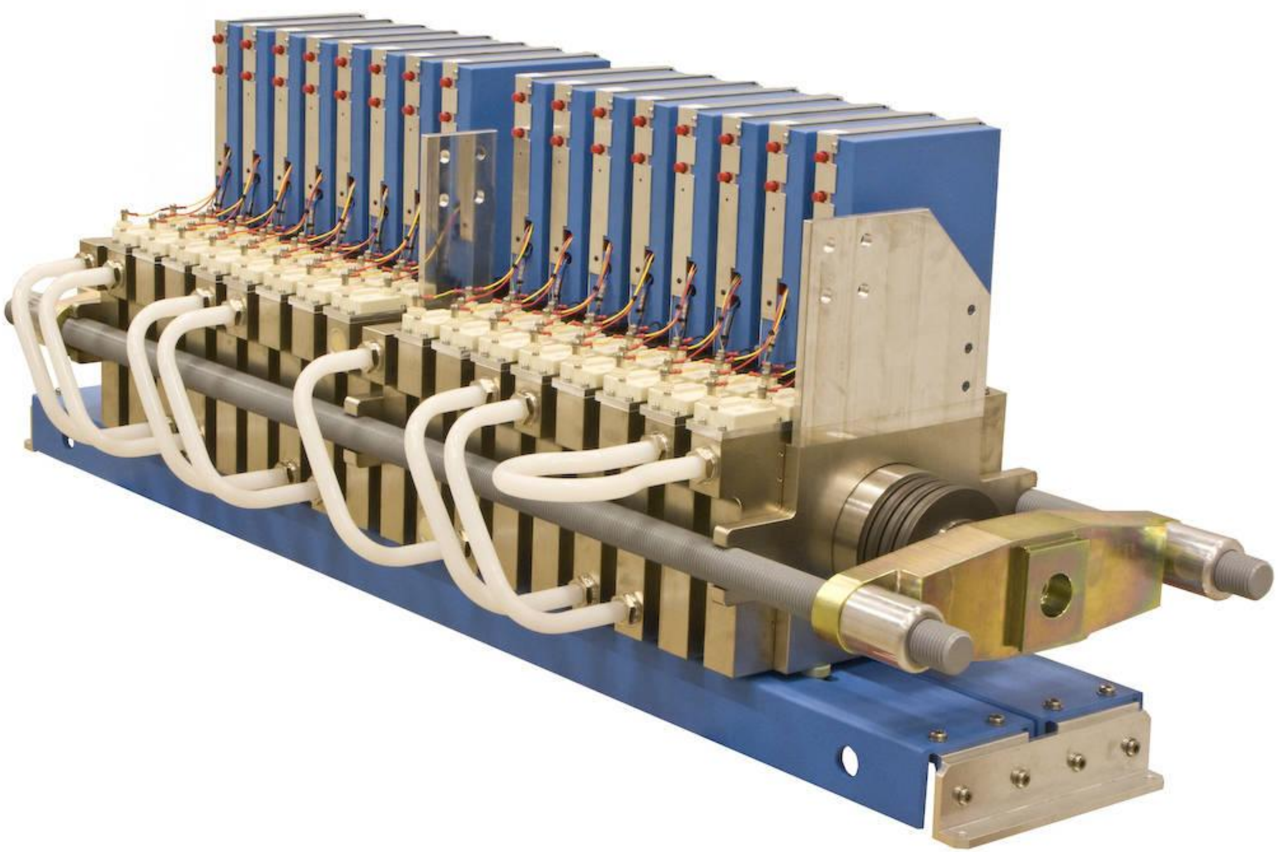


The converter valve
Cell main components – IGBTs and Capacitors



IGBT Module



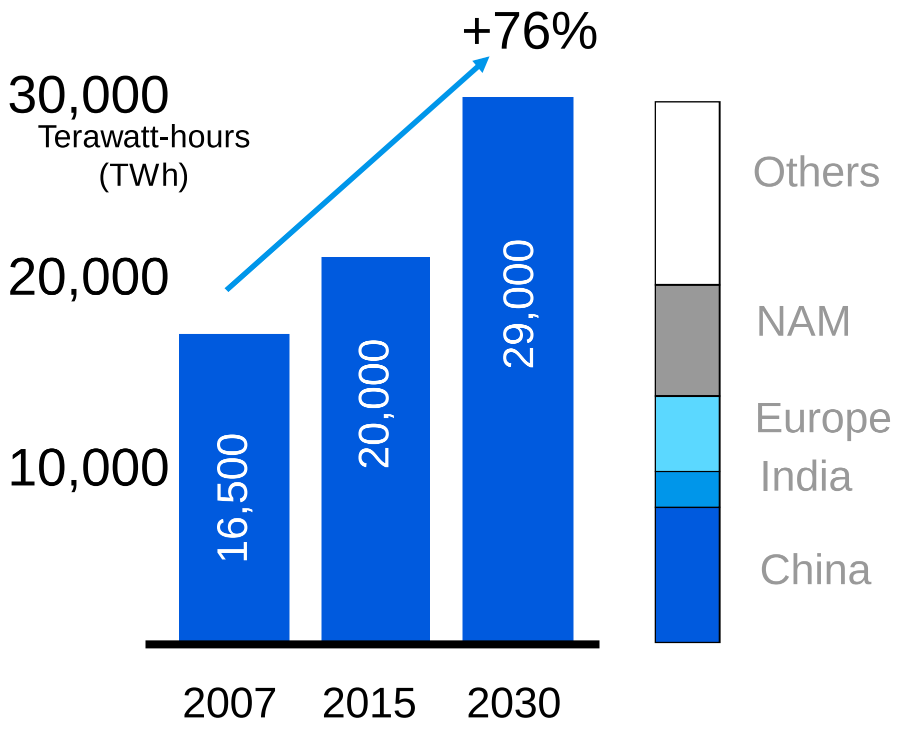


IGBT inner structure

Tackling society’s challenges on path to low-carbon era means helping utilities do more using less

Forecast rise in electricity consumption by 2030

- Source: IEA, World Energy Outlook 2009



Solutions are needed for:

- Rising demand for electricity – more generation
- Increasing energy efficiency - improving capacity of existing network
- Reducing CO_2 emissions – Introduce high level of renewable integration

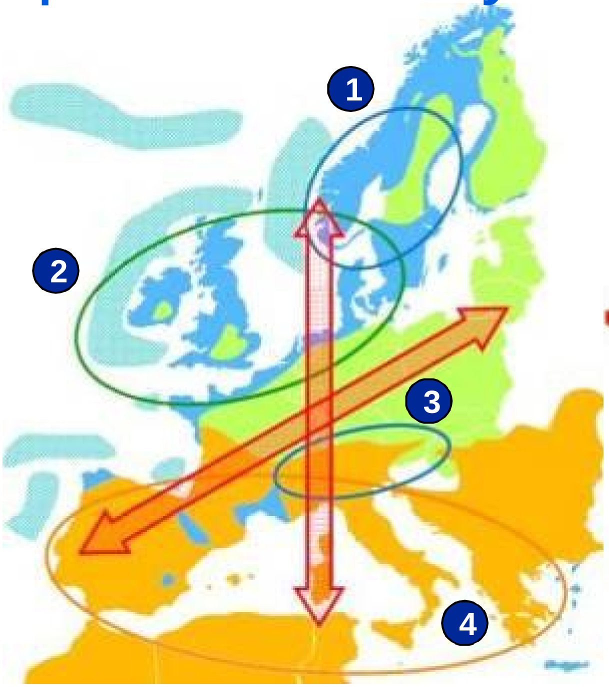
Meeting the rise in demand will mean adding a 1 GW power plant and all related infrastructure every week for the next 20 years

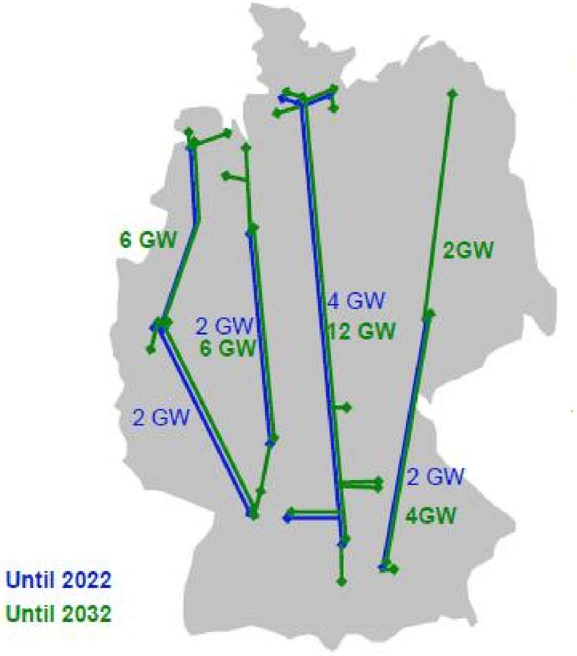
IEA World Energy Outlook 2012 - 2035

- **5 890 GW of capacity additions (> the total installed capacity in 2011) is required**
- One-third of this is to replace retiring plants; the rest is to meet growing electricity demand.
- Renewables represent half : 3000 GW. Gas 1400 GW.
- The power sector requires investment of $16.9 trillion,
- Investment in generation capacity, > 60% is for renewables: wind (22%), hydro (16%), solar PV (13%).

The evolution of HVDC grids: Connect remote renewables

Europe & Germany are planning large scale HVDC





Source: DG Energy, European Commission

European Visions

① Hydro power & pump storage -Scandinavia

② >50 GW wind power in North Sea and Baltic Sea

③ Hydro power & pump storage plants - Alps

④ Solar power in S.Europe, N.Africa & Middle East

Germany (draft grid master plan)

- Alternatives to nuclear-distributed generation
- Role of offshore wind / other renewables
- Political commitment
- Investment demand and conditions
- Need to strengthen existing grid

Lecture 1

Power electronic systems {Ch1}
Power basics
Circuit theory

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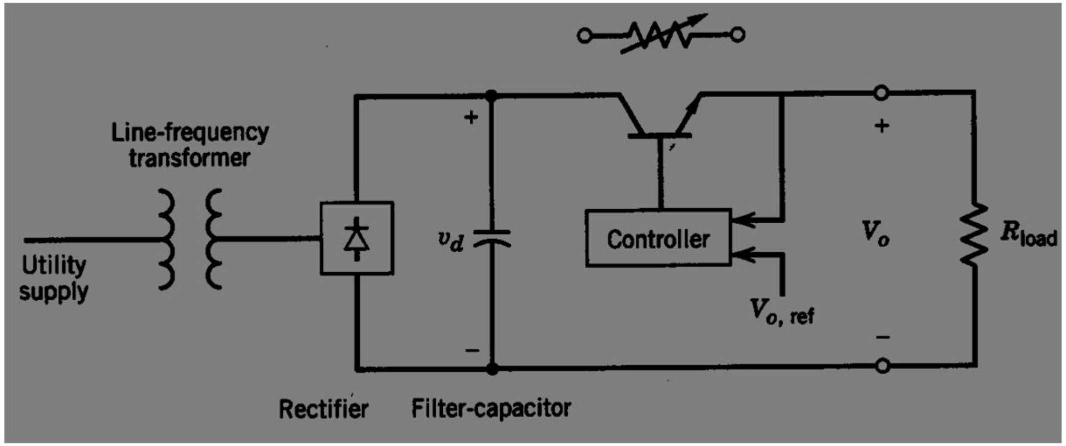
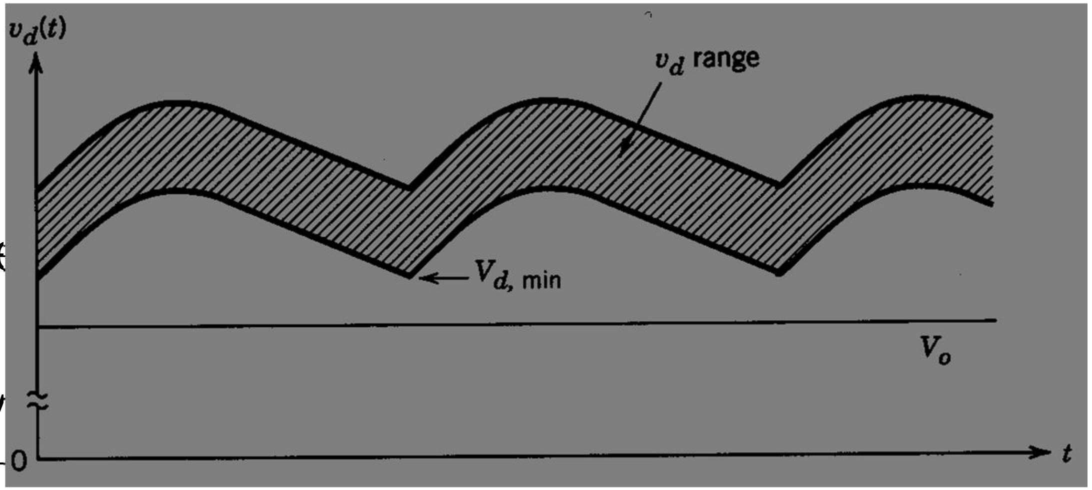
Example: Power Supply

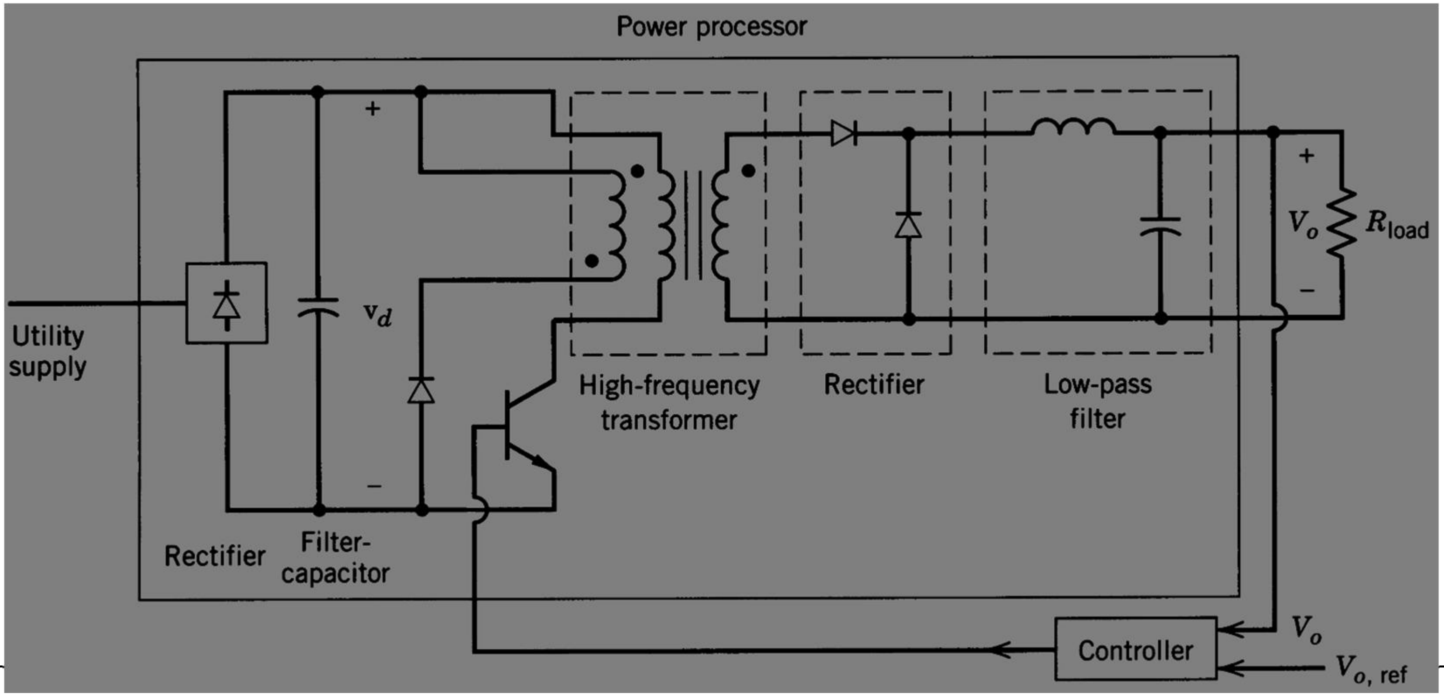
- Goal
  - Fixed DC voltage
  - Accept variation on input voltage
- Linear power supply
  - Adjustable resistor implemented using a transistor
  - Low efficiency,
    lot of power dissipate
    in transistor
  - Bulky line-frequency transformer





Example: 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

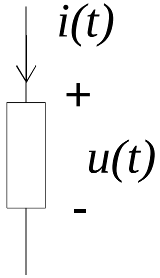
Symbol definitions

- u_{ab}, U_{ab} Voltage. U_{ab} is the voltage between points a and b.
- v_a Potential. The voltage to ground at point a.
- OBS, the course book uses american standard:
  v for voltages in general.
- i_a, I_a Current in path (phase) a.
- p_a, P_a Power. Active power

- Lower case symbols denotes instantaneous values
- Upper case symbols denotes average or RMS values

Power Basics

$$p(t) = u(t) * i(t)$$



- For AC signal (pure sinusoidal)

$$u(t) = \hat{U}\sin(\omega t + \phi_u)[V]$$

$$i(t) = \hat{I}\sin(\omega t + \phi_i)[A]$$

$$\text{where}\ \omega = 2\pi f = \frac{2\pi}{T}$$

$$P = \int_0^T p(t)dt = \frac{\hat{U}}{\sqrt{2}} \cdot \frac{\hat{I}}{\sqrt{2}}\cos(\phi_u - \phi_i) = U_e * I_e * \cos\phi[W]$$

- For DC signals

$$P = UI$$

Average power and rms current

Instantaneous power

$$p(t) = u(t) \cdot i(t)$$

Average power

$$P_{av} = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T u(t) \cdot i(t)\, dt$$

$$P_{av} = R\frac{1}{T}\int_0^T i^2(t)dt$$

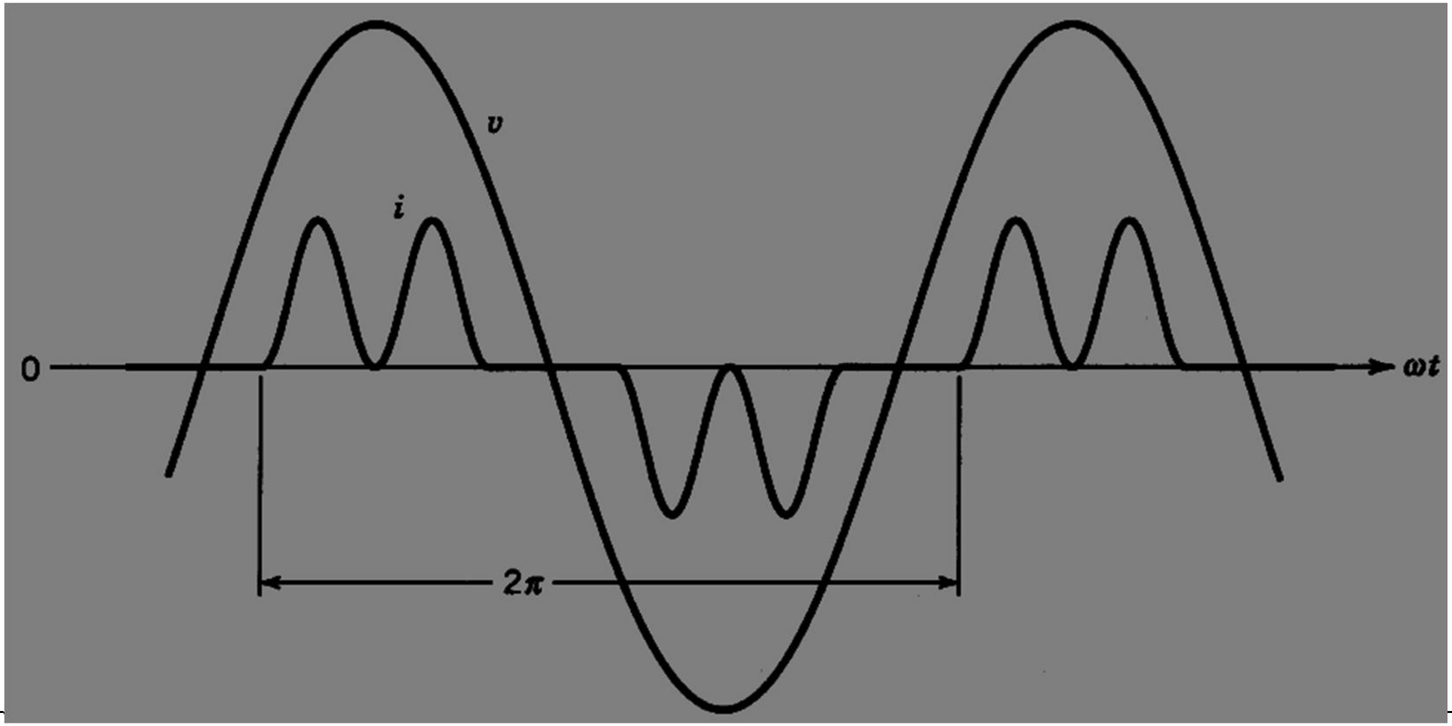
$$P_{av} = RI^2$$

RMS current:
the current value
that defines the
average power

$$I = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt}$$

Steady state voltages and currents

- Assume repeating waveform
- Ignore startup sequence (steady state)



Fourier analysis

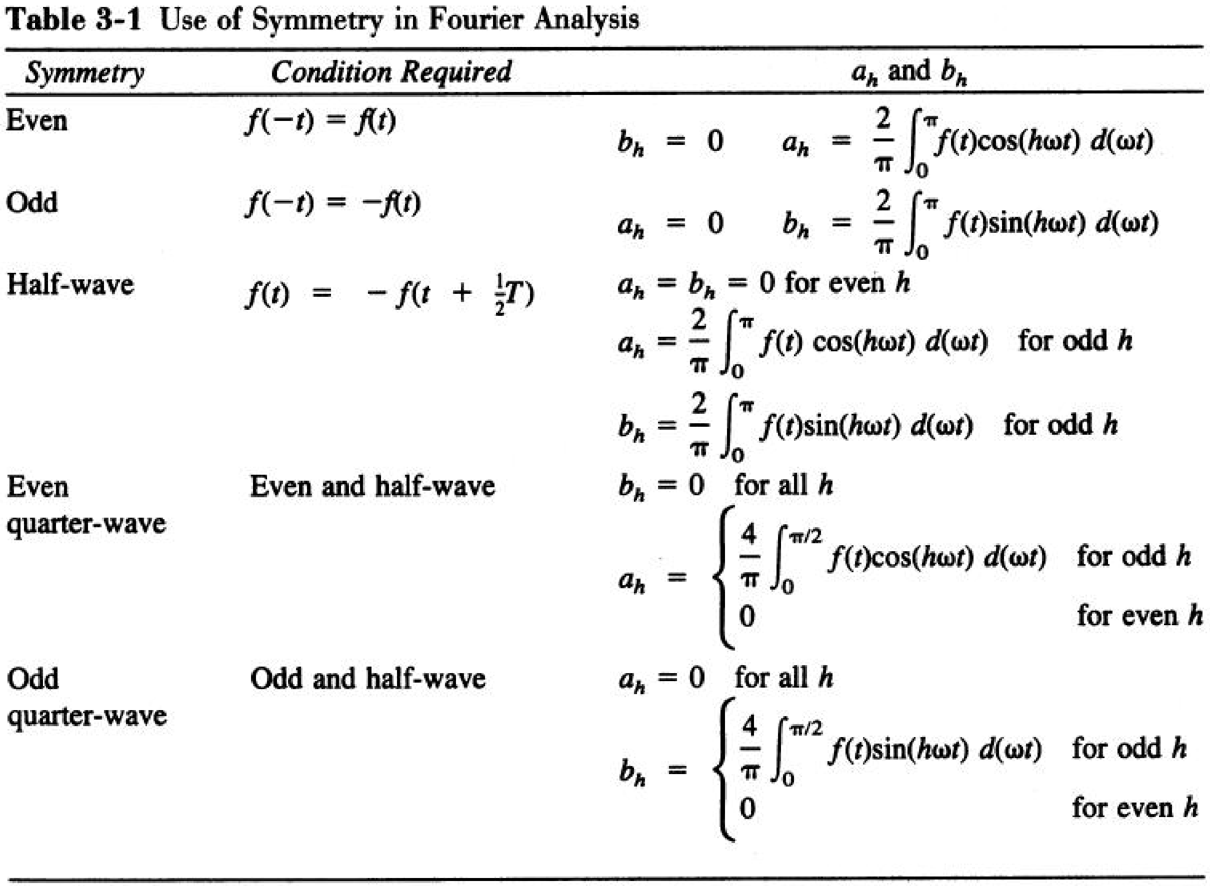


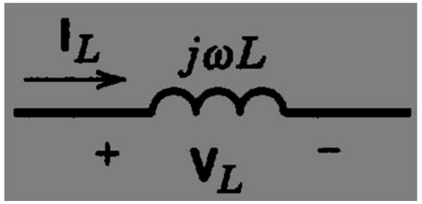
Table 3-1 Use of Symmetry in Fourier Analysis

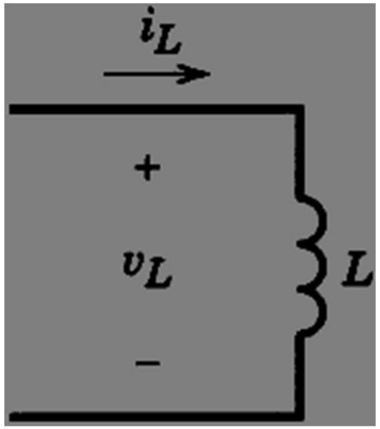
Symmetry	*Condition Required*	a_h and b_h
Even	$f(-t) = f(t)$	$b_h = 0 \quad a_h = \frac{2}{\pi}\int_0^{\pi} f(t)\cos(h\omega t)\, d(\omega t)$
Odd	$f(-t) = -f(t)$	$a_h = 0 \quad b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)\, d(\omega t)$
Half-wave	$f(t) = -f(t + \frac{1}{2}T)$	$a_h = b_h = 0$ for even h $a_h = \frac{2}{\pi}\int_0^{\pi} f(t)\cos(h\omega t)\, d(\omega t)$ for odd h $b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)\, d(\omega t)$ for odd h
Even quarter-wave	Even and half-wave	$b_h = 0$ for all h $a_h = \begin{cases} \frac{4}{\pi}\int_0^{\pi/2} f(t)\cos(h\omega t)\, d(\omega t) & \text{for odd } h \\ 0 & \text{for even } h \end{cases}$
Odd quarter-wave	Odd and half-wave	$a_h = 0$ for all h $b_h = \begin{cases} \frac{4}{\pi}\int_0^{\pi/2} f(t)\sin(h\omega t)\, d(\omega t) & \text{for odd } h \\ 0 & \text{for even } h \end{cases}$

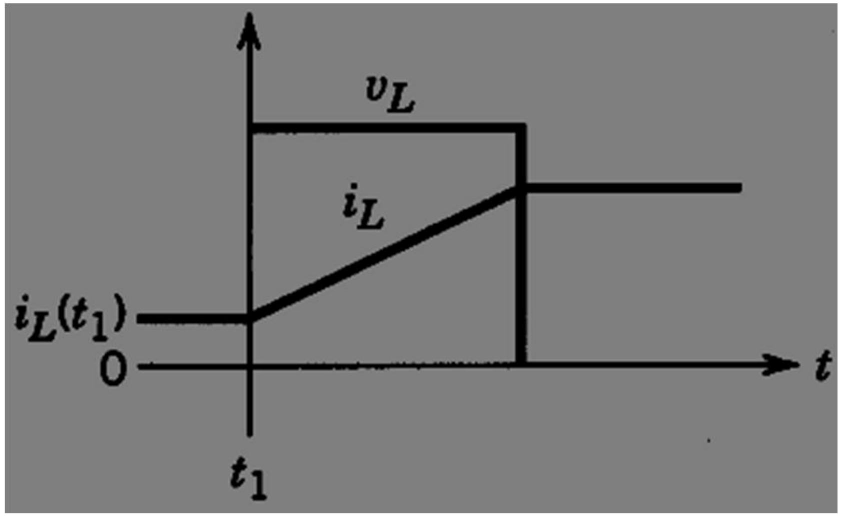
Inductor behaviour

- Frequency and time domain
- $v_L = L\frac{di_L}{dt}$ $V_L = j\omega L I_L$

$$i_L(t) = i_L(t_1) + \frac{1}{L}\int_{t_1}^{t} v_L d\xi$$

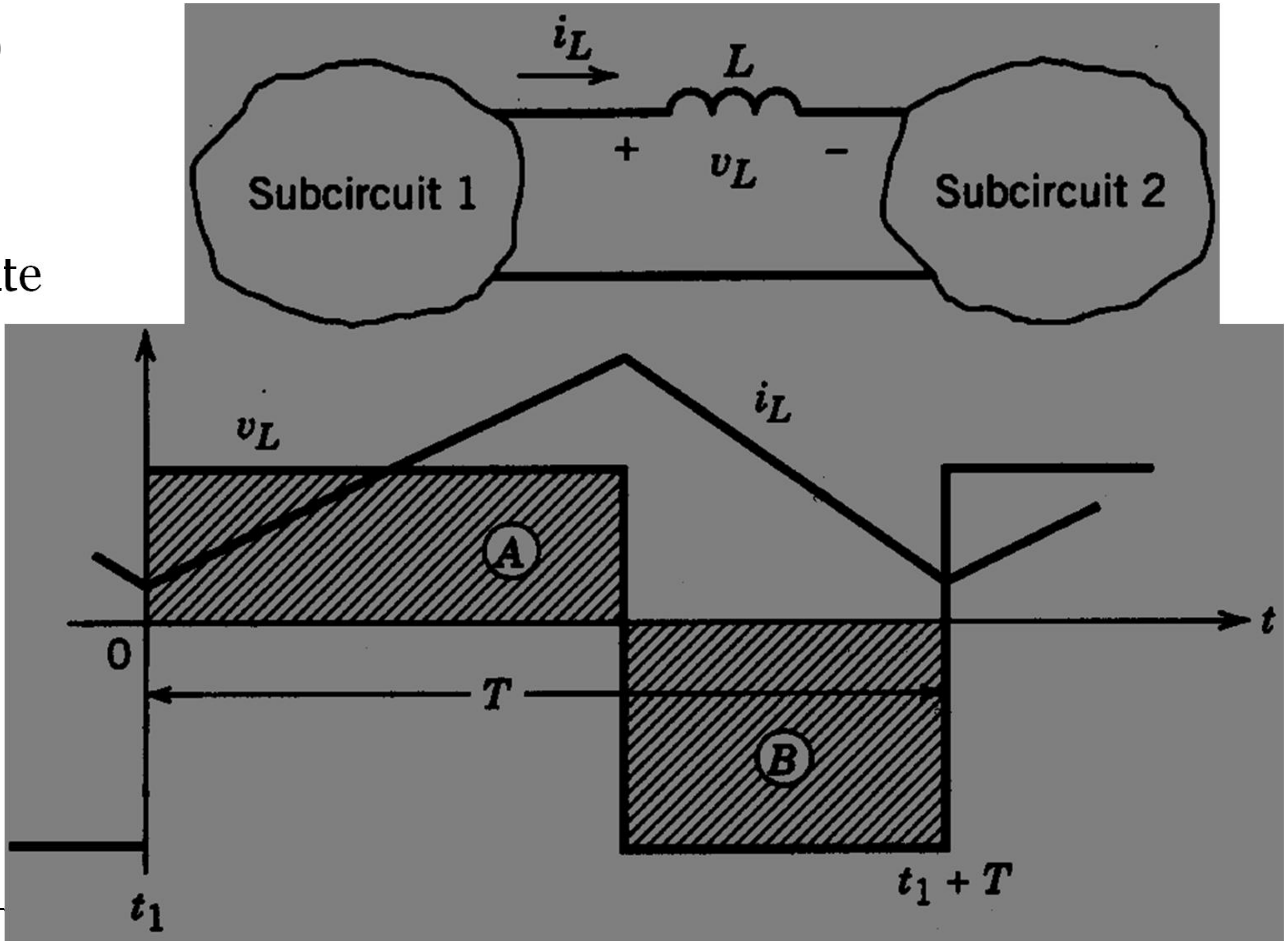






Inductor in steady state

- v(t+T) = v(t)
- i(t+T) = i(t)
- A = B
  in steady state

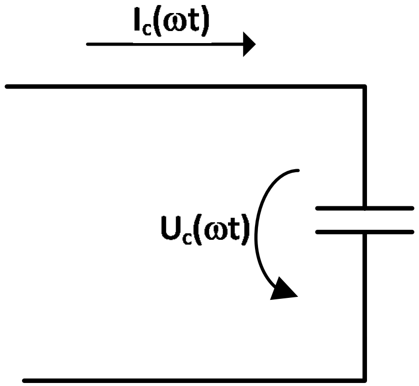


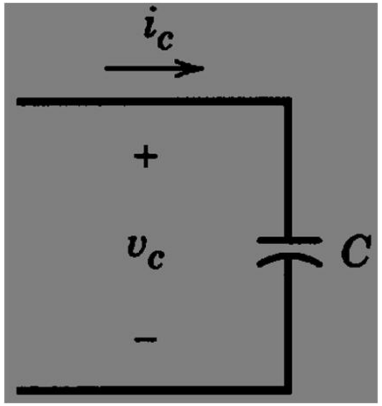
Capacitor behavior

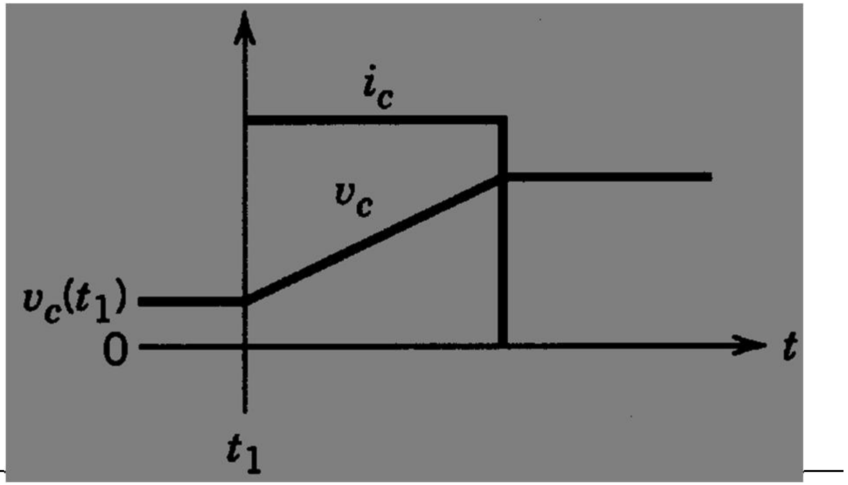
- Frequency and time domain

$$V_C = \frac{1}{j\omega C} I_C$$

$$v_C(t) = v_C(t_1) + \frac{1}{C}\int_{t_1}^{t} i_C \, d\xi$$

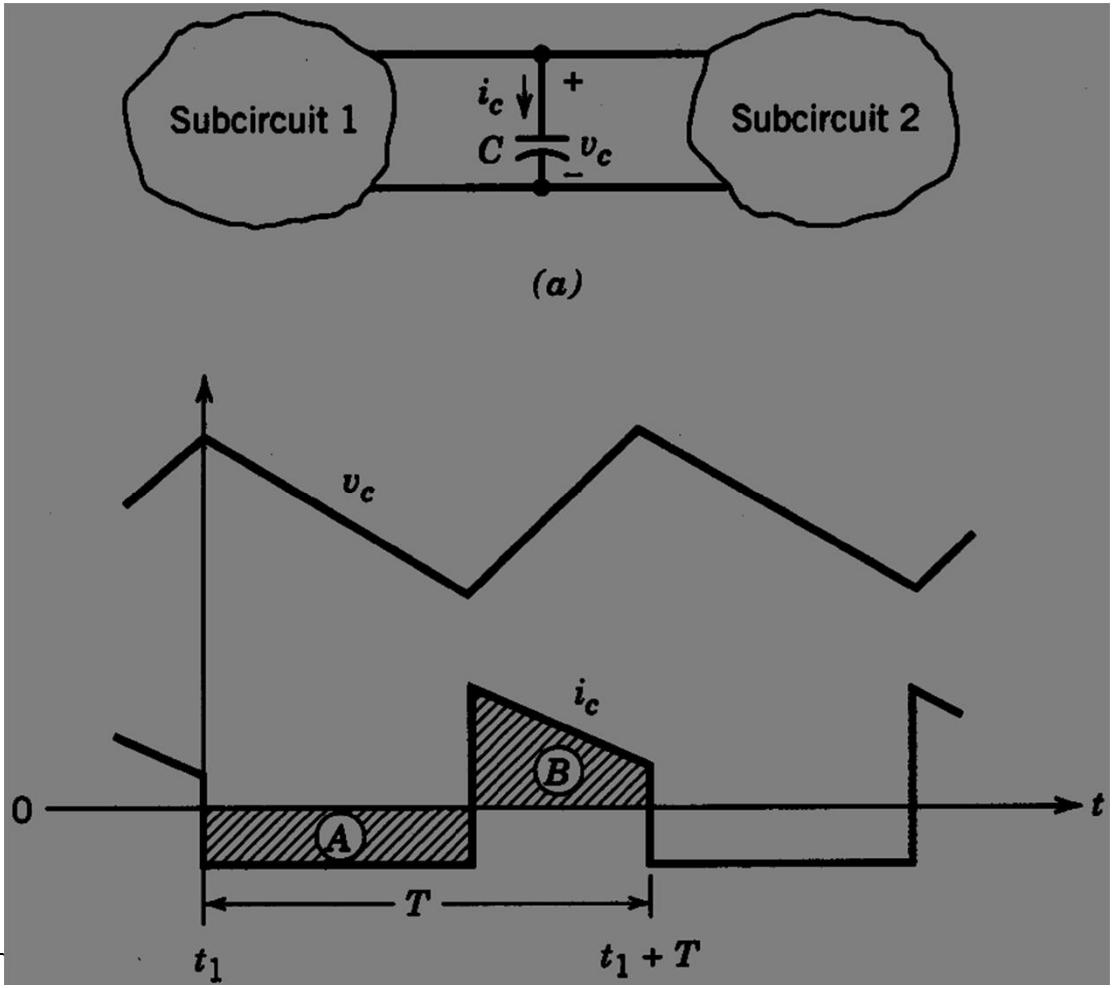






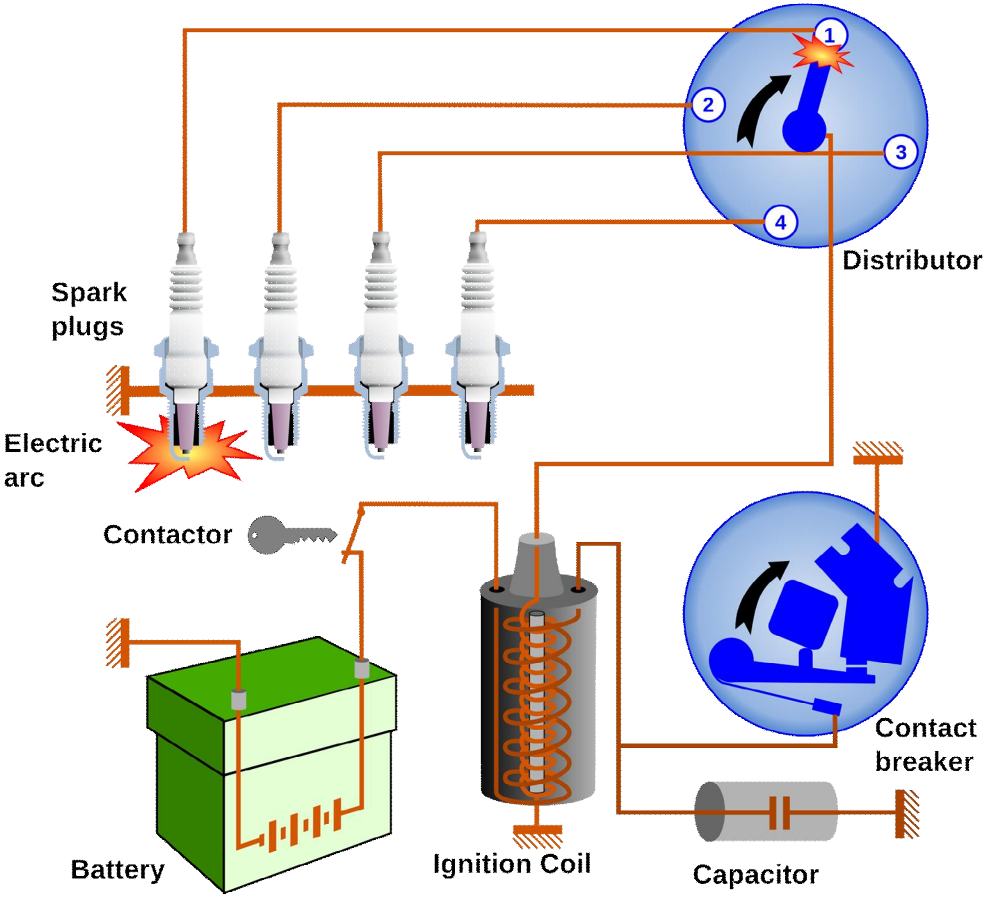
Capacitor in steady state

- v(t+T) = v(t)
- i(t+T) = i(t)
- A = B
  in steady state



Car ignition system

- Sudden opening of the contact breaker give high dI/dt through the ignition coil
- 20-50kV obtained at the spark plug
- Capacitor protects the contact breaker from excessive voltage

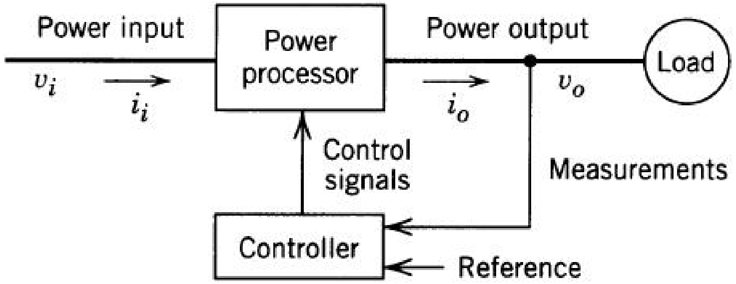


Exercises, lecture 1

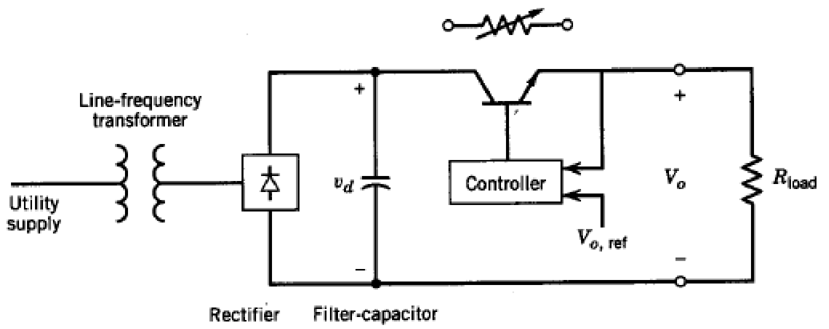
1-1, 1-2, 1-3, 1-4, 1-5

3-3, 3-4, 3-5

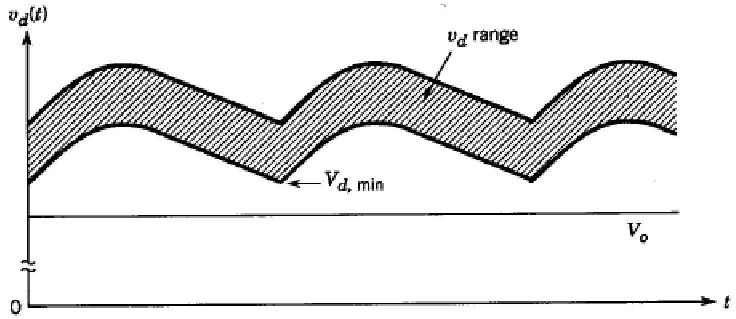
1-1 In the power processor of Fig. 1-1, the energy efficiency is 95%. The output to the three-phase load is as follows: 200 V line-to-line (rms) sinusoidal voltages at 52 Hz and line current of 10 A at a power factor of 0.8 (lagging). The input to the power processor is a single-phase utility voltage of 230 V at 60 Hz. The input power is drawn at a unity power factor. Calculate the input current and the input power.



1-2 Consider a linear regulated dc power supply (Fig. 1-2*a*). The instantaneous input voltage corresponds to the lowest waveform in Fig. 1-2*b*, where $V_{d,\min} = 20$ V and $V_{d,\max} = 30$ V. Approximate this waveform by a triangular wave consisting of two linear segments between the above two values. Let $V_o = 15$ V and assume that the output load is constant. Calculate the energy efficiency in this part of the power supply due to losses in the transistor.



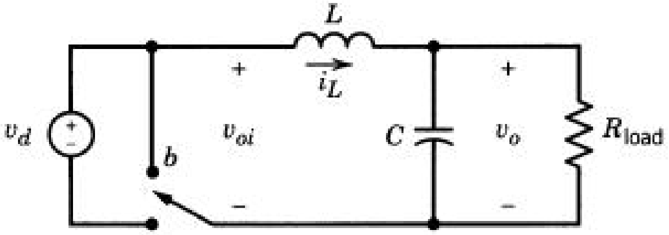
(a)



(b)

1-5 In Problem 1-4, assume the output voltage to be a pure dc $V_o = 15$ V. Calculate and draw the voltage and current associated with the filter inductor L, and the current through C. Using the capacitor current obtained above, estimate the peak-to-peak ripple in the voltage across C, which was initially assumed to be zero. (*Hint:* Note that under steady-state conditions, the average value of the current through C is zero.)

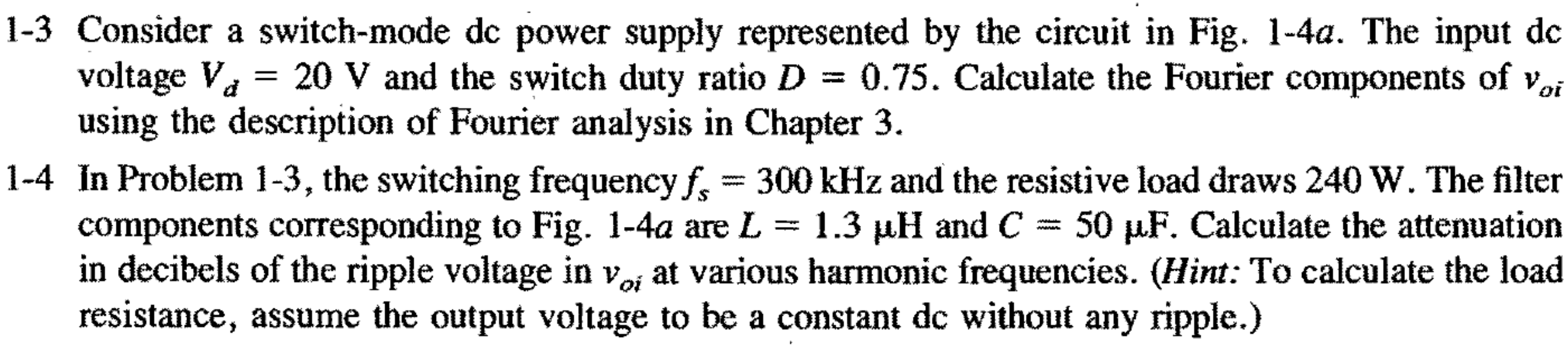
Vd=20V
Duty cycle D=0.75
fs = 300kHz
L=1.3 µH
C=50 µF
Pload = 240W



(a)

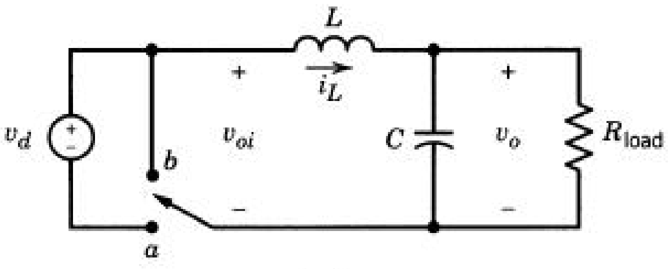
Extra questions:

a) What is the efficiency?
b) Calculate rms values for v_{oi} and i_L



1-3 Consider a switch-mode dc power supply represented by the circuit in Fig. 1-4*a*. The input dc voltage $V_d = 20$ V and the switch duty ratio $D = 0.75$. Calculate the Fourier components of v_{oi} using the description of Fourier analysis in Chapter 3.

1-4 In Problem 1-3, the switching frequency $f_s = 300$ kHz and the resistive load draws 240 W. The filter components corresponding to Fig. 1-4*a* are $L = 1.3$ µH and $C = 50$ µF. Calculate the attenuation in decibels of the ripple voltage in v_{oi} at various harmonic frequencies. (*Hint:* To calculate the load resistance, assume the output voltage to be a constant dc without any ripple.)



(*a*)

Vd=20V
Duty cycle D=0.75
fs = 300kHz
L=1.3 µH
C=50 µF
Pload = 240W

3-3

- For the waveforms in Fig. P3-3, calculate their average value and the rms values of the fundamental and the harmonic frequency components.

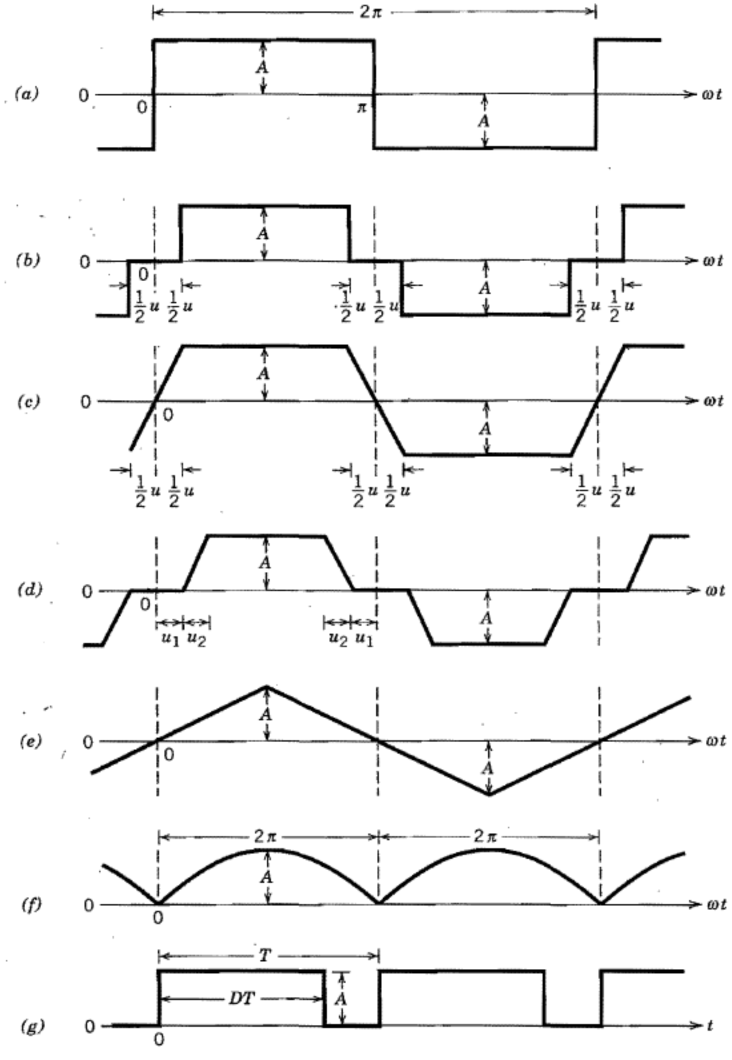


Figure P3-3

3-4

In the waveforms of Fig. P3-3 of Problem 3-3, *A* = 10 and *u* = 20° (ul = *U2 = u/2)* , where applicable. Calculate their total rms values as follows:

a) By using the results of Problem 3-3 in Eq. 3-28.

b) By using the definition of the rms value as given in Eq. 3-5.

3-5

Refer to Problem 3-4 and calculate the following:

a) For each of the waveforms *a-e,* calculate
    i. the ratio of the fundamental frequency component to the total rms value
    ii. the ratio of the distortion component to the total rms value.

b) For the waveforms f and g, calculate the ratio of the average value to the total rms value.

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