Electric Energy Conversion

1. Introduction to the course

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Outline

- Course basic information
- Initial concepts
- RMS calculation
- Characteristics of switches

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Basic information

- Lecturer: Vinícius Lacerda
- Department: Electrical Engineering
- Research group: CITCEA-UPC (ETSEIB)
  - Subgroup: Energy conversion and AC/DC networks
- Email: vinicius.lacerda@upc.edu
- Office ETSEIB. Office 23-21 (Building G)
- Research fields:
  - HVDC short-circuit analysis
  - HVDC protection
  - VSC modelling and simulation
  - Power quality
  - HVDC pre-fault detection
  - Modern power grids

Main objectives

This course aims to provide the basic knowledge about electric energy conversion, power electronics and applications in modern power grids.

The course objectives are:

- Achieve basic knowledge of semiconductor devices
- Study the power electronics components and their roles
- Understand the operating principles of uncontrolled and controlled rectifiers
- Understand the operating principles of DC/DC converters
- Understand the operating principles of DC/AC converters
- Explain the transition of the power system to a power-electronics dominated network.

Methodology

- Three-hour classes
- Theory classes, problem solving
  - Students to bring the laptop to class to perform simulations
  - Install Matlab (and Simulink Simscape Electrical)
  - The classes are organized as follows:
    - Lectures
    - Discussion on the lectures
    - Simulations related to the theory
    - Clarification of questions
    - Exercises
- Course material will be uploaded to ATENEA

Schedule

Course structure (main contents). To be adapted based on progress

Week nr:	Date of event	Time/Length	Type of event	Lecture topic
37	Sep. 20	15:00-18:00	Lecture	Introduction
38	Sep. 27	15:00-18:00	Lecture	Power semiconductor devices and Diode rectifiers
39	Oct. 4	15:00-18:00	Lecture/Lab	Diode rectifiers
40	T.B.D	15:00-18:00	Lecture	Invited speaker
42	Oct. 18	15:00-18:00	Lecture/Lab	DC/DC converters - Part 1
43	Oct. 25	15:00-18:00	Lecture/Lab	DC/DC converters - Part 2
45	Nov. 8	15:00-18:00	Lecture/Lab	DC/AC converters - Part 1
46	Nov. 15	15:00-18:00	Lecture/Lab	DC/AC converters - Part 2
47	Nov. 22	15:00-18:00	Lecture	Controlled rectifiers and AC/AC converters
48	Nov. 29	15:00-18:00	Lecture/Lab	Control of power electronics - Part 1
49	Dec.13	15:00-18:00	Lecture/Lab	Control of power electronics - Part 2
50	TBD	15:00-18:00	Lecture	Applications of power electronics in energy conversion
January	TBD		Exam	Final Exam

Activities and grading

Activities

- Simulation of a rectifer
- Simulation of a DC/DC converter
- Simulation of a DC/AC converter
- Implementation of a control system

Examination and Grading

- Final grade = Final exam (50%) + Labs (50%)
- Each lab is pass/fail graded

References

Power electronics

- Muhammad H. Rashid. *Power Electronics: Circuits, Devices, and Applications.* Pearson Education
- Daniel W. Hart (2010). *Power electronics*. McGraw-Hill
- Ned Mohan (2012). *Power electronics: a first course*. John Wiley & Sons
- Ned Mohan, Tore. N. Undeland and William. P. Robbins. *Power electronics: converters, applications and design.* John Wiley & Sons
- Simões, M. G., & Farret, F. A. (2016). *Modeling Power electronics and interfacing energy conversion systems*. John Wiley & Sons.
- Robert W. Erickson and Dragan Maksimovic. Fundamentals of Power Electronics. Kluwer Academic Publishers

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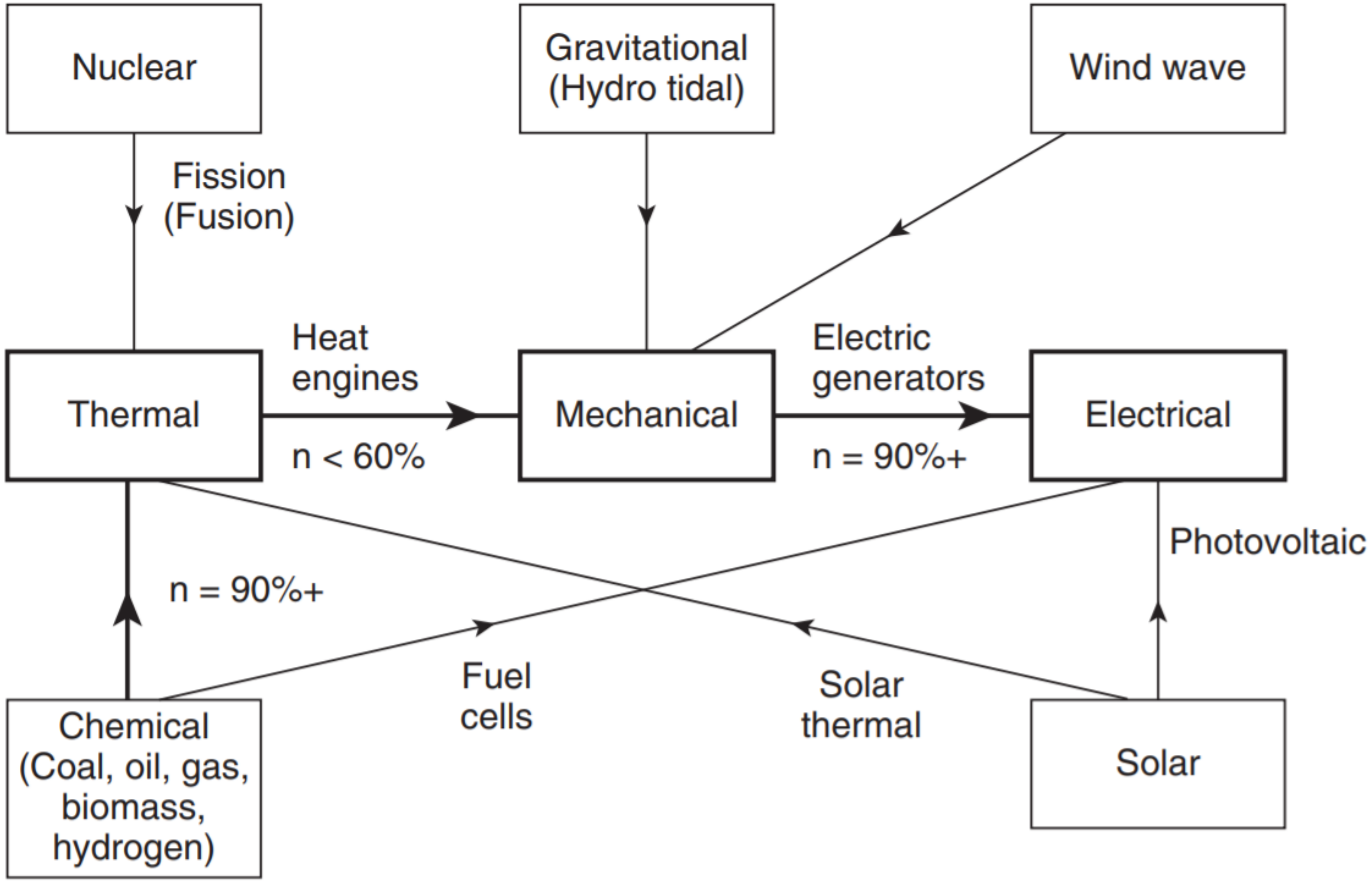
Energy conversion

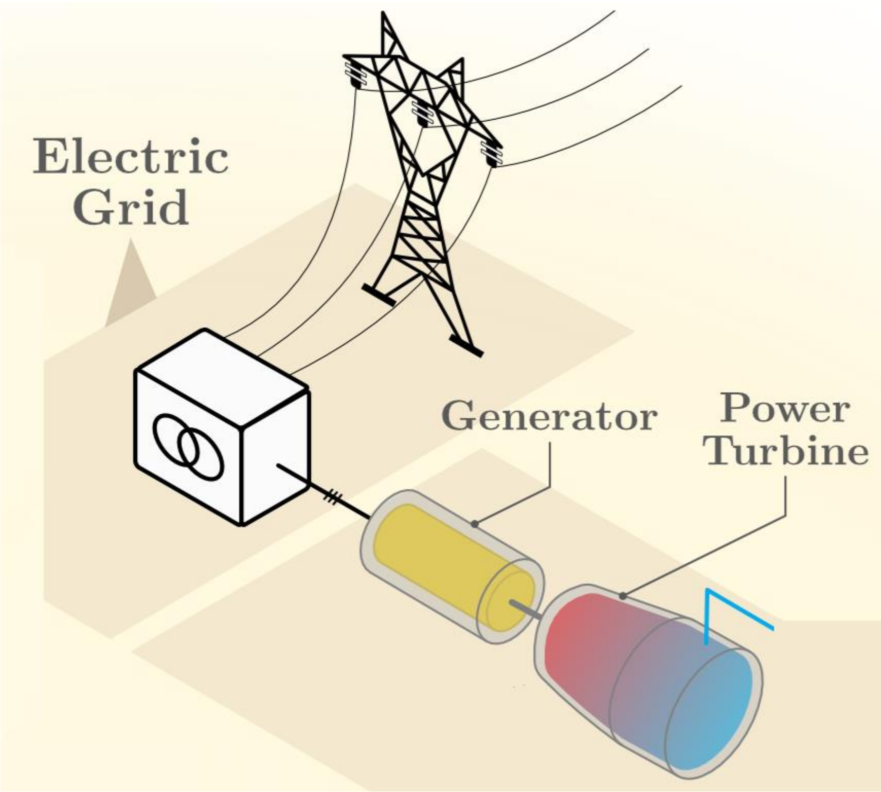


Source: Infield, D., & Freris, L. (2020). Renewable energy in power systems. John Wiley & Sons.

Energy conversion

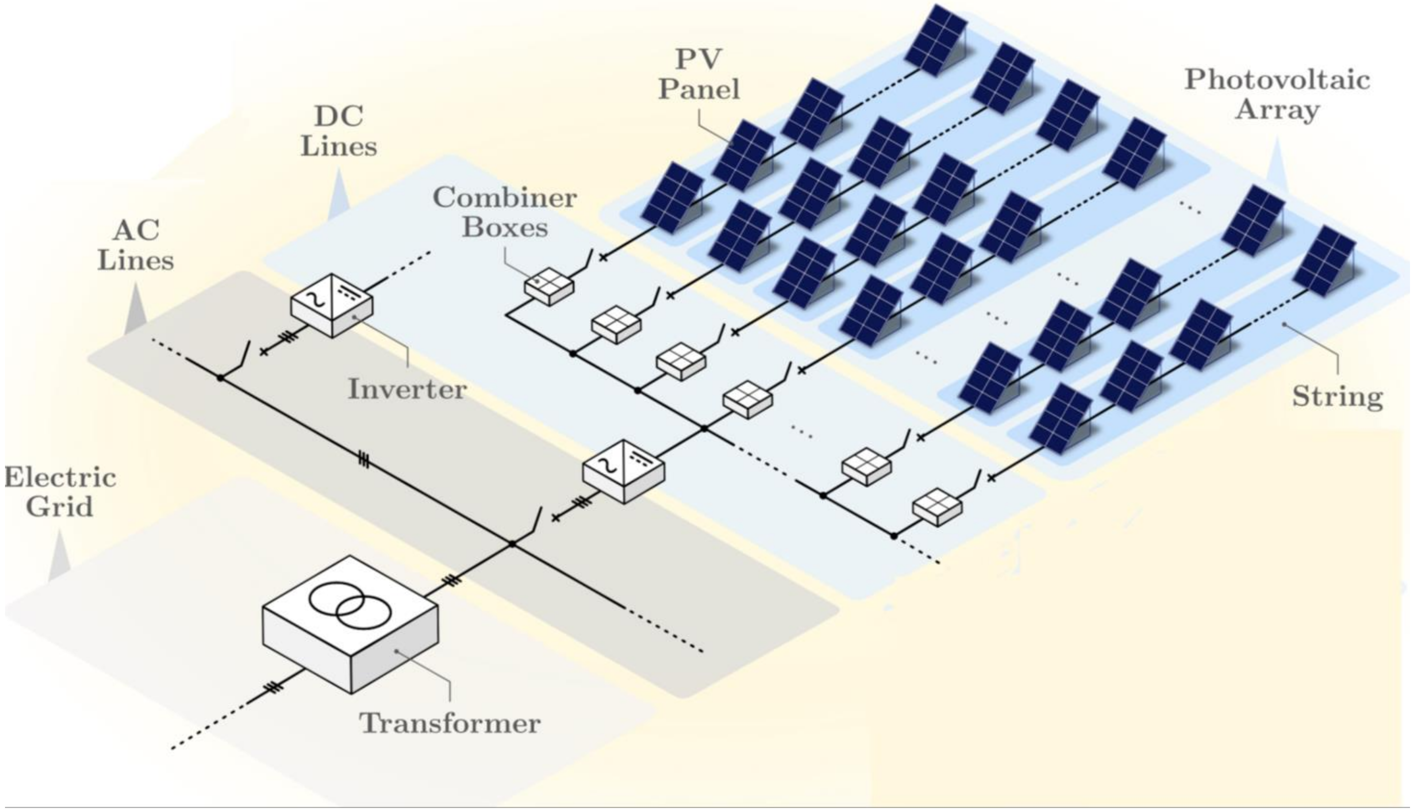
Rotating conversion

Coal, Hydro, Nuclear, Solar thermal, etc



Static conversion

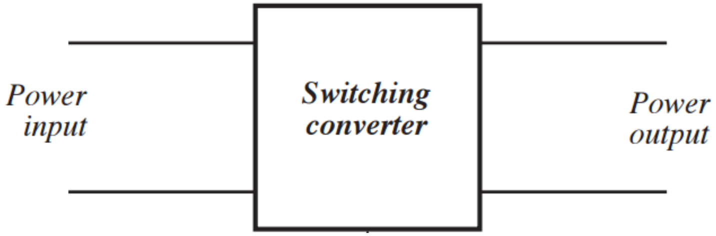
PV, Batteries, some Wind

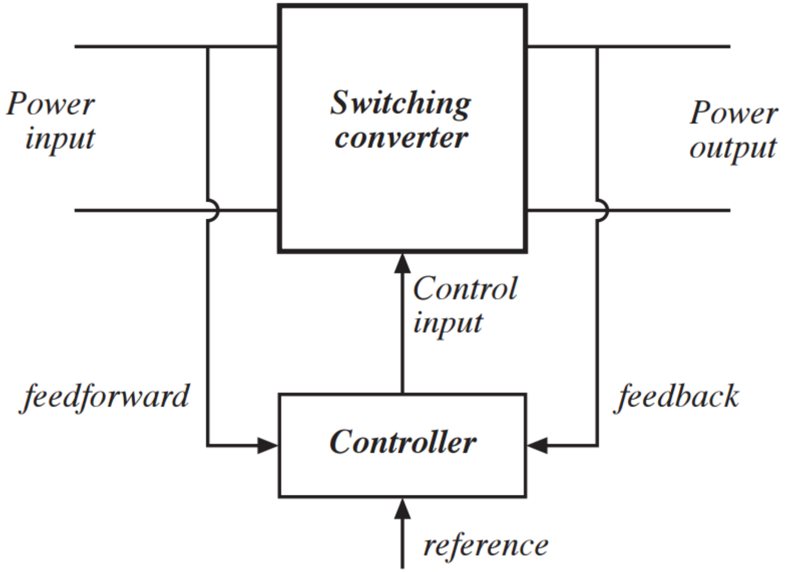


Source: POSYTYF Project

Power electronics

- Power electronics is the area of Electrical Engineering that manipulates power flow using electronic devices.
  - Power electronic devices can be controlled or uncontrolled
  - They are mainly used to convert AC/DC, DC/DC and AC/AC
  - They are used in many applications: filtering, power factor correction, motor drives, HVDC, etc

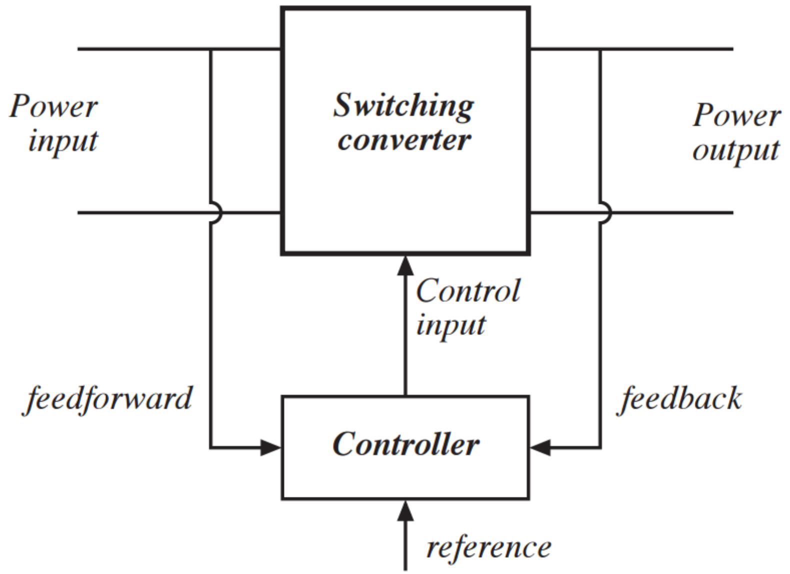




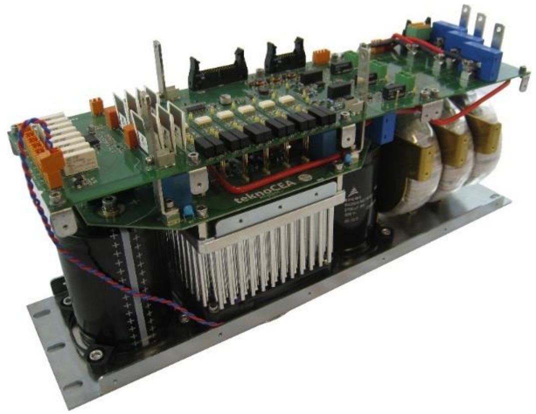
Source: Mònica Aragüés and Jaume Girona Badia

Power converters

- The power converters are classified in many types:
  - **Rectifiers**: power flow from AC to DC
  - **Inverters**: power flow from DC to AC
  - **Bidirectional**: power flow possible in both directions



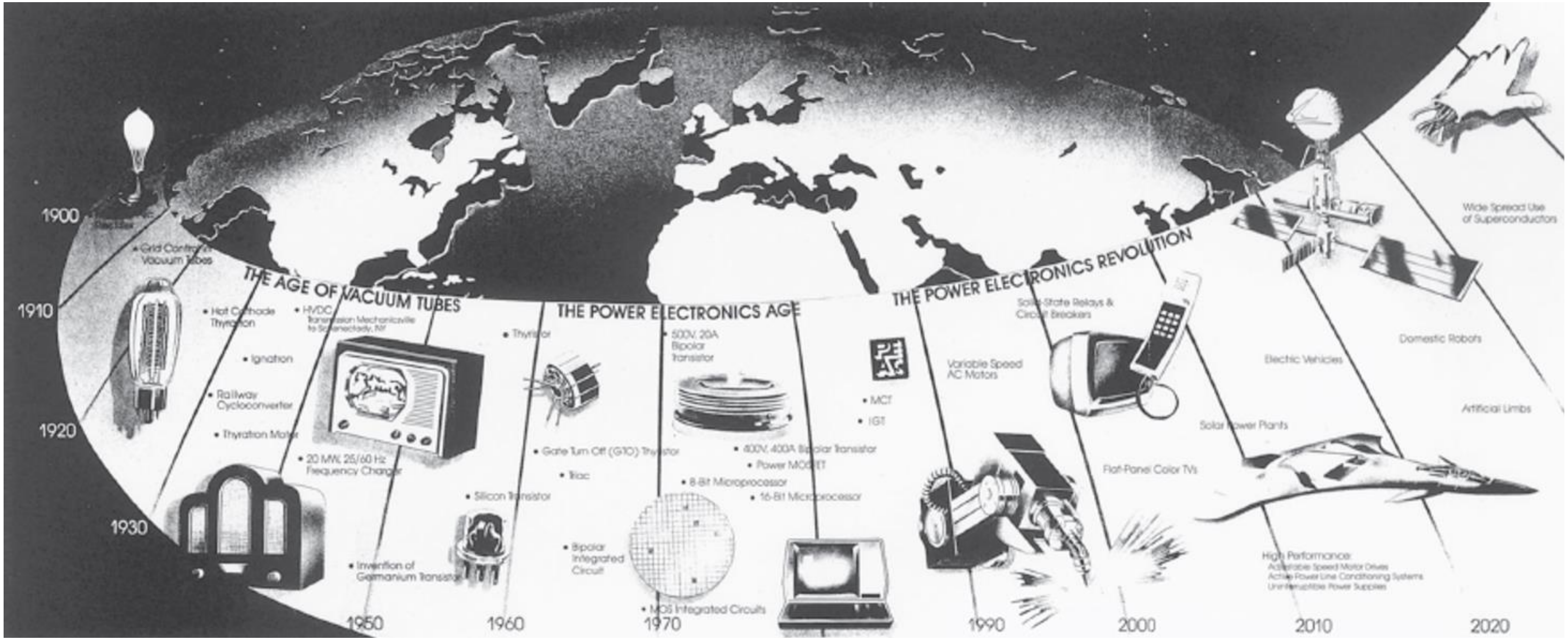
teknoCEA



Source: Mònica Aragüés and Jaume Girona Badia

History of power electronics

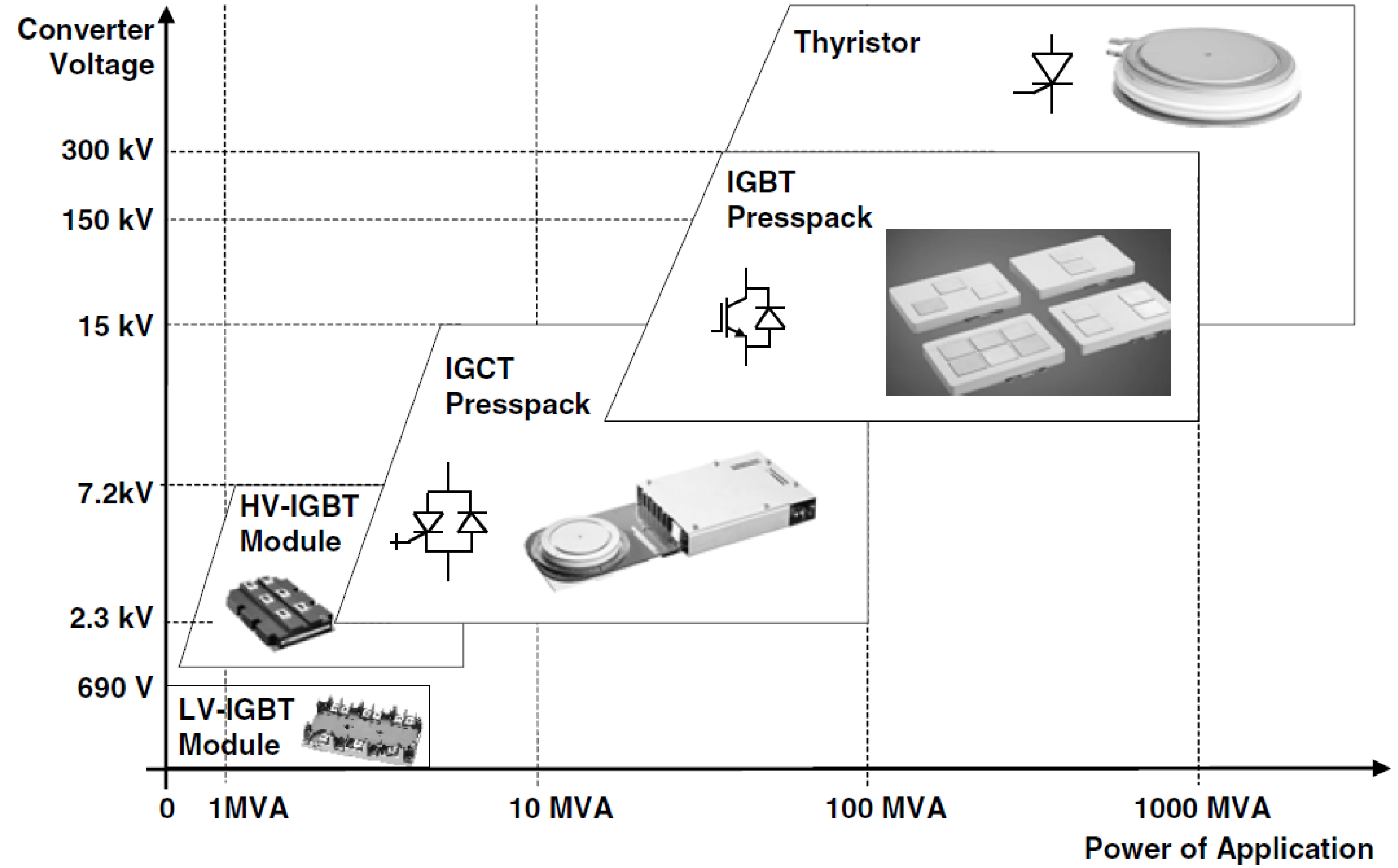
- 1900 introduction of the mercury arc rectifier
- 1948 Silicon transistor - Bell Labs
- 1956 PNPN transistor (thyristor) - Bell Labs



Source: Tennessee Center for Research and Development, a University of Tennessee Affiliated Center.

History of power electronics

- Today



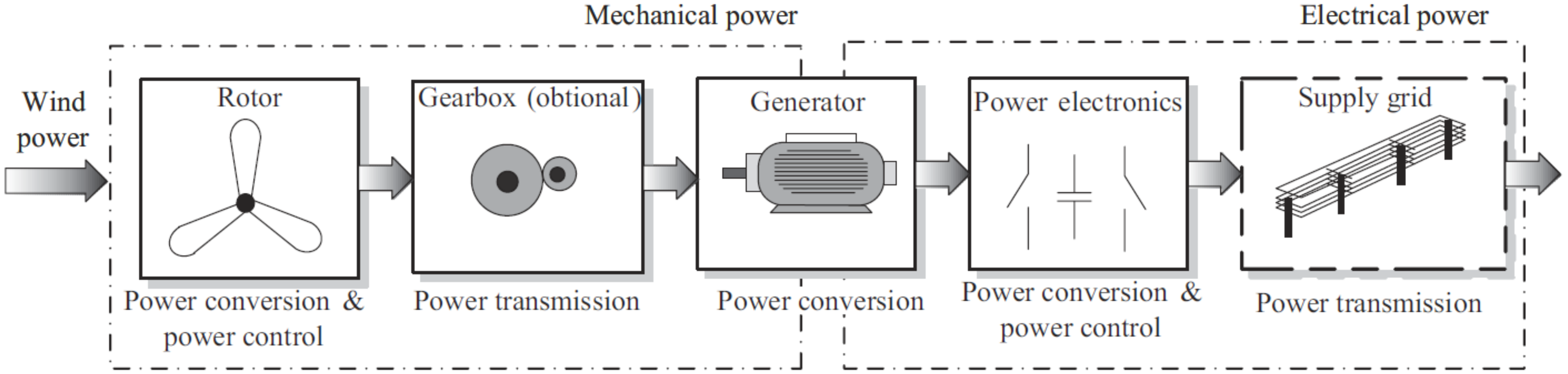
Source: X. Zhang, C. Rehtanz and B. Pal. Flexible AC Transmission Systems: Modelling and Control. Springer

Power electronics applications

- From electric vehicles to power generation

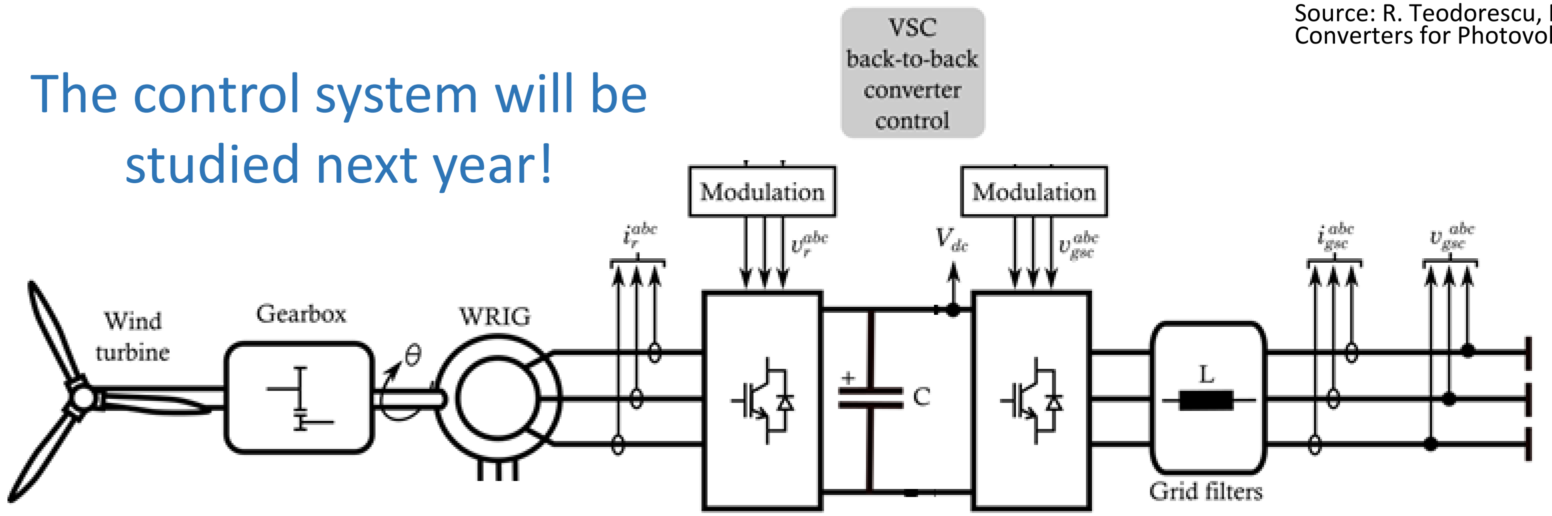
Power electronics in wind generation

- Using a VSC is it possible to create an AC wave with lower and higher frequency, to extract optimal power from the wind turbine.



Source: R. Teodorescu, M. Liserre and P. Rodríguez (2011), Grid Converters for Photovoltaic and Wind Power Systems, ohn Wiley & Sons.

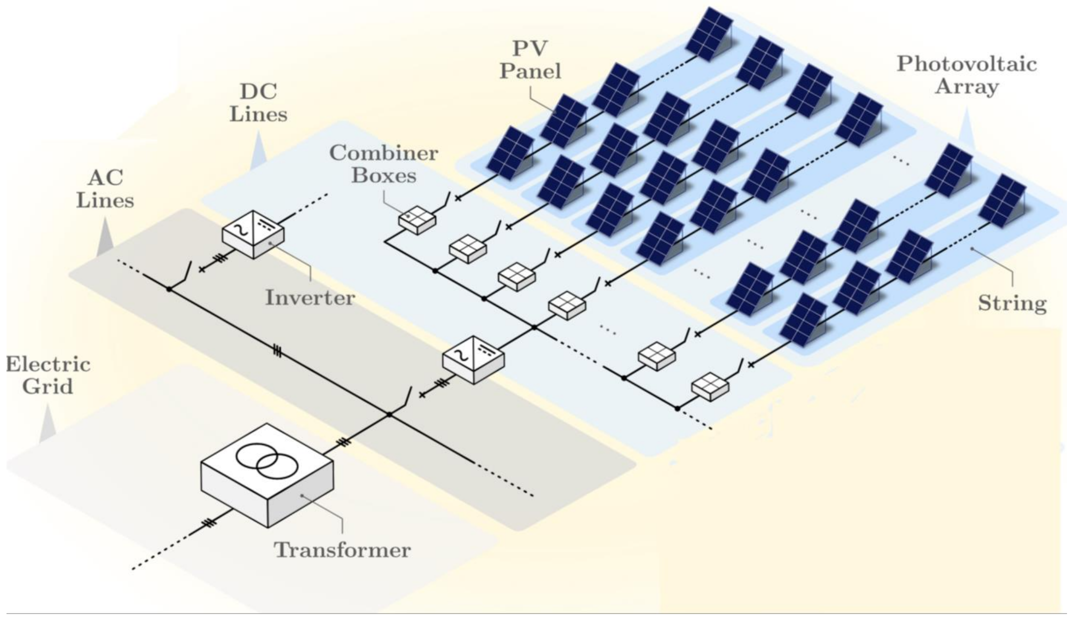
The control system will be studied next year!

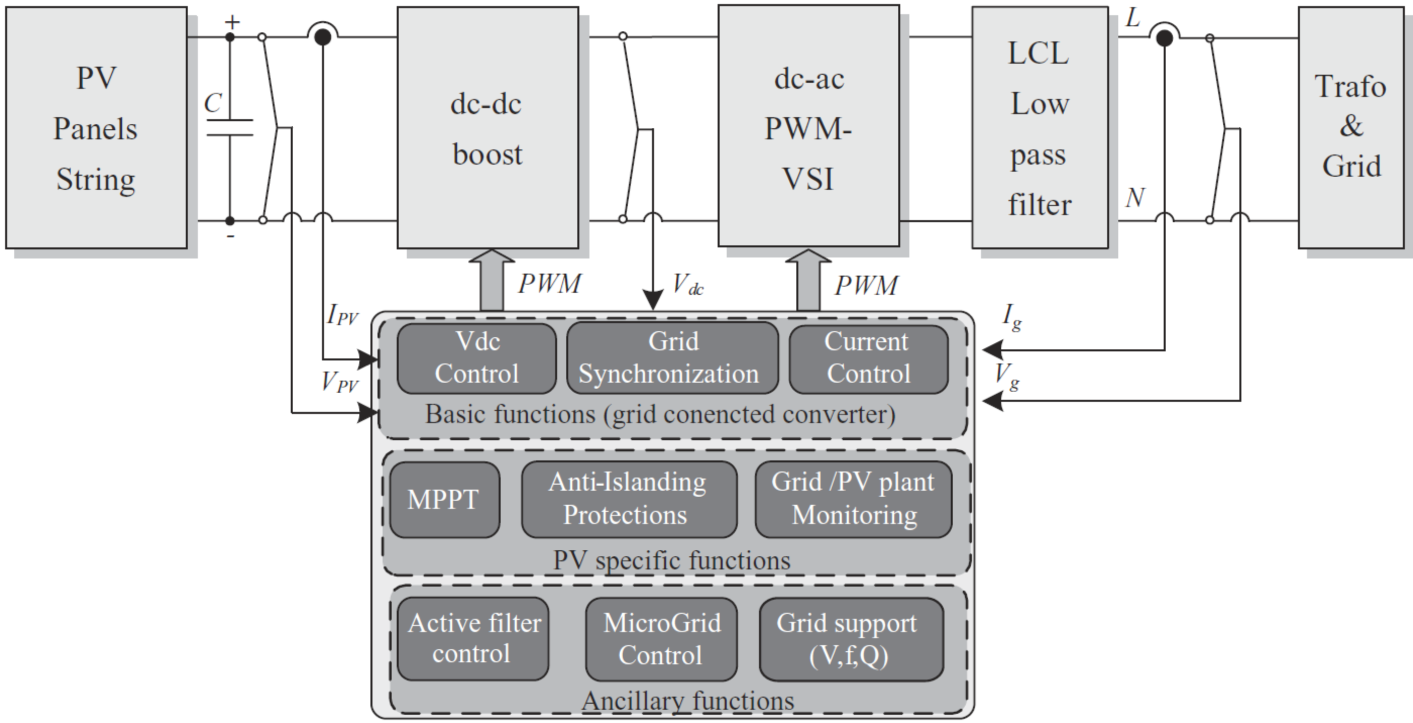


Power electronics in PV generation

- The DC current from the PV charges the DC capacitor and the VSC creates the AC voltage by modulating the DC voltage across the capacitor

The control system will be studied next year!

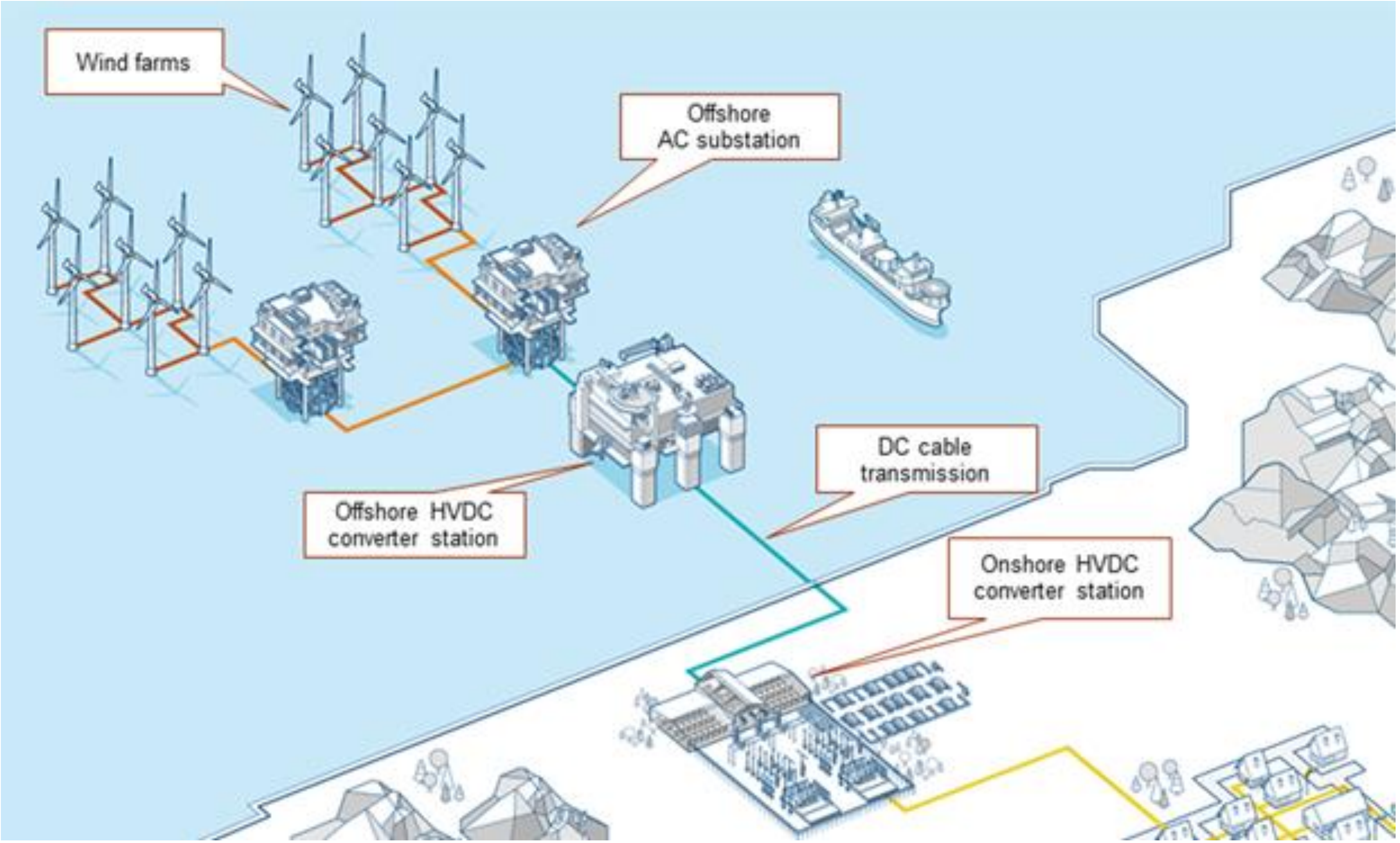




Source: R. Teodorescu, M. Liserre and P. Rodríguez (2011), Grid Converters for Photovoltaic and Wind Power Systems, ohn Wiley & Sons.

High-Voltage Direct Current (HVDC) systems

- **Submarine power transmission**. One station offshore, a DC link and another station onshore.



Fonte:http://new.abb.com/systems/offshore-wind-connections/dc-solutions

Photo gallery

Source: ABB

Photo gallery

DYNEX
Power through Innovation

Source: ABB

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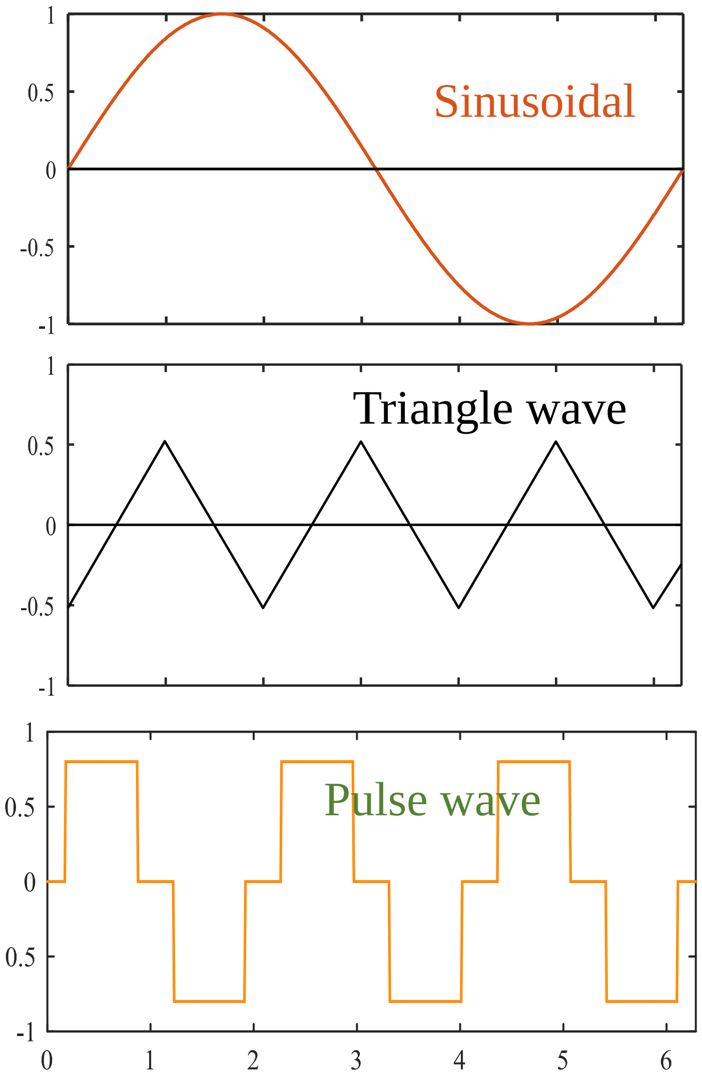
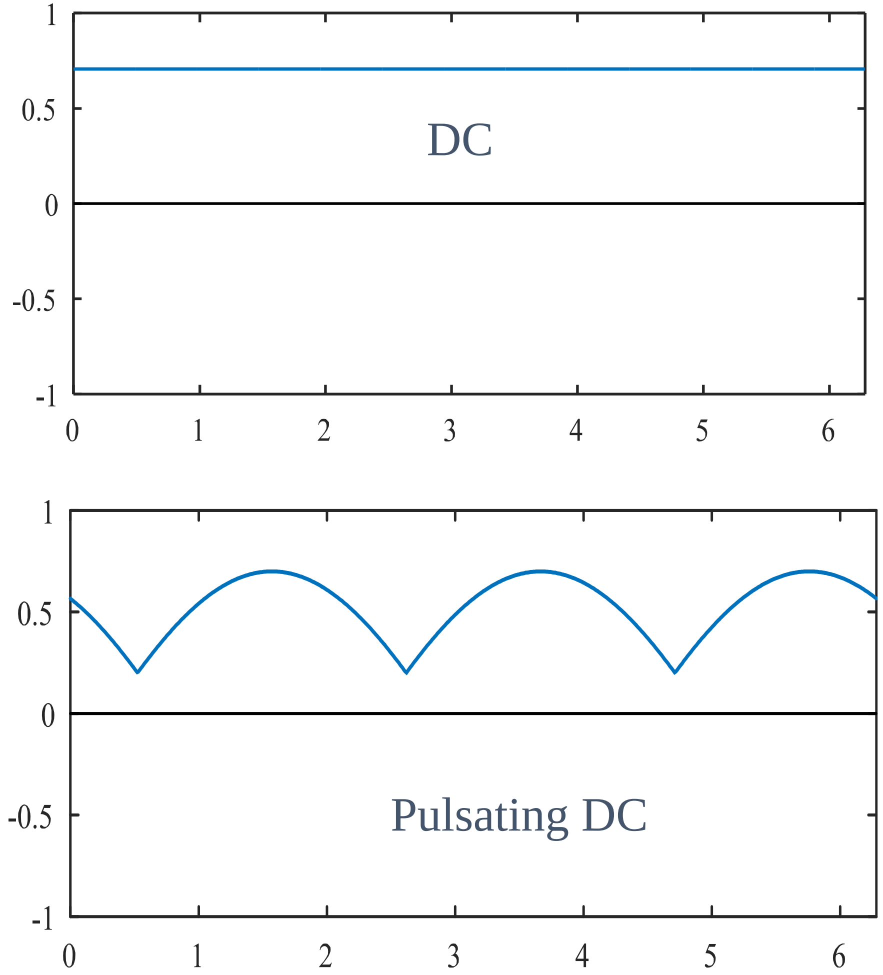
AC and DC

Ideal AC has zero average



How to convert
AC/DC or DC/AC ?

Ideal DC has zero ripple



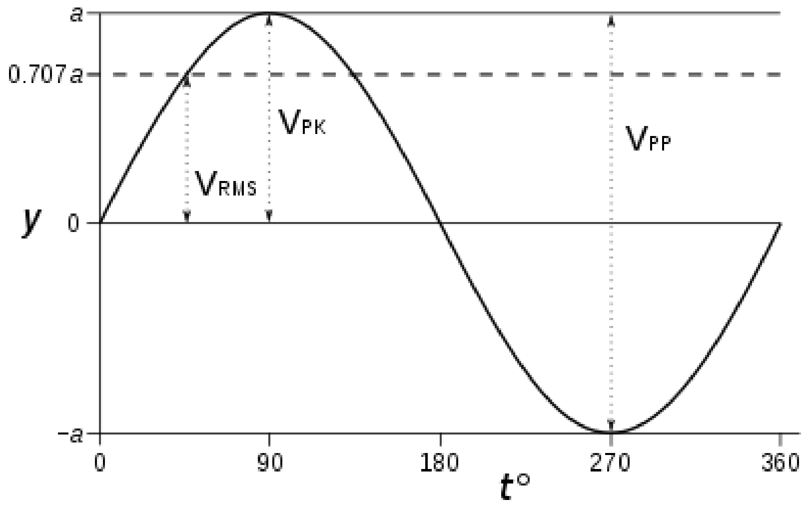
Root Mean Square value (RMS)

- For alternating electric current, **RMS value is equal to the value of the direct current** that would produce the same average power dissipation in a resistive load.

$$p(t) = Ri^2(t) \longrightarrow P_{av} = \frac{1}{T}\int_{t_0}^{t_0+T} Ri^2(\tau)d\tau = RI_{rms}^2 \longrightarrow \boxed{I_{rms} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} i^2(\tau)d\tau}}$$

- If the waveform is a **pure sine wave** (as in AC), the **relationships between amplitudes** (peak-to-peak, peak) and **RMS are fixed and known**, as they are for any continuous periodic wave.
- For a sine wave, the relation between the peak and RMS value is:

$$\boxed{V_{rms} = \frac{V_p}{\sqrt{2}}}$$



- Typically voltages are provided in RMS values
- Verify this in simulation

Root Mean Square value (RMS)

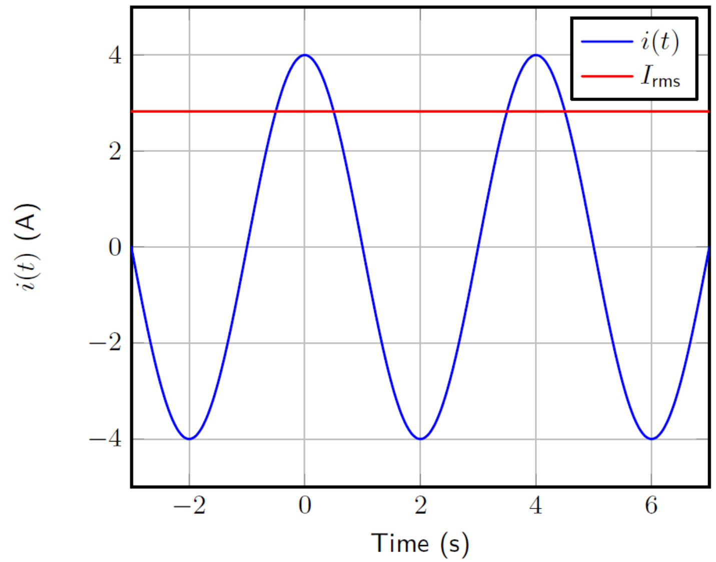
Effective (RMS) value of a sinusoidal waveform

The RMS value of a sinusoidal current, $i(t) = I_a \cos(\omega t + \varphi)$, is

$$I_{\text{rms}} = \left\{ \frac{1}{T} \int_0^T I_a^2 \cos^2(\omega t + \varphi) \mathrm{d}t \right\}^{\frac{1}{2}}$$

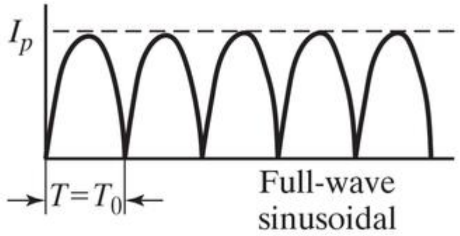
$$= I_a \left\{ \frac{\omega}{2\pi} \int_0^{\frac{2\pi}{\omega}} \left(\frac{1}{2} + \frac{1}{2} \cos(2\omega t + 2\varphi) \right) \mathrm{d}t \right\}^{\frac{1}{2}} = \frac{I_a}{\sqrt{2}}$$

where $\cos^2 \theta = \frac{1}{2} + \frac{1}{2} \cos(2\theta)$ has been used.



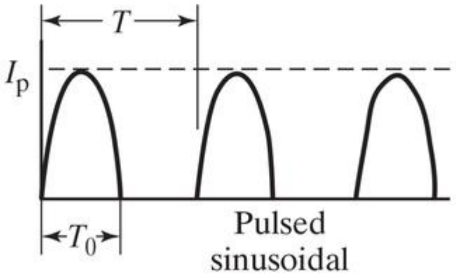
RMS calculation

- If the wave has harmonics, the total RMS is given by: $I_{\text{rms}} = \sqrt{I_{\text{dc}}^2 + I_{\text{rms}(1)}^2 + I_{\text{rms}(2)}^2 + \cdots + I_{\text{rms}(n)}^2}$



(a)

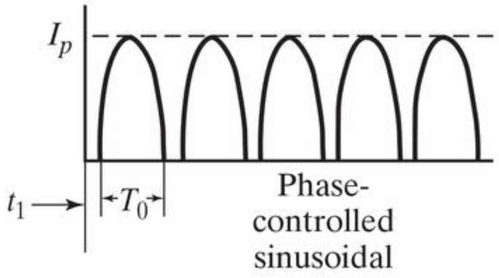
$$I_{\text{rms}} = \frac{I_p}{\sqrt{2}}$$



(b)

$$I_{\text{rms}} = I_p \sqrt{\frac{k}{2}}$$

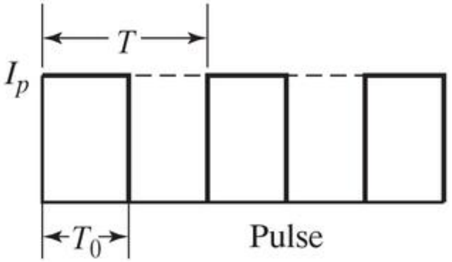
$$k = \frac{T_0}{T}$$



(c)

$$I_{\text{rms}} = I_p \left[\frac{k}{2} + \frac{\sin T_0(1-k) \cos\pi (1-k)}{2\pi} \right]^{1/2}$$

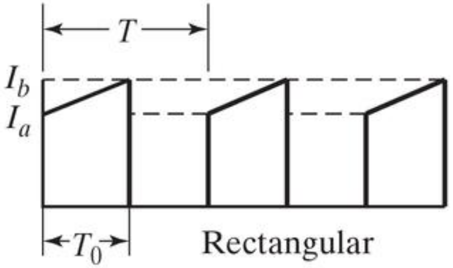
$$k = 1 - \frac{t_1}{T}$$



(d)

$$I_{\text{rms}} = I_p \sqrt{k}$$

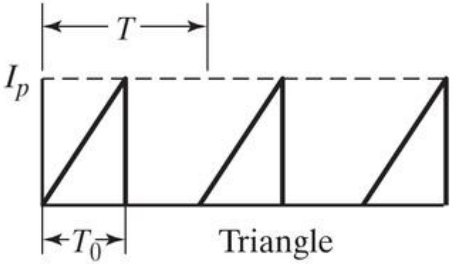
$$k = \frac{T_0}{T}$$



(e)

$$I_{\text{rms}} = \left[k(I_b^2 + I_a I_b + I_a^2)/3 \right]^{1/2}$$

$$k = \frac{T_0}{T}$$



(f)

$$I_{\text{rms}} = I_p \sqrt{\frac{k}{3}}$$

$$k = \frac{T_0}{T}$$

Harmonics

Harmonic analysis

Any periodic signal can be represented by its Fourier decomposition as

$$u(t) = U_0 + \sum_{n=1}^{\infty} U_{\mathrm{pk},n} \cos(n\omega t + \alpha_n)$$

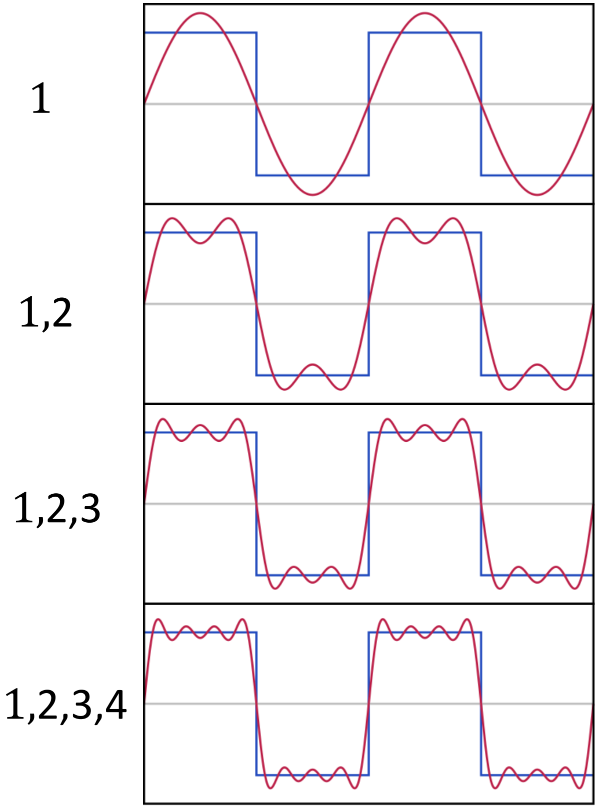
$$U_{pk,n} = \sqrt{a_n^2 + b_n^2}$$

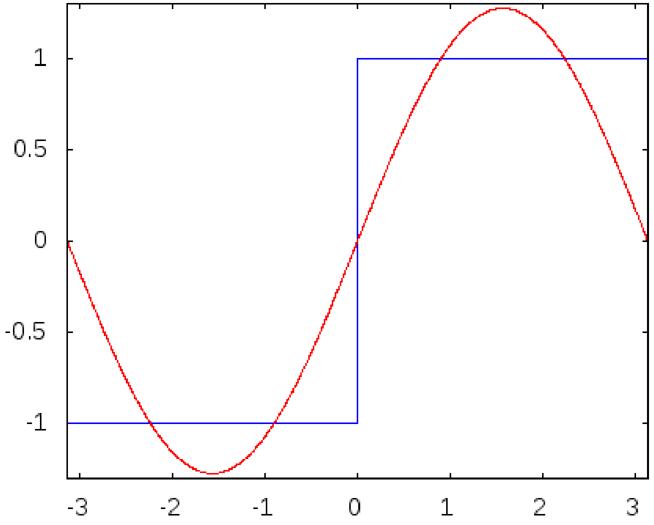
$$\alpha_n = \tan^{-1}\left(-\frac{b_n}{a_n}\right)$$

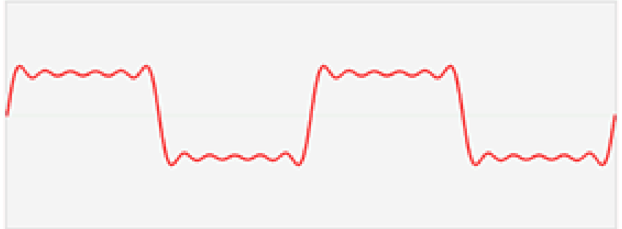
where

- U_0 is the DC component
- n is the harmonic component
- $U_{\mathrm{pk},n}$ is the amplitude (or peak) of the n-th component
- α_n is the phase of the n-th component

Harmonics of a square wave



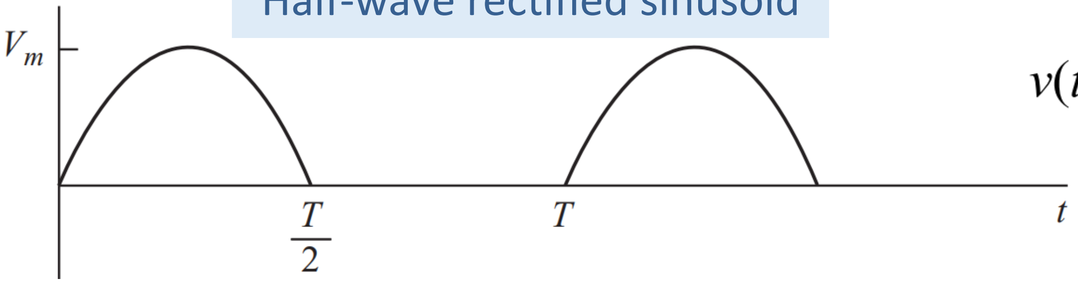




$$a_0 = \frac{1}{T}\int_{-T/2}^{T/2} f(t)\,dt \qquad a_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\cos(n\omega_0 t)\,dt \qquad b_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\sin(n\omega_0 t)\,dt$$

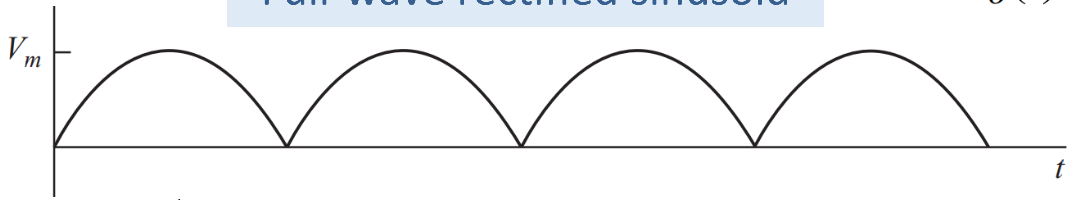
Harmonics - examples

Half-wave rectified sinusoid



$$v(t) = \frac{V_m}{\pi} + \frac{V_m}{2}\sin(\omega_0 t) - \sum_{n=2,4,6\ldots}^{\infty} \frac{2V_m}{(n^2-1)\pi}\cos(n\omega_0 t)$$

Full-wave rectified sinusoid

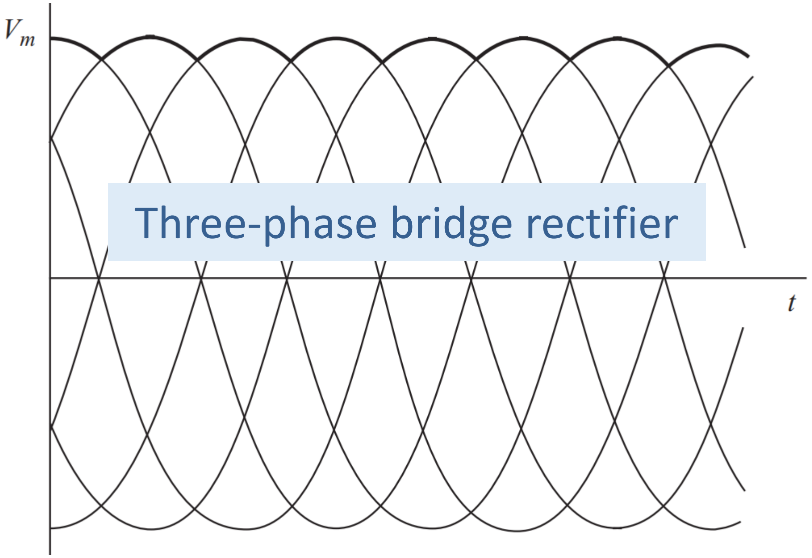


$$v_o(t) = V_o + \sum_{n=2,4,\ldots}^{\infty} V_n \cos(n\omega_0 t + \pi)$$

$$V_o = \frac{2V_m}{\pi}$$

$$V_n = \frac{2V_m}{\pi}\left(\frac{1}{n-1} - \frac{1}{n+1}\right)$$

Three-phase bridge rectifier



$$v_o(t) = V_o + \sum_{n=6,12,18,\ldots}^{\infty} V_n \cos(n\omega_0 t + \pi)$$

$$V_o = \frac{3V_{m,\mathrm{L-L}}}{\pi}$$

$$V_n = \frac{6V_{m,\mathrm{L-L}}}{\pi(n^2-1)}$$

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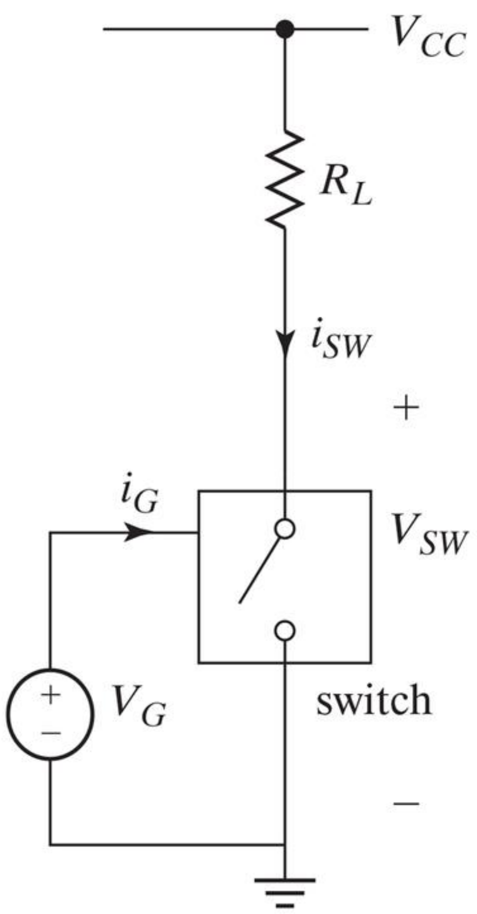
Characteristics of switches

The ideal switch would have the following characteristics

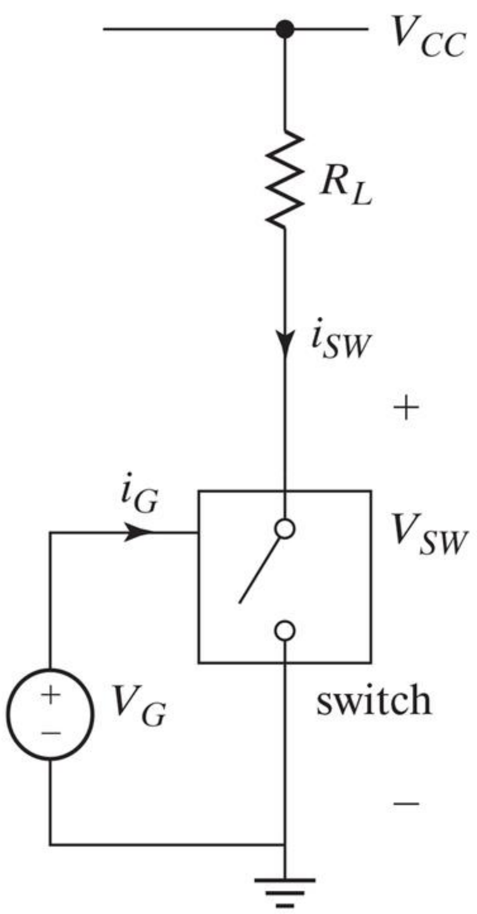
- Zero impedance in ON state
- Infinity impedance in OFF state
- Infinity current carry capability
- Infinity voltage withstand capability
- Turn on or off instantaneously
- Require zero energy to turn on or off
- Totally controllable turn-on and turn-off
- Have infinity dv/dt (can handle rapid changes of voltage across it)
- Have infinity di/dt (can handle rapid changes of current through it)
- Low price



Characteristics of switches

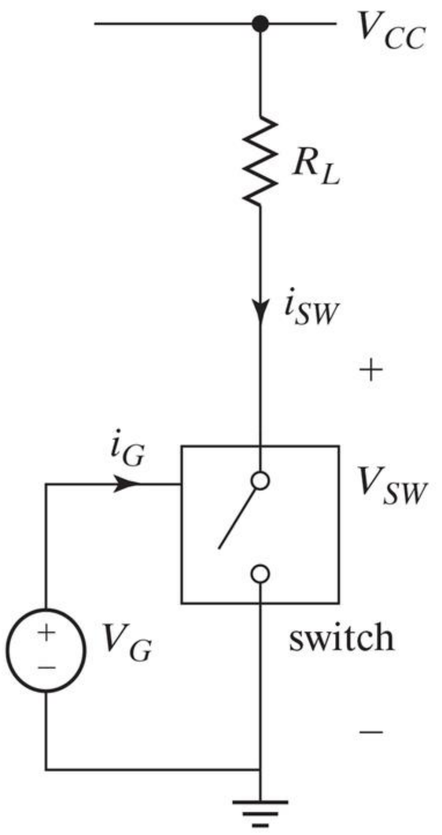
The practical switch has

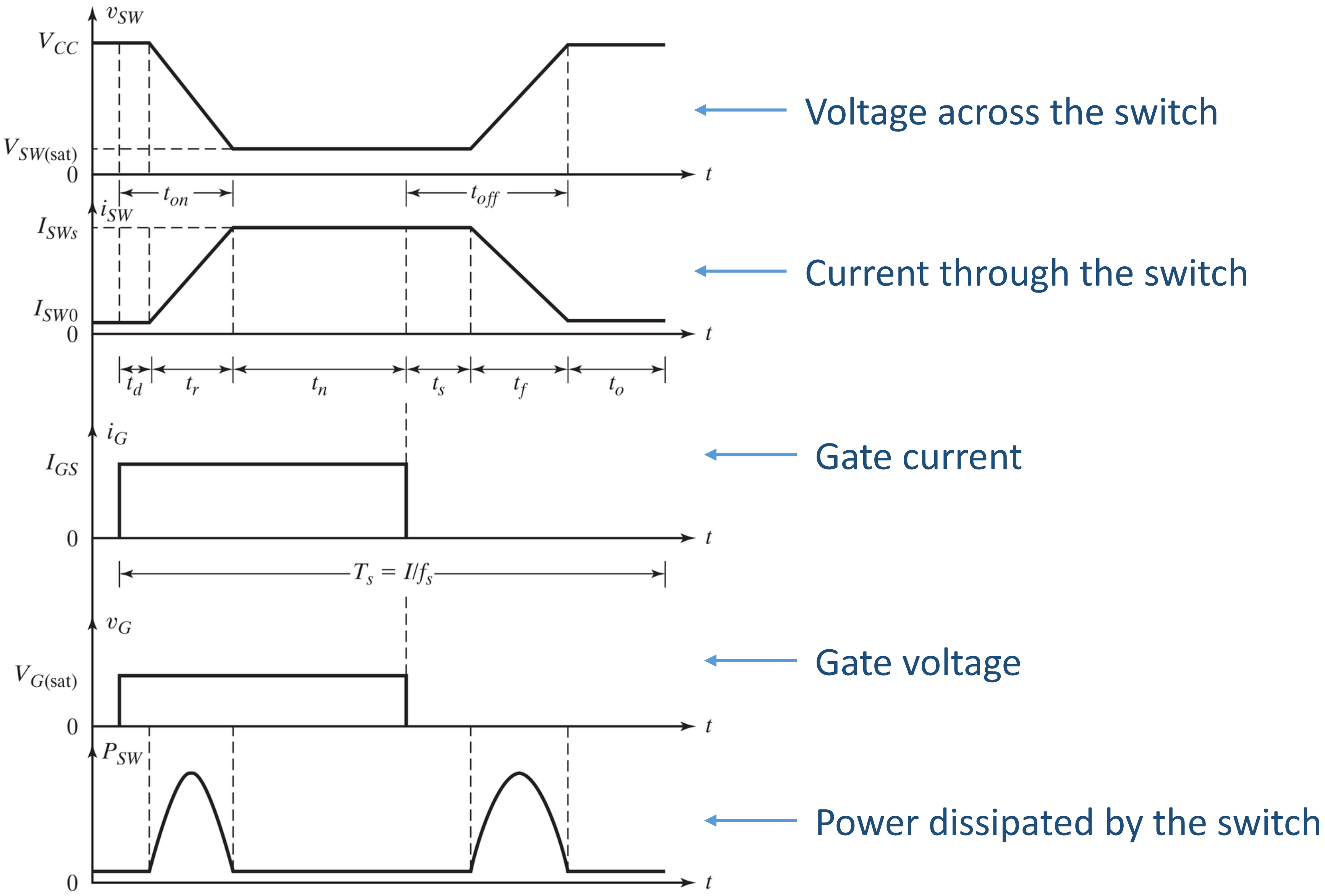
- ~~Zero~~ low impedance in ON state
- ~~Infinity~~ high impedance in OFF state
- ~~Infinity~~ high current carry capability
- ~~Infinity~~ high voltage withstand capability
- Turn on or off ~~instantaneously~~ fast
- Require ~~zero~~ low energy to turn on or off
- Totally controllable turn-on and turn-off
- Have ~~infinity~~ high dv/dt (can handle rapid changes of voltage across it)
- Have ~~infinity~~ high di/dt (can handle rapid changes of current through it)
- Low price not always



Characteristics of switches

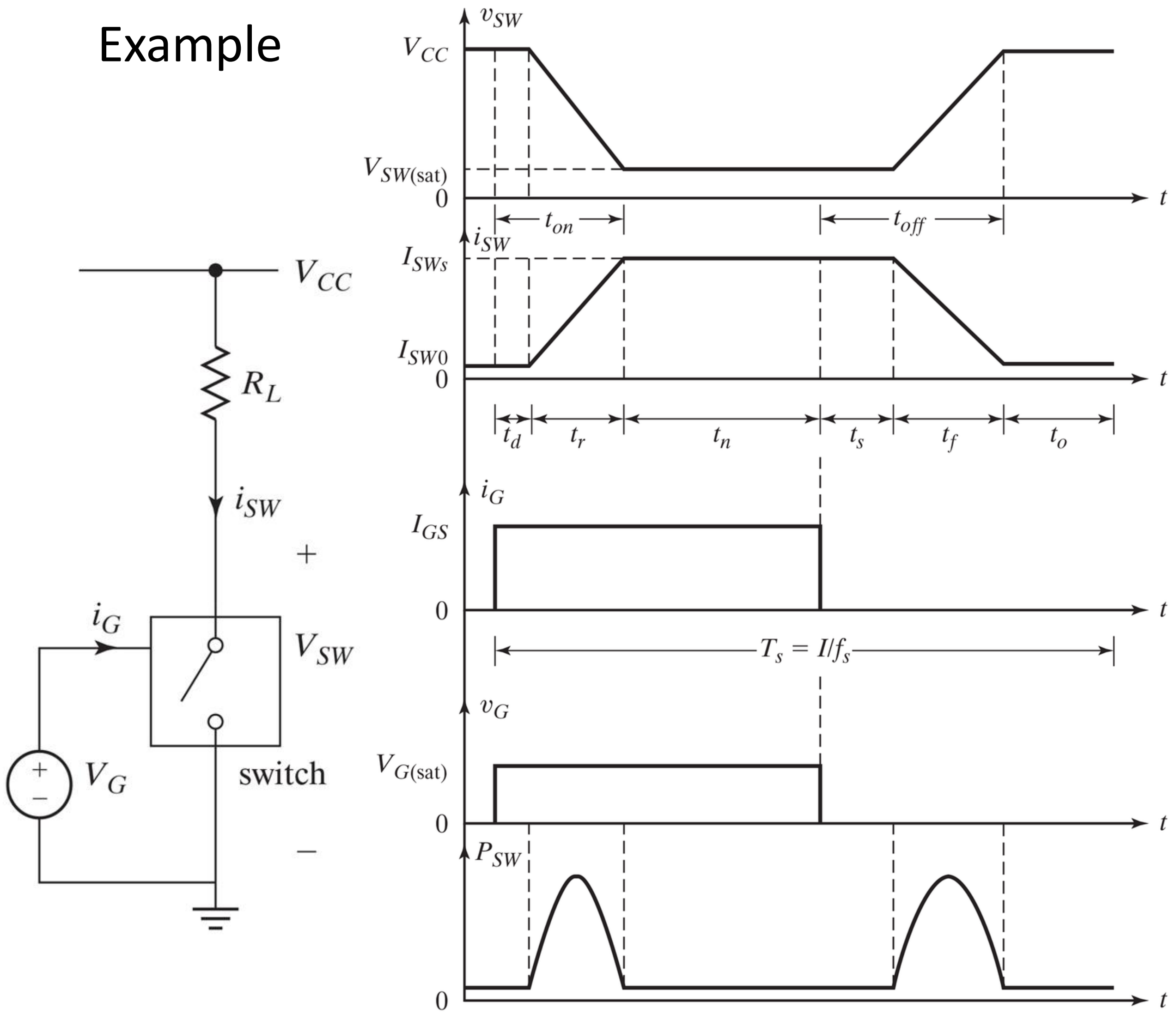
Example





Characteristics of switches

Example



The average dissipated power (P_D) can be calculated as:

$$P_D = P_{ON} + P_{SW} + P_G$$

ON-state power

switching power

gate power

$$P_{ON} = \frac{1}{T_s}\int_0^{t_n} p\, dt$$

$$P_{SW} = f_s\left(\int_0^{t_d} p\, dt + \int_0^{t_r} p\, dt + \int_0^{t_s} p\, dt + \int_0^{t_f} p\, dt\right)$$

Where f_s is the switching frequency, t_d, t_r , t_s and t_f are the delay time, rise time, storage time and fall time, respectively

Specifications of switches

Voltage ratings: Forward and reverse repetitive peak voltages, and an on-state forward voltage drop.

Current ratings: Average, root-mean-square (rms), repetitive peak, nonrepetitive peak

Switching speed or frequency: Transition from a fully nonconducting to a fully conducting state (turn-on) and from a fully conducting to a fully nonconducting state (turn-off)

di/dt rating: The device needs a minimum amount of time before its whole conducting surface comes into play in carrying the full current.

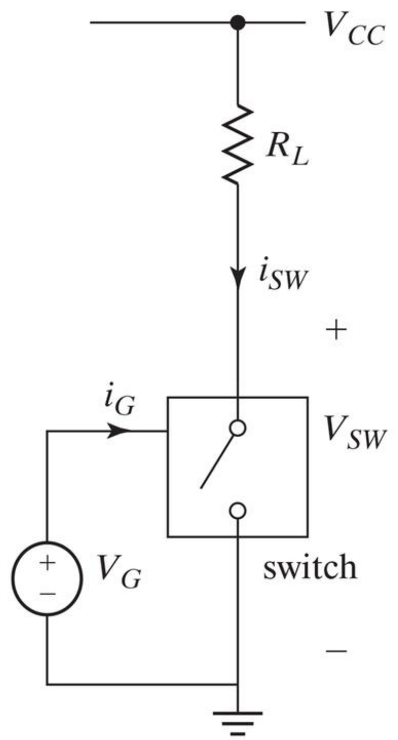
dv/dt rating

Switching losses

Gate-drive requirements: The gate-drive voltage and current are important parameters to turn on and off a device.

Temperatures: Maximum allowable junction, case and storage temperatures

Thermal resistance



Examples

V_{CE} = 6500 V
I_C = 400 A

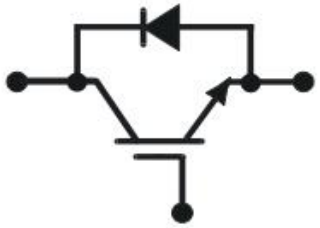


ABB HiPak

IGBT Module

5SNA 0400J650100

Doc. No. 5SYA 1592-04 05-2016

- Low-loss, rugged SPT chip-set
- Smooth switching SPT chip-set for good EMC
- High insulation package
- AlSiC base-plate for high power cycling capability
- AlN substrate for low thermal resistance
- Improved high reliability package
- Recognized under UL1557, File E196689

Source: ABB

Examples

Maximum rated values [1]

Parameter	Symbol	Conditions	min	max	Unit
Collector-emitter voltage	V_{CES}	V_{GE} = 0 V, $T_{vj} \geq$ 25 °C		6500	V
DC collector current	I_C	T_c = 85 °C		400	A
Peak collector current	I_{CM}	t_p = 1 ms, T_c = 85 °C		800	A
Gate-emitter voltage	V_{GES}		-20	20	V
Total power dissipation	P_{tot}	T_c = 25 °C, per switch (IGBT)		7350	W
DC forward current	I_F			400	A
Peak forward current	I_{FRM}			800	A
Surge current	I_{FSM}	V_R = 0 V, T_{vj} = 125 °C, t_p = 10 ms, half-sinewave		4000	A
IGBT short circuit SOA	t_{psc}	V_{CC} = 4400 V, $V_{CEM\,CHIP} \leq$ 6500 V $V_{GE} \leq$ 15 V, $T_{vj} \leq$ 125 °C		10	µs
Isolation voltage	V_{isol}	1 min, f = 50 Hz		10200	V
Junction temperature	T_{vj}			125	°C
Junction operating temperature	$T_{vj(op)}$		-50	125	°C
Case temperature	T_c		-50	125	°C
Storage temperature	T_{stg}		-50	125	°C

Source: ABB

Examples

FZ3600R17HP4_B2

infineon

Images are for reference only
See Product Specifications

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Mouser No:	641-FZ3600R17HP4_B2
Mfr. No:	FZ3600R17HP4_B2
Mfr.:	Infineon Technologies
Customer No:	Customer No
Description:	IGBT Modules IGBT 1700V 3600A
Datasheet:	FZ3600R17HP4_B2 Datasheet (PDF)
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Electric Energy Conversion

1. Introduction to the course

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