Electronics and
Computer Science

ELEC2208 Power Electronics and Drives

Power Electronics

- Introduction -

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Part 1: Power Electronics

Dr Yoshi Tsuchiya

1. Introduction

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2. Diode
3. Thyristor
4. Transistor

Individual devices

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5. Heating and Cooling

Thermal management

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6. Phase-Controlled Thyristor Converter and Diode Rectifier
7. Cycloconverter
8. Inverter
9. DC-to-DC Converter

Convertors

Part 1: Timetable 2022/23

W/C	Tuesday 3pm	Wednesday 11am	Thursday 3pm
30th Jan	Introduction	Diode	Diode/Thyristor
6th Feb	Thyristor	Tutorial 1	Transistor
13th Feb	Cooling	Tutorial 2	Phase-Controlled Converter
20th Feb	Rectifier	Cycloconverter	Tutorial3
27th Feb	Inverter	DC-DC converter	DC-DC converter
6th Mar	Tutorial 4	Drive Systems (Fred & Zehor)	…
Room	46/2003	02A/2065	58/1007

12 lectures and 4 tutorials

Part 1: Power Electronics

Tutorials

Tutors will work out the questions in a tutorial sheet to be delivered in advance to tutorials

Revision sessions

Example questions to be worked out: 10 & 11 May 2023

Lecture recording

All the sessions will be recorded.

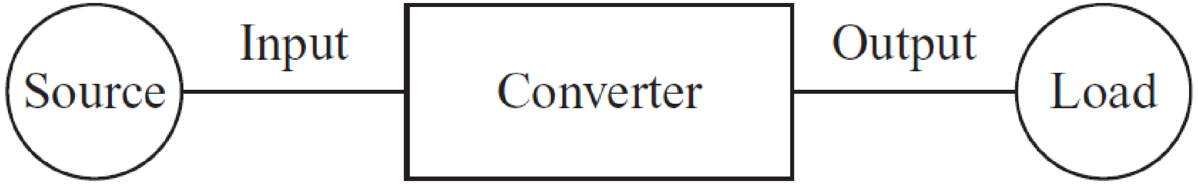
Further textbook

Daniel W. Hart, "Power Electronics" 201, McGraw-Hill Companies, Inc

What is Power Electronics?

Definition

Branch of **electrical engineering** devoted to **conversion and control of electric power** using electronic converters based on **semiconductor power switches**.



The input and output may be **alternating current (AC)** or **direct current (DC)** and may differ in magnitude and frequency.

Elements of Power Converters

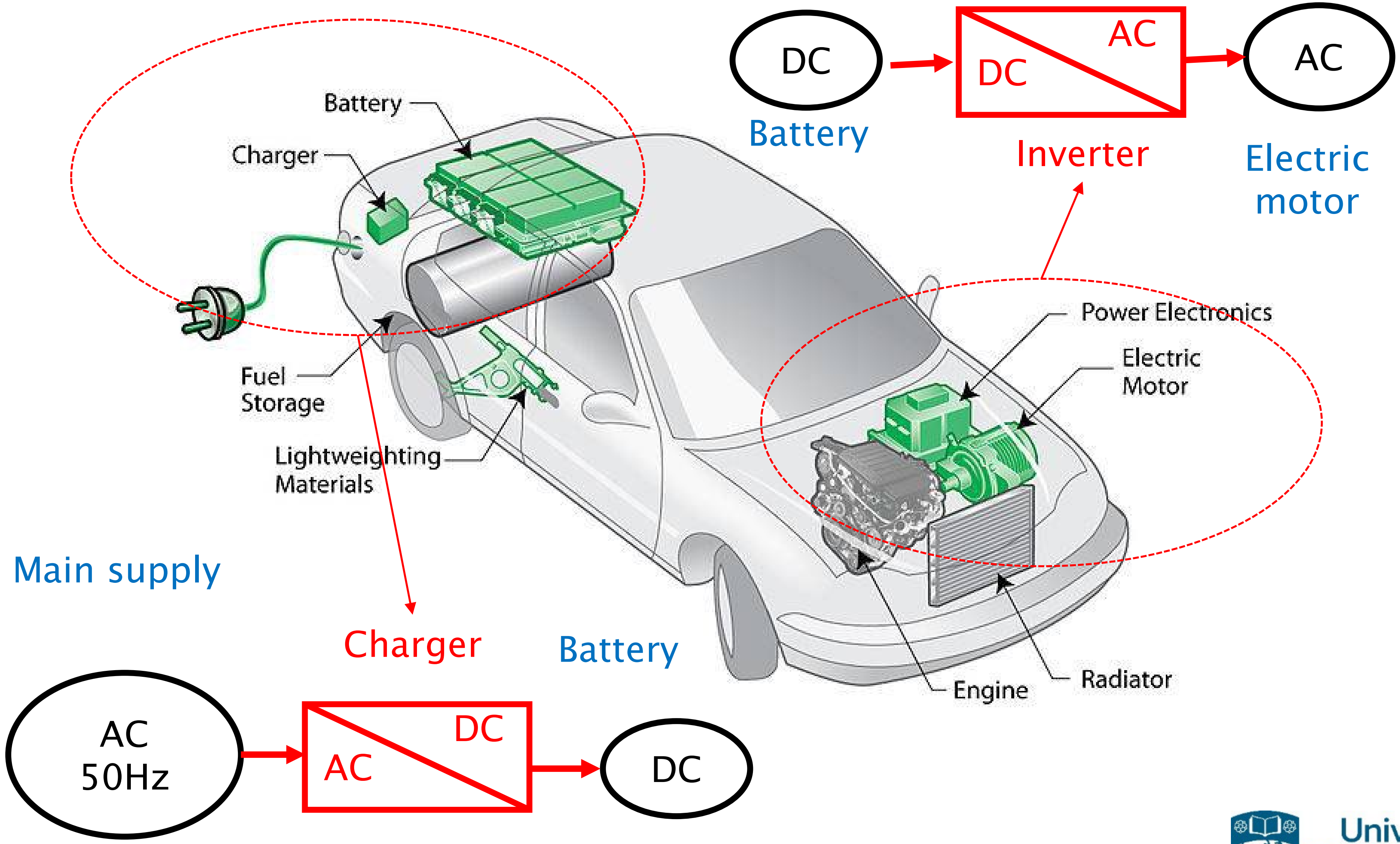
Passive components

- Capacitors
- Inductors
- Transformers

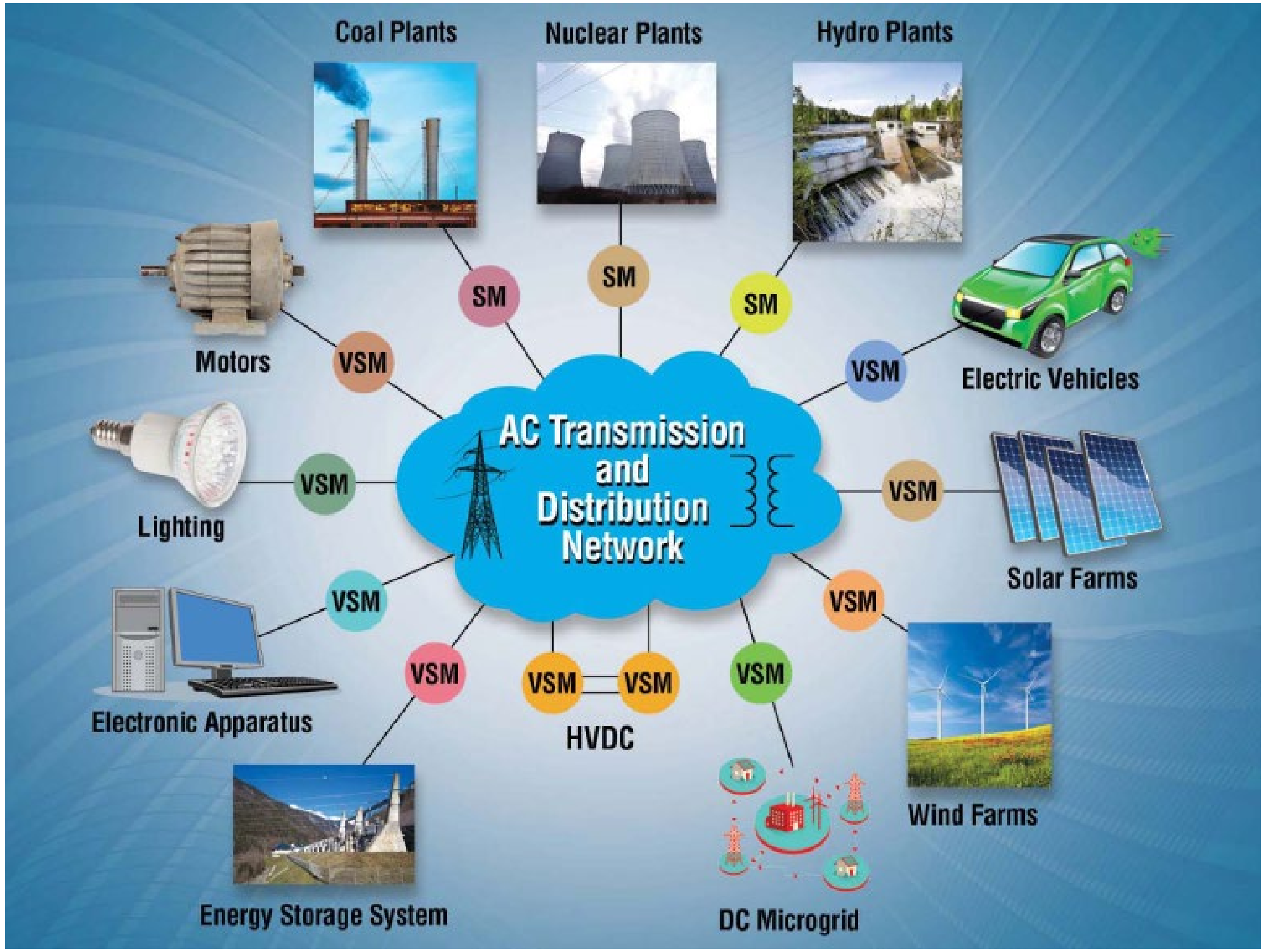
Power switches

- Diodes
- Thyristors
- Transistors

Application – Electric Vehicle



Further applications



Power electronics is a key enabling technology for a sustainable world.

Classification of Power Converters

Electrical supplies: **AC** or **DC**

→ **4 input output combinations**

AC input/DC output – Rectifier

Half-wave, full-wave rectifier, etc.

DC input/AC output – Inverter

Half-bridge, full-bridge, multilevel inverter, etc.

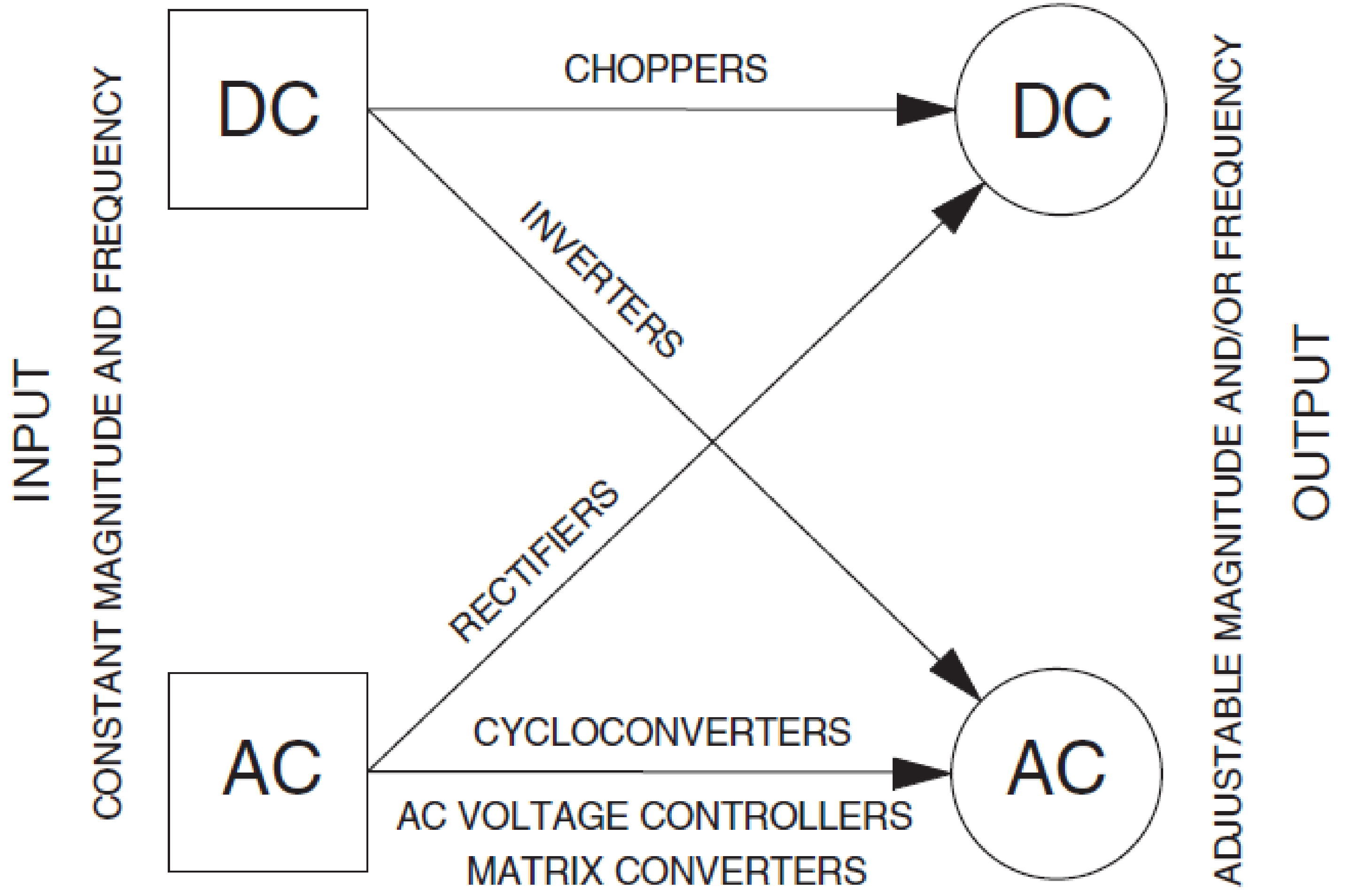
DC input/DC output – DC-DC converter

Buck, boost, buck-boost, etc.

AC input/AC output – AC-AC converter

Matrix converter, cycloconverter, etc.

Classification of Power Converters

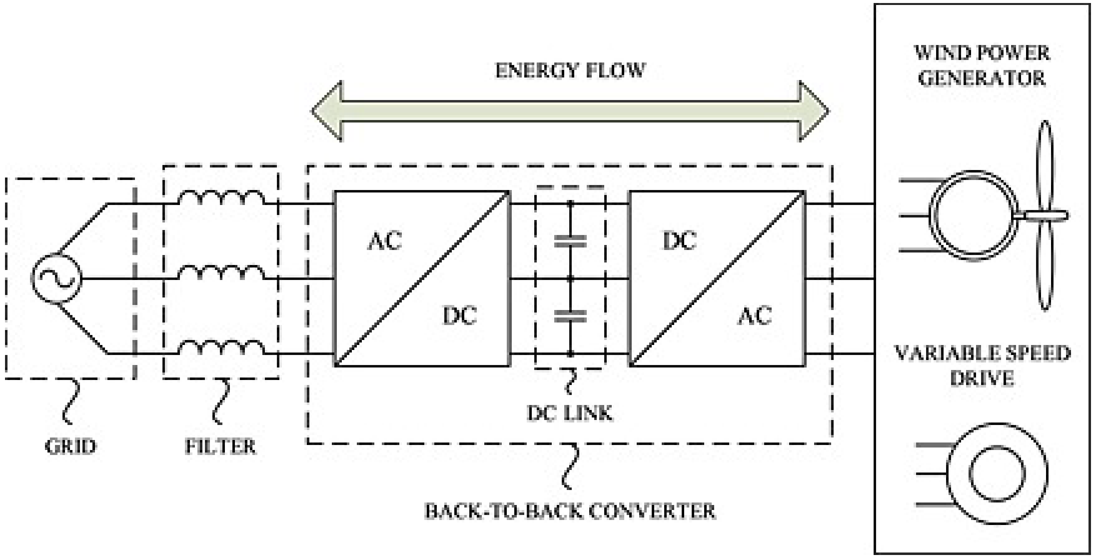


Power Converters - Features

- The voltages on either side of a power converter do not have to be equal.
- For AC supplies, the frequency and phase angle on either side of a power converter can be the same or different.
- Power conversion can be a multistep process (combination of multiple power converters) involving more than one type of converter.

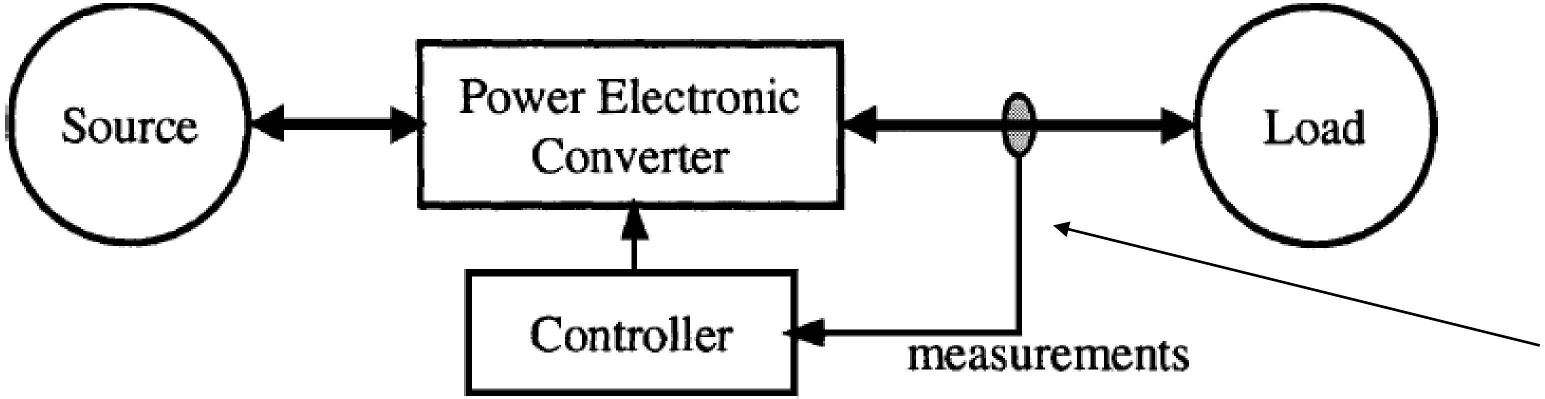
Example:

AC to DC then DC to AC for motor drive system.



Power Converter Systems

- Power converter system consists of semiconductor devices as power switches and passive components as filter or energy storage elements to synthesize voltage and current waveforms according to the demand.
  - Power supply with constant (in most cases) magnitude and frequency.
  - Demand with specific magnitude and frequency which is different from the source.



Feedback for safe operation

Circuit analysis revision

1. Passive components

- Capacitors
- Inductors

2. Wave form analysis

- Fourier series

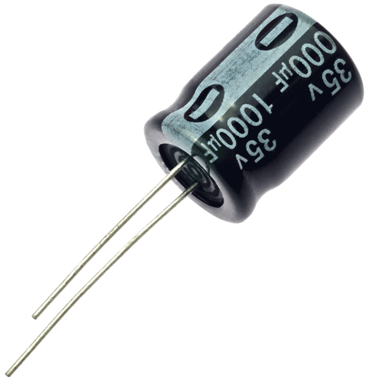
3. Circuit analysis

- KVL, KCL, RMS

4. Average power

5. Ideal vs Practical switches

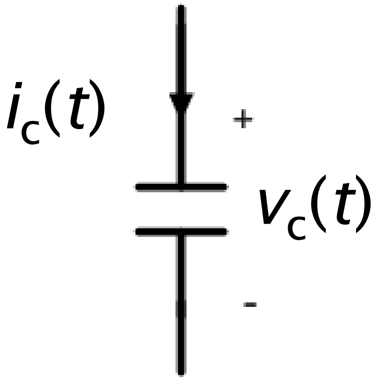
Capacitors



Capacitors can store energy in electric field.

Amount of charge stored is proportional to the voltage:

$$Q(t) = C v_C(t) \qquad \Delta Q = C \Delta V$$



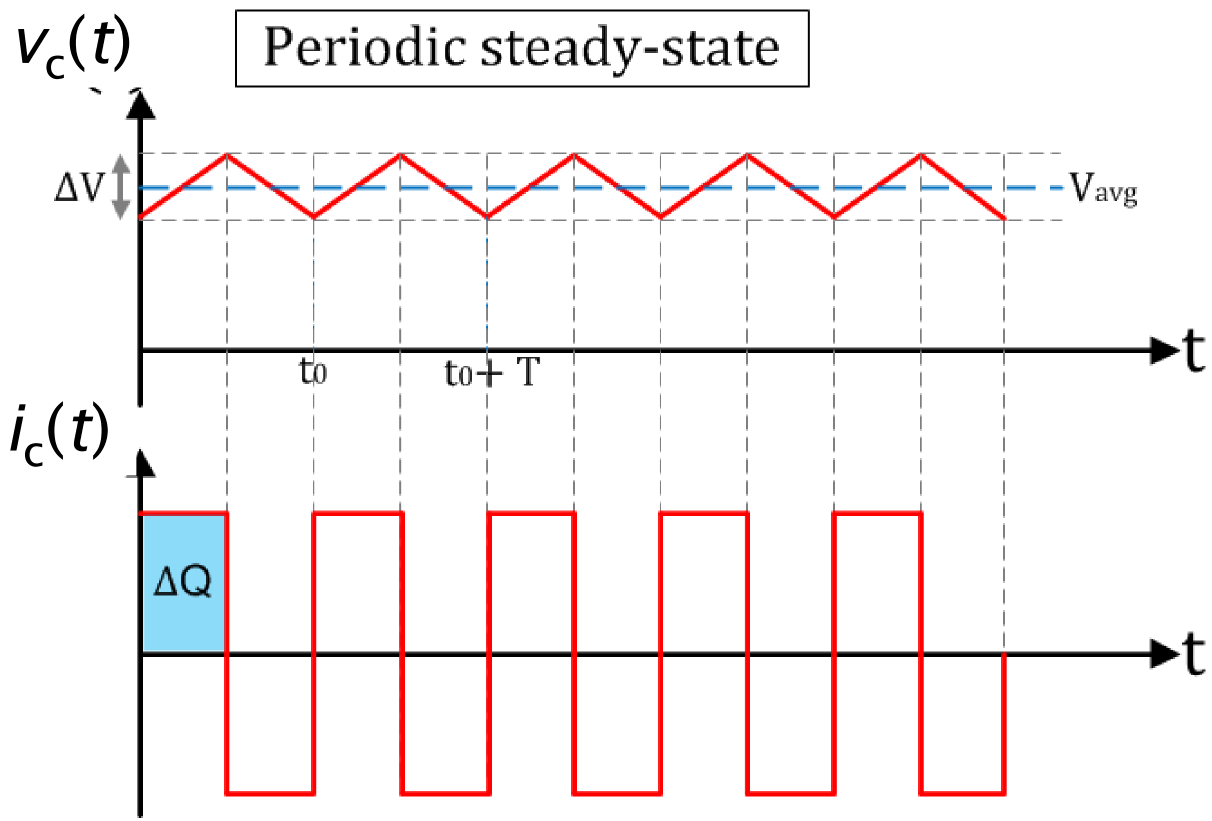
Energy stored

$$w(t) = \frac{1}{2} C {v_C}^2$$

Current and voltage

$$i_C(t) = C \frac{d v_C(t)}{dt} \qquad v_C(t) = \frac{1}{C} \int_{t_0}^{t} i_C(t) dt + v_C(t_0)$$

Capacitors



Response to periodic voltage waveform at steady state

$$v_C(t+T) = v_C(t)$$

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

$$\langle i_C(t)\rangle = I_C$$
$$= \frac{1}{T}\int_t^{t+T} i_C(t)dt = 0$$

Average current is zero.

Average power: $P_C = 0$

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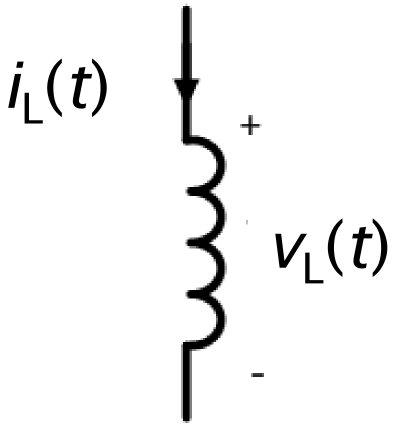
Inductors

Inductors can store energy in magnetic field.

Flux linkage is proportional to the current:

$$\lambda(t) = L i_L(t) \qquad \Delta\lambda = L\Delta I$$



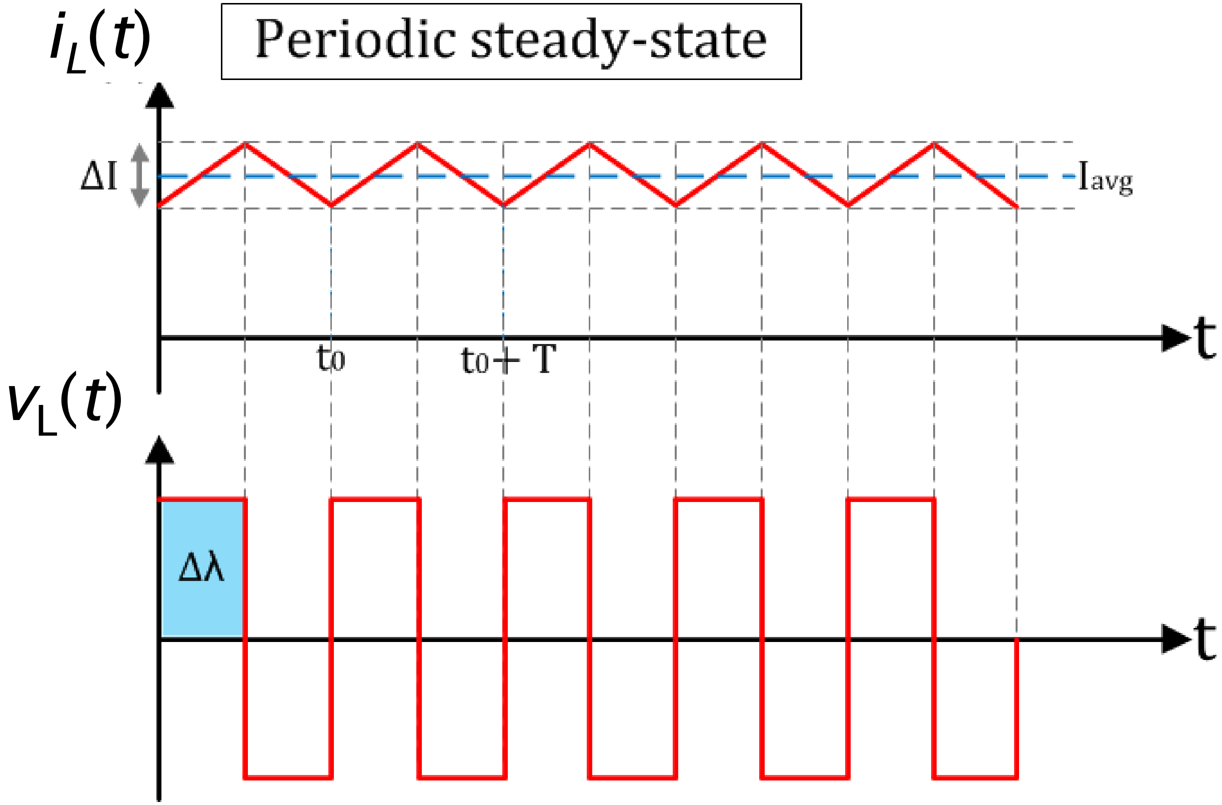
Energy stored

$$w(t) = \frac{1}{2} L {i_L}^2$$

Voltage and current

$$v_L(t) = L\frac{di_L(t)}{dt} \qquad i_L(t) = \frac{1}{L}\int_{t_0}^{t} v_L(t)dt + i_L(t_0)$$

Inductors



Response to periodic current waveform at steady state

$$i_L(t+T) = i_L(t)$$

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

$$\langle v_L(t)\rangle = V_L$$
$$= \frac{1}{T}\int_t^{t+T} v_L(t)dt = 0$$

Average voltage is zero.

Average power: $P_L = 0$

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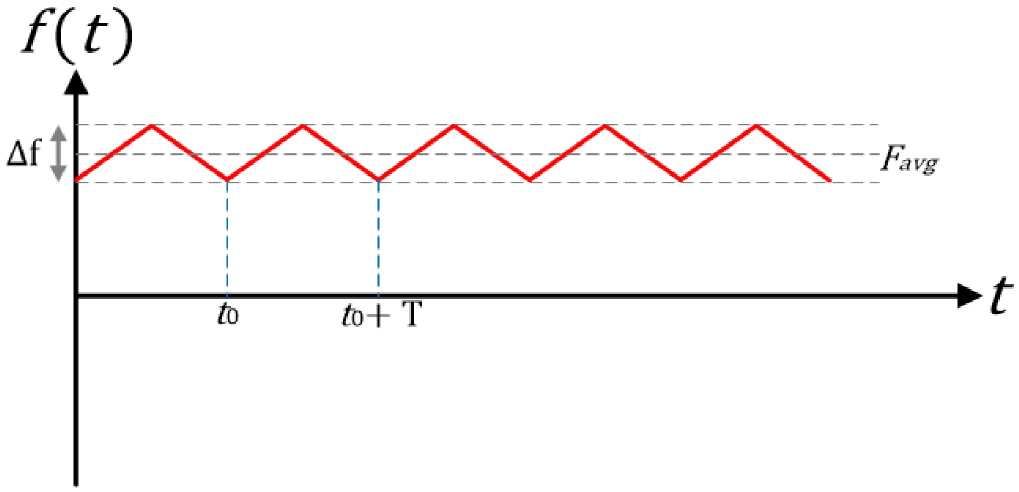
Analysis of Waveform

Periodic waveforms

The magnitude at the end of one period is the same as the beginning.

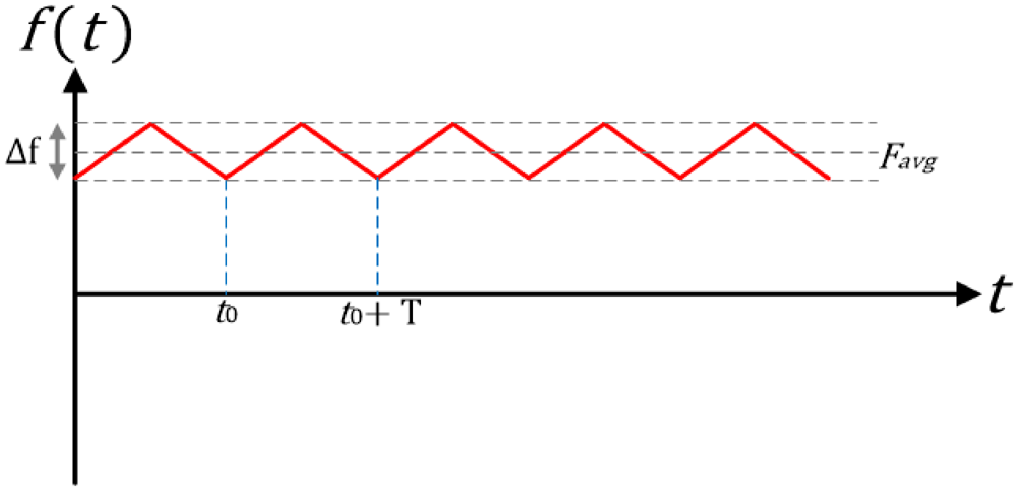
$$f(t+T) = f(t)$$

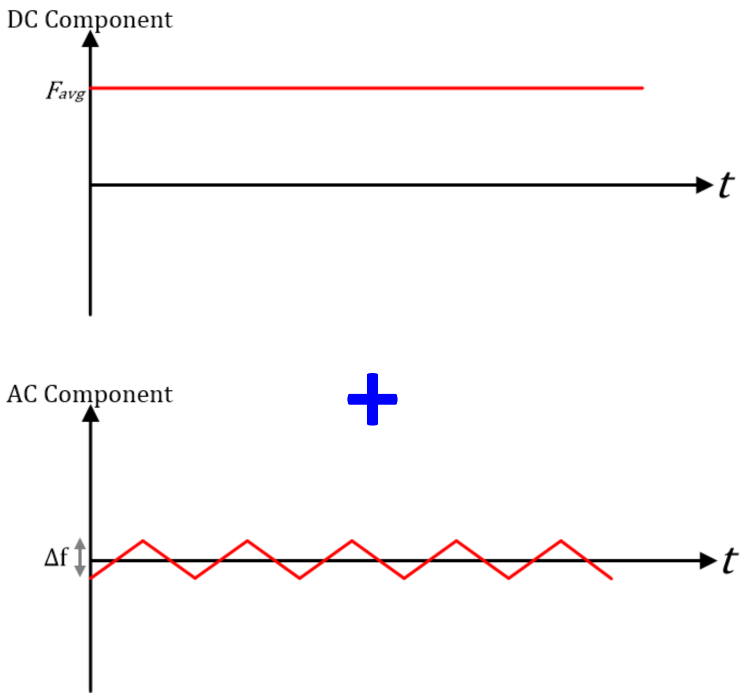


The periodic waveform consists of DC and AC components and can be described by a **Fourier Series** of sinusoids.

Analysis of Waveform

Periodic waveforms





Fourier Series

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos(n\omega_0 t) + b_n \sin(n\omega_0 t)]$$

$$= \frac{a_0}{2} + \sum_{n=1}^{\infty} C_n \cos(n\omega_0 t + \theta_n)$$

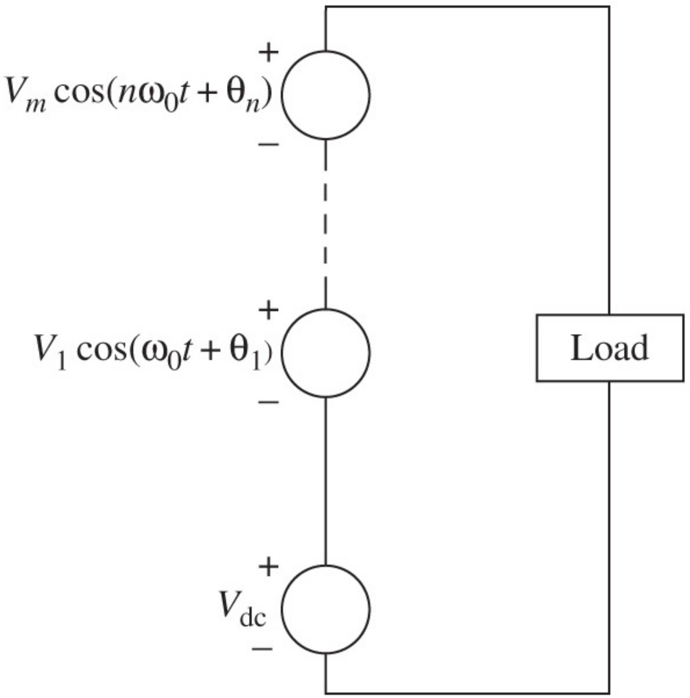
AC components

DC component

KVL and KCL

$$v(t) = V_{dc} + \sum_{n=1}^{n} V_n \cos(n\omega_0 t + \theta_n) \qquad i(t) = I_{dc} + \sum_{n=1}^{n} I_n \cos(n\omega_0 t + \phi_n)$$

Circuit analysis methods, KVL and KCL apply individually to DC and AC components.



KVL $v(t) = V_{dc} + v_{ac}(t)$

$$\sum_{loop} V_{dc} = 0$$

$$\sum_{loop} v_{ac}(t) = 0$$

KCL $i(t) = I_{dc} + i_{ac}(t)$

$$\sum_{node} I_{dc} = 0$$

$$\sum_{node} i_{ac}(t) = 0$$

Root Mean Square (RMS)

RMS of a function *f*(*t*)

$$F_{rms} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} f^2(t)dt}$$

If *f*(*t*) is sum of *N* periodic waveforms:

$$f(t) = f_1(t) + f_2(t) + \cdots + f_N(t)$$

$$F_{rms} = \sqrt{F_{1,rms}^2 + F_{2,rms}^2 + \cdots + F_{N,rms}^2} = \sqrt{\sum_{n=1}^{N} F_{n,rms}^2}$$

If *f*(*t*) is Fourier Series:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} C_n\cos(n\omega_0 t + \theta_n)$$

$$F_{rms} = \sqrt{\sum_{n=1}^{\infty} F_{n,rms}^2} = \sqrt{\left(\frac{a_0}{2}\right)^2 + \sum_{n=1}^{\infty}\left(\frac{C_n}{\sqrt{2}}\right)^2}$$

Power

Average of a function $f(t)$: $$F_{mean} = \frac{1}{T}\int_{t_0}^{t_0+T} f(t)dt$$

Power

Instantaneous power $$p(t) = v(t)i(t)$$

Average power/real power $$P = \frac{1}{T}\int_{t_0}^{t_0+T} p(t)dt = \frac{1}{T}\int_{t_0}^{t_0+T} v(t)i(t)dt$$

DC average power $\boldsymbol{P = V_{dc}I_{dc}}$ if $v(t) = V_{dc}$ and $i(t) = I_{dc}$.

If $v(t)$ and $i(t)$ are sinusoidal waveforms,

AC average power $$\boldsymbol{P = V_{rms}I_{rms}\cos(\theta - \phi)}$$

Power factor $$\boldsymbol{pf = \cos(\theta - \phi)}$$

θ : Phase of voltage
ϕ : Phase of current

Power

If $v(t)$ and $i(t)$ are non-sinusoidal periodic waveforms,

$$v(t) = V_{dc} + \sum_{n=1}^{n} V_n \cos(n\omega_0 t + \theta_n) \qquad i(t) = I_{dc} + \sum_{n=1}^{n} I_n \cos(n\omega_0 t + \phi_n)$$

Average power

$$P = V_{dc}I_{dc} + \sum_{n=1}^{\infty} V_{n,rms}I_{n,rms}\cos(\theta_n - \phi_n)$$

Power factor

$$pf = \frac{P}{S} = \frac{P}{V_{rms}I_{rms}}$$

$S = V_{rms}I_{rms}$ Magnitude of apparent power

Ideal power devices

Ideal characteristics of power switches

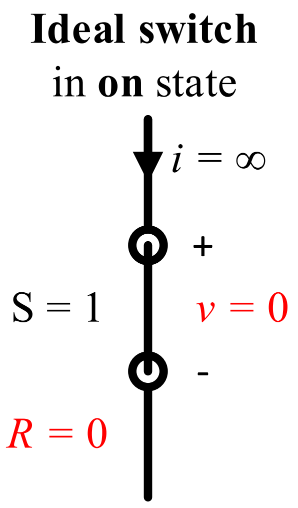
- Turn on and off instantaneously without delay
- High speed switching
- Zero power loss

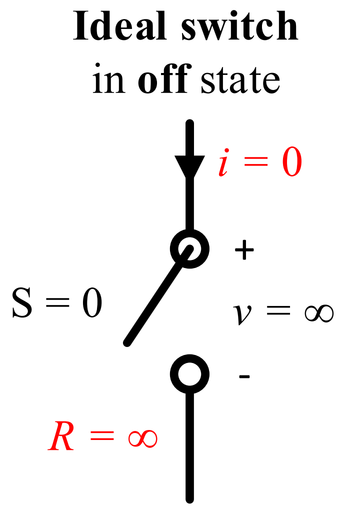
Ideal ON-state

Zero voltage drop across the switch and it can conduct infinite current due to zero impedance.

Ideal OFF-state

Zero current flow due to infinite impedance and it can block infinite voltage.





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Practical power devices

- Real power switches are semiconductor devices.
- They consume some power during operation.
- **Leakage current flows during Off state.**
- **Voltage drop occurs during On state** due to on resistance.
- Semiconductor power devices does not switch instantly. Delay during switching instant causes **switching loss**.
- Switching loss limits the switching frequency.
- Voltage and current of semiconductor power devices should be kept within **the safe operating value** to prevent failure.
- Due to power losses, **cooling by attaching the devices to heat sink is usually required** to keep the temperature of the devices within limits.

We need to study Power Electronics!