Tallinn University of Technology, May 2025

TAL TECH

Estonian Doctoral School

“Example of Wind Energy Conversion System”

………………

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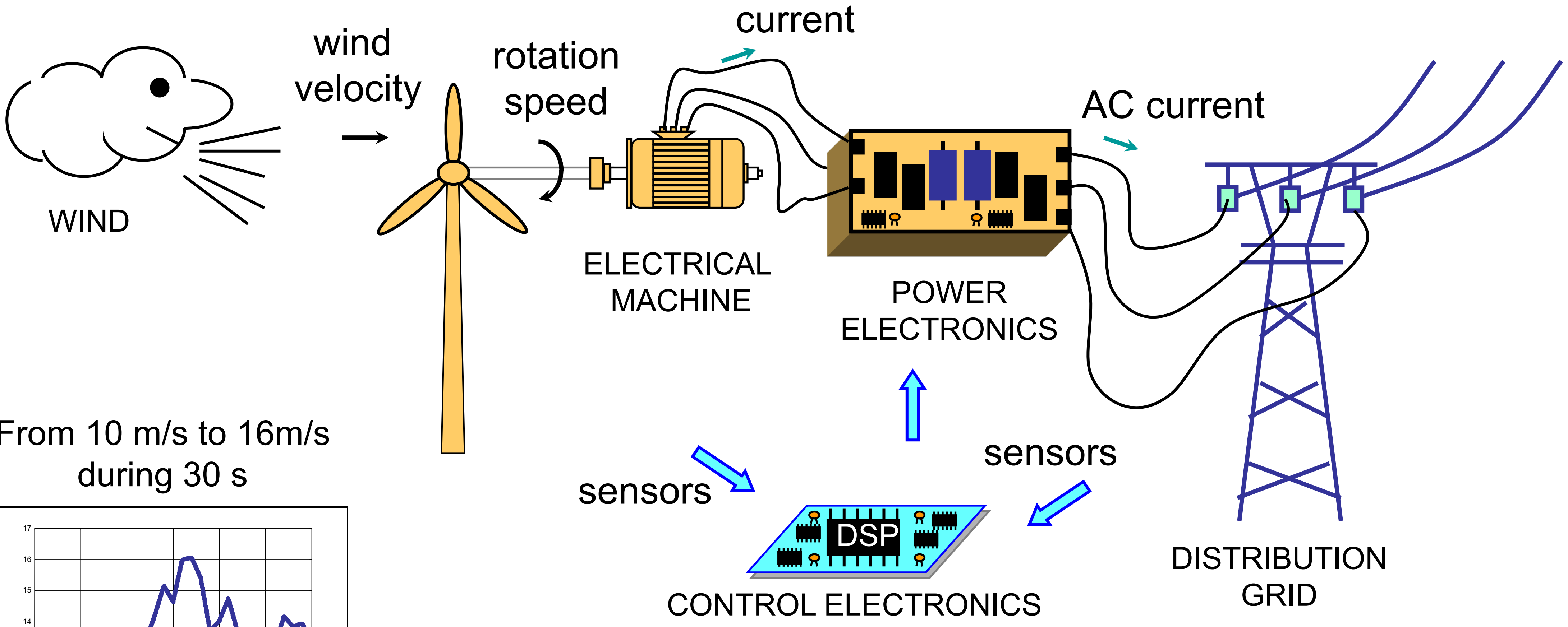
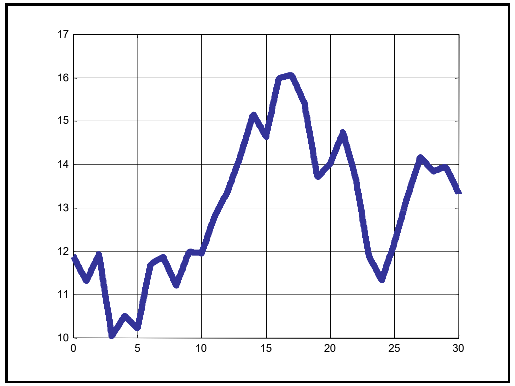
1. Wind Energy
2. EMR of a WECS
3. Control of a WECS
4. MPPT strategy

1. **Wind Energy**
2. EMR of a WECS
3. Control of a WECS
4. MPPT strategy

WECS = Wind Energy Conversion System

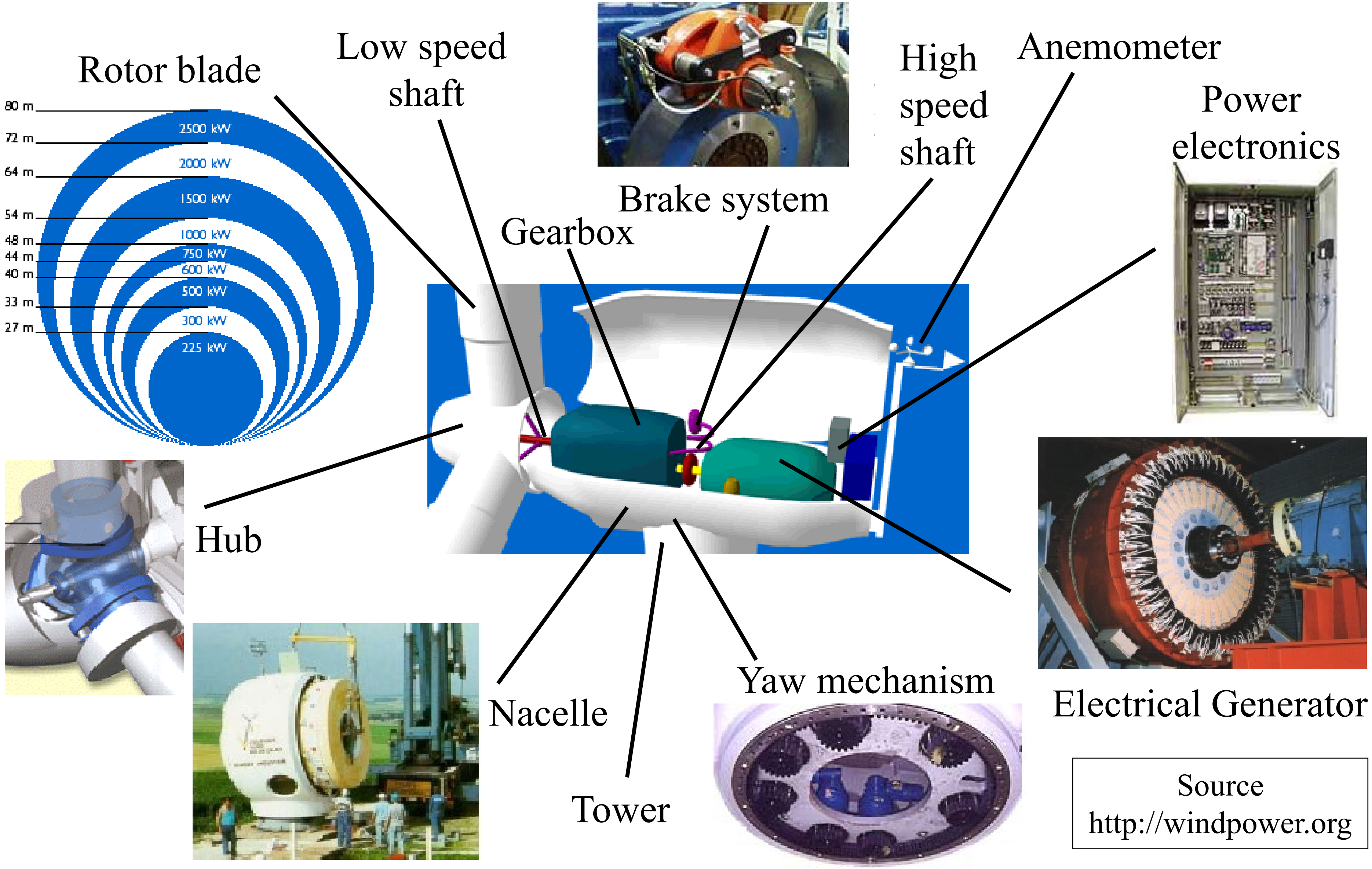


From 10 m/s to 16m/s during 30 s



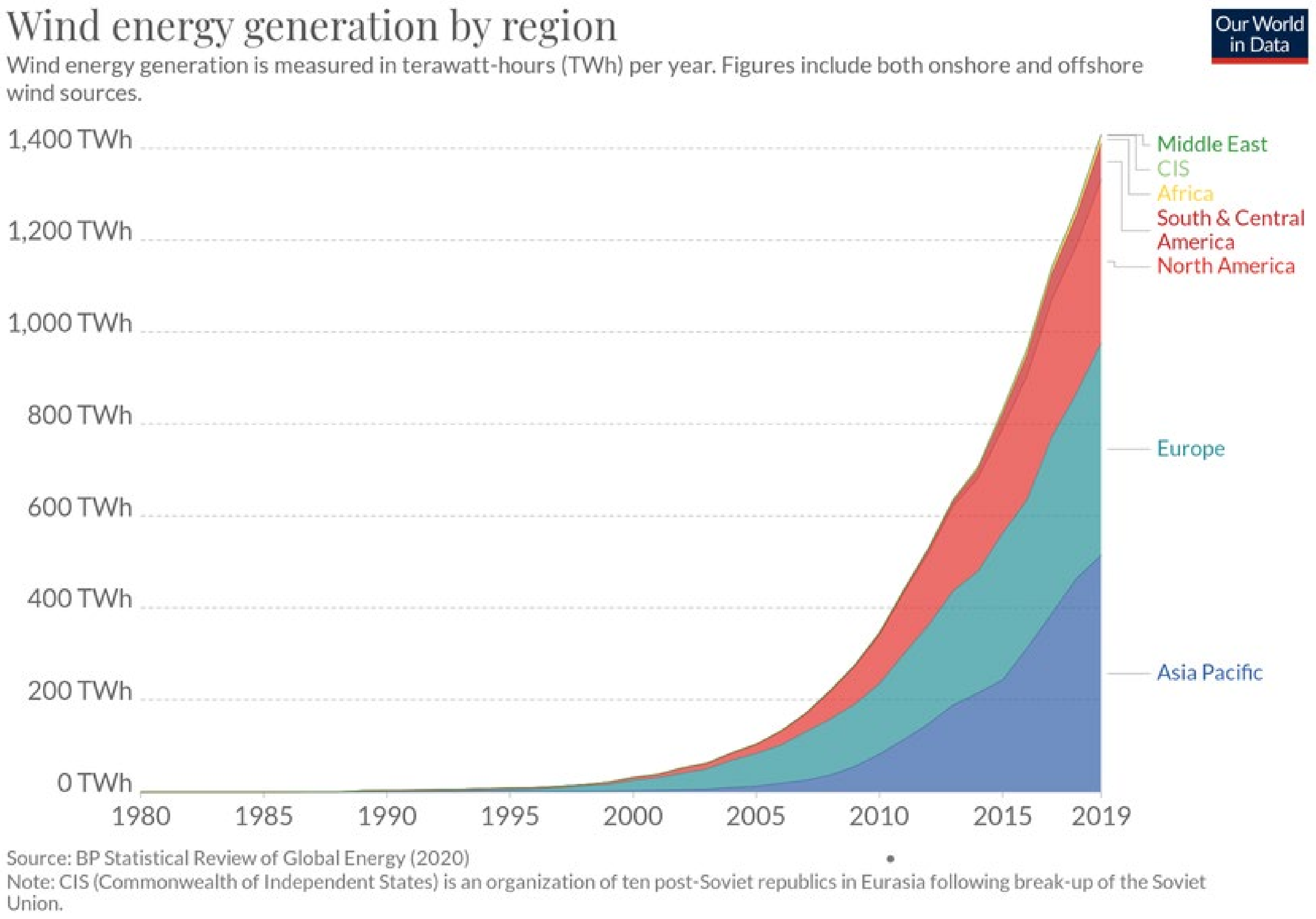
Wind velocity variations ⇒ Electrical power variations

WECS components

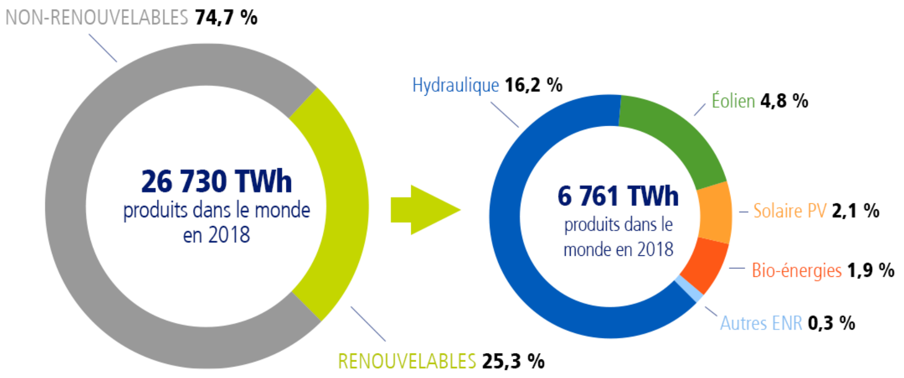


Source
http://windpower.org

Wind energy production



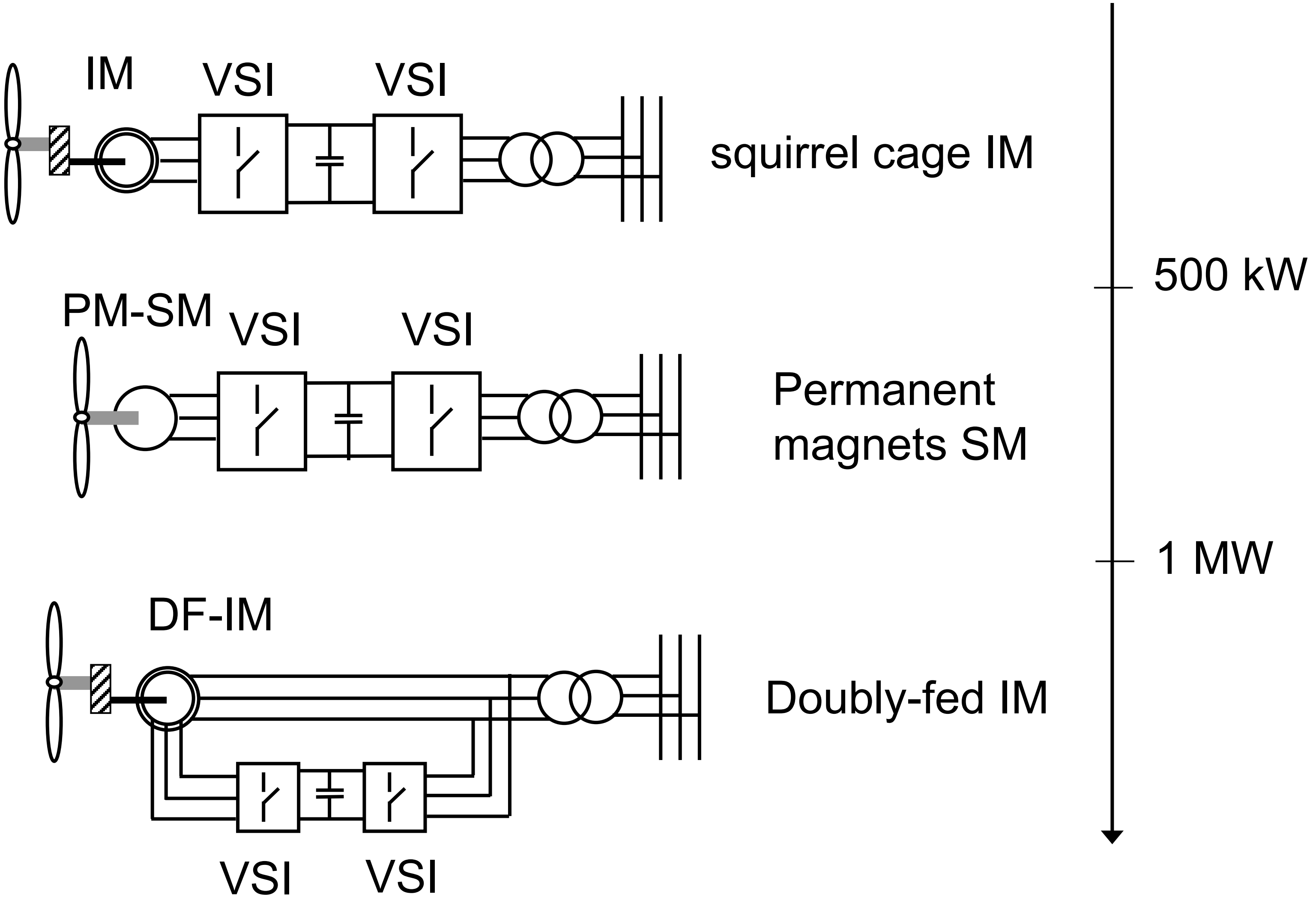
but only 5%
of the electricity production
In the world in 2018



Part des renouvelables dans la production mondiale d'électricité en 2018

Source : International Energy Agency

© EDF

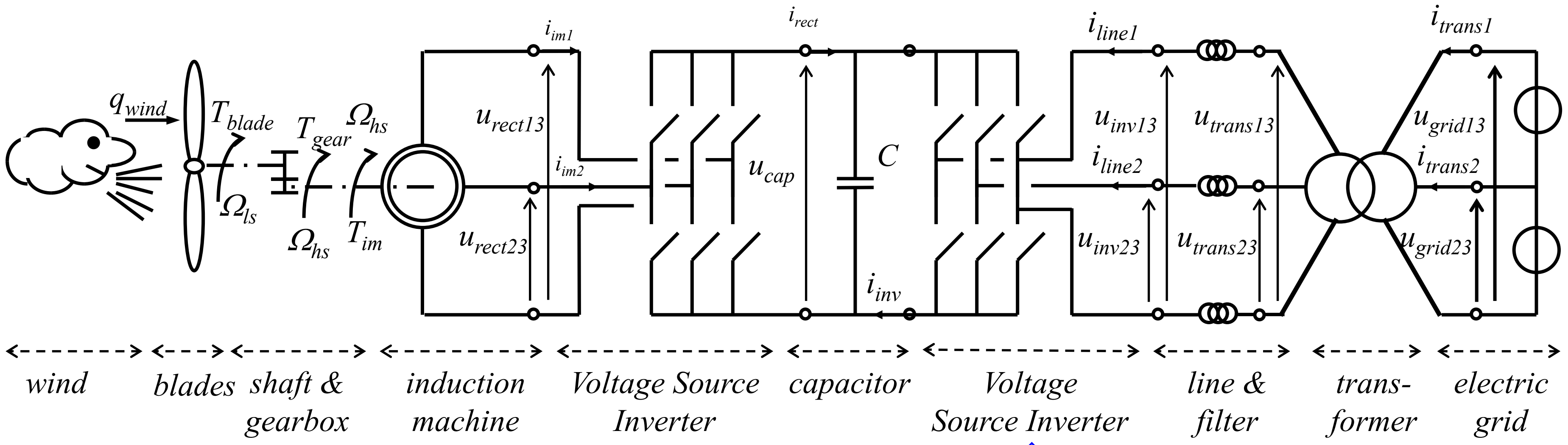


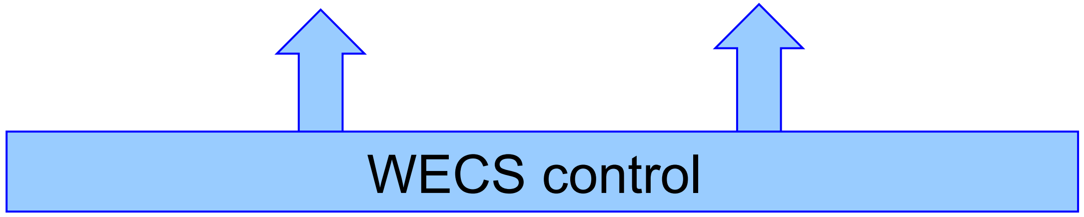
IM: induction machine
SM: synchronous machine

VSI: voltage source inverter

1. Wind Energy
2. **EMR of a WECS**
3. Control of a WECS
4. MPPT strategy

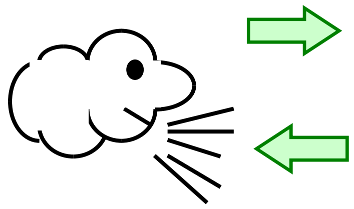
Chosen WECS for variable speed and variable frequency:
a squirrel cage IM and two VSI





Technical requirements: - provide the maximum active power P
- control the reactive power Q

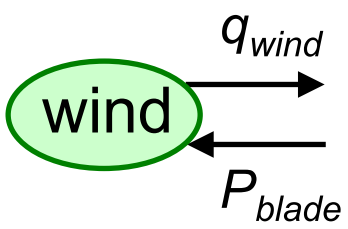
EMR of the wind



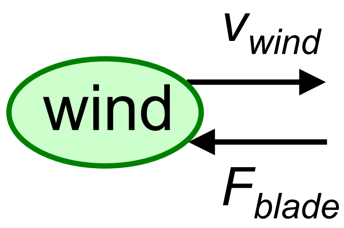
q_{wind} [m³/s]

P_{blade} [Pa]

Unidirectional energy source



or



q_{wind} air flow

P_{blade} pressure

v_{wind} wind velocity

F_{blade} blade force

$$Power = q_{wind} \times P_{blade} = v_{wind} \times F_{blade}$$

Constraints: the air flow has great instantaneous variations

$$F_{blade} = \frac{1}{2} \rho \, S \, v_{wind}^2$$

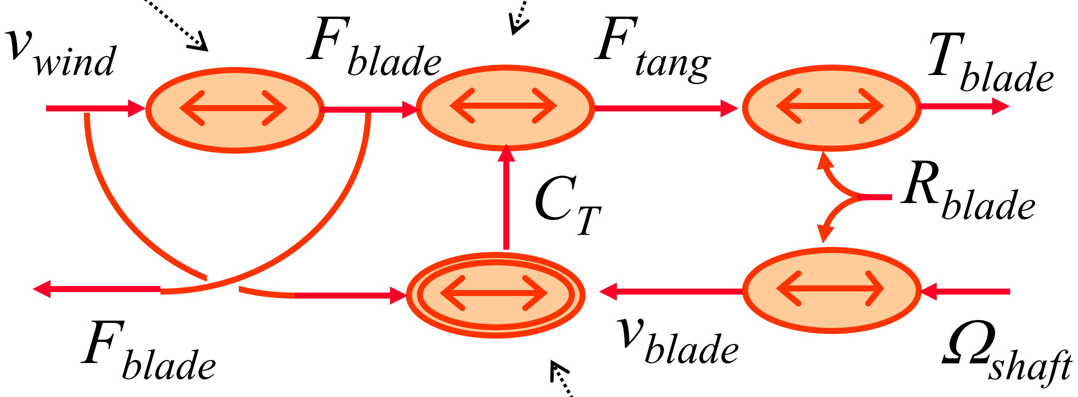
ρ ☞ air density;
S ☞ area swept by blades.

$$F_{tang} = C_T(\lambda) F_{blade}$$

$$\begin{cases} T_{blade} = R_{blade} F_{tang} \\ v_{blade} = R_{blade} \Omega_{shaft} \end{cases}$$

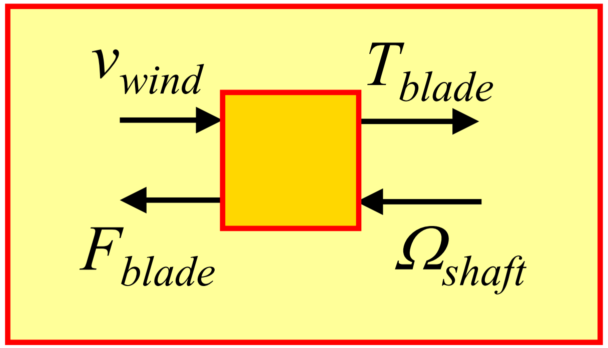
R_{blade} ☞ blade radius;

Causal Ordering Graph (COG)

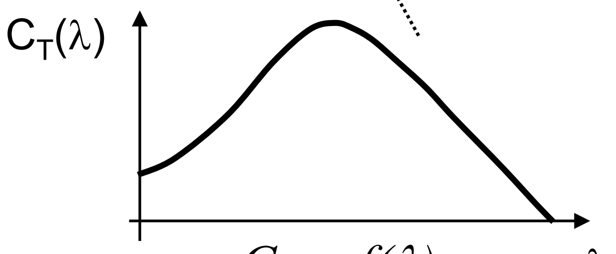


No derivative Relation

No energy accumulation



EMR of the blades



$$C_T = f(\lambda)$$

Non-linear curve
Related to the blade shape

$$\lambda = \frac{v_{blade}}{v_{wind}} = \frac{R_{blade} \Omega_{shaft}}{v_{wind}}$$

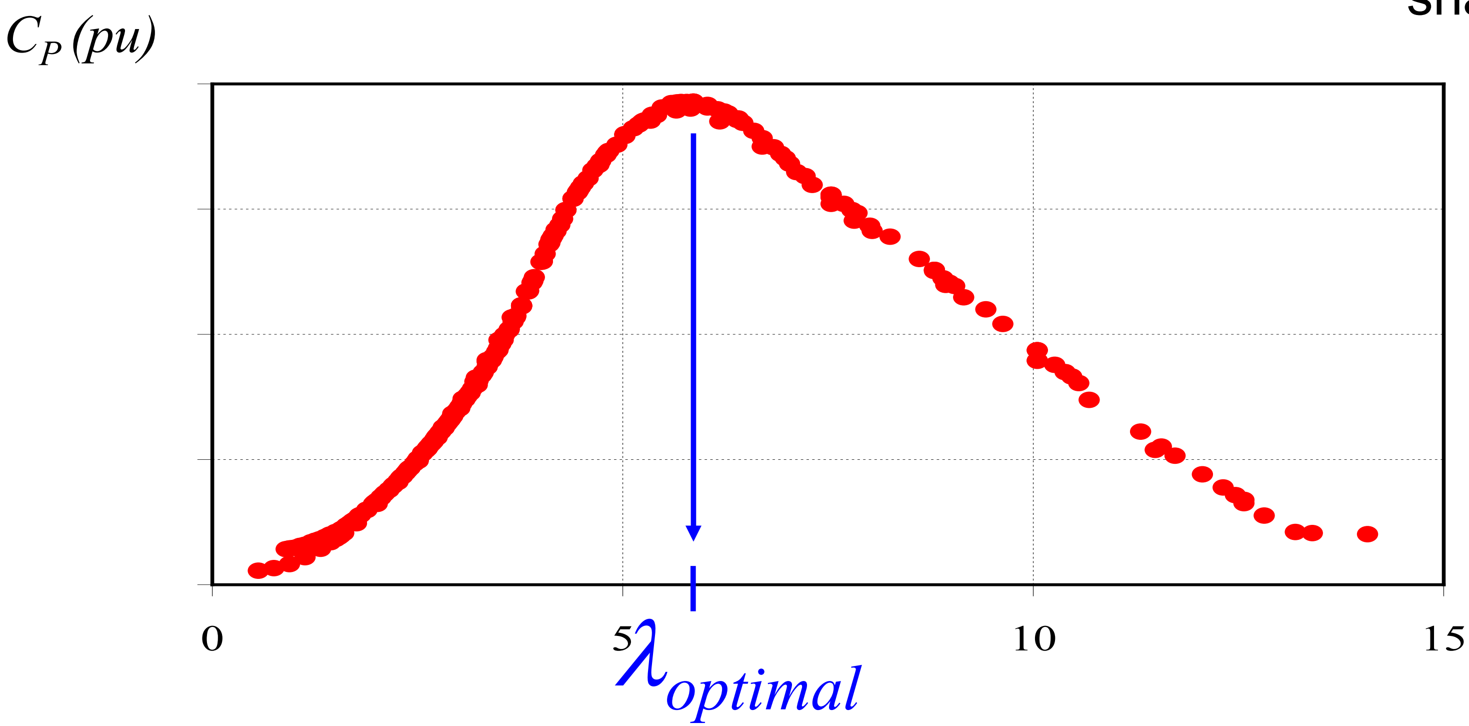
λ ☞ tip-slip ratio;

$$P_{wind} = F_{blade} v_{wind} = \frac{1}{2} \rho \, S \, v_{wind}^{3}$$

$$P_{target} = Cp(\lambda) \, P_{wind}$$

Only a part of the power acting on the blade
Is converted in mechanical
Power depending on the blade shape

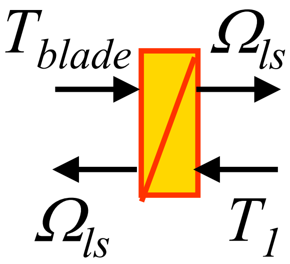
Power coefficient

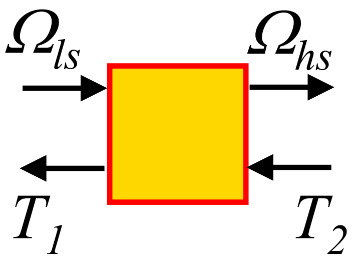


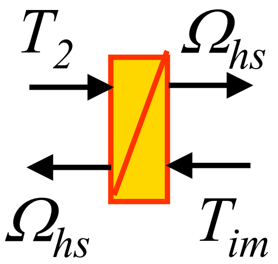
$$\lambda = \frac{v_{blade}}{v_{wind}} = \frac{R_{blade} \Omega_{shaft}}{v_{wind}}$$

tip slip ratio

$$J_1 \frac{d}{dt}\Omega_{ls} + f_1\Omega_{ls} = T_{blade} - T_1 \qquad \begin{cases} T_1 = k_{gear} T_2 \\ \Omega_{hs} = k_{gear}\Omega_{ls} \end{cases} \qquad J_2 \frac{d}{dt}\Omega_{hs} + f_2\Omega_{hs} = T_2 - T_{im}$$



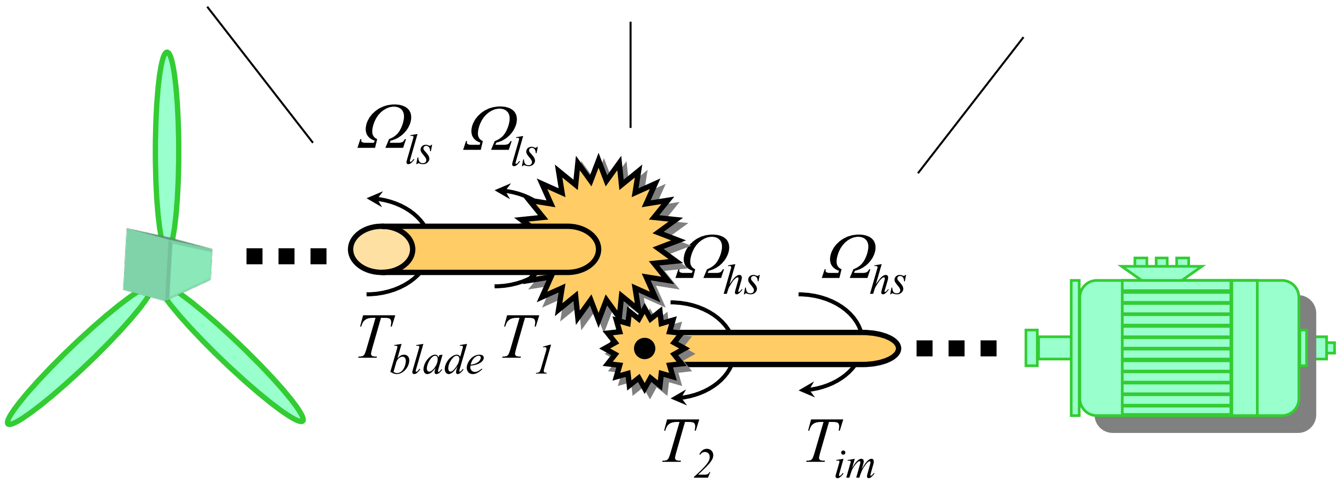




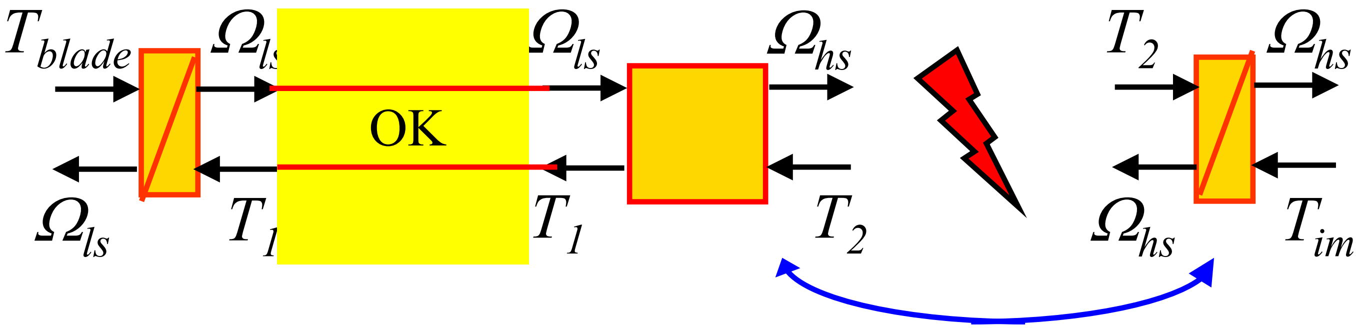
low speed shaft

gearbox

high speed shaft

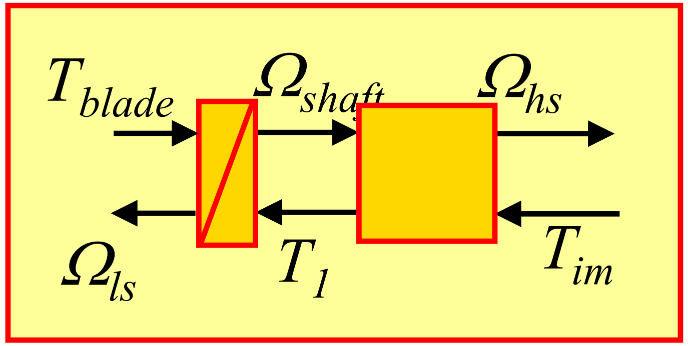


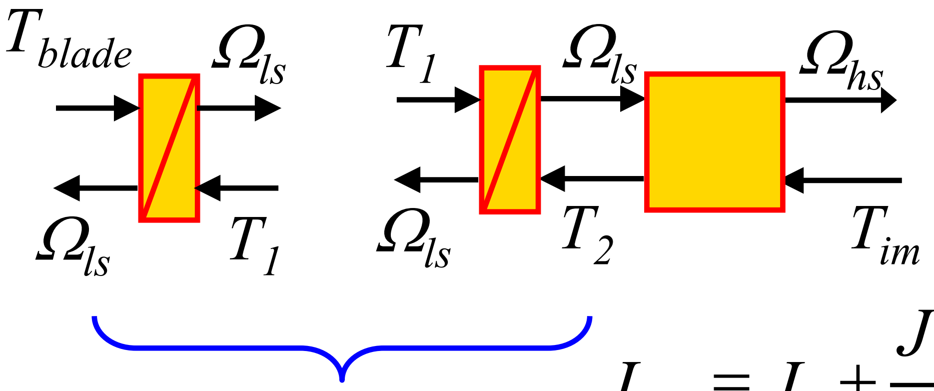
$$J_1 \frac{d}{dt}\Omega_{ls} + f_1\Omega_{ls} = T_{blade} - T_1 \qquad \begin{cases} T_1 = k_{gear} T_2 \\ \Omega_{hs} = k_{gear}\Omega_{ls} \end{cases} \qquad J_2 \frac{d}{dt}\Omega_{hs} + f_2\Omega_{hs} = T_2 - T_{im}$$



1. permutation

Equivalent power train

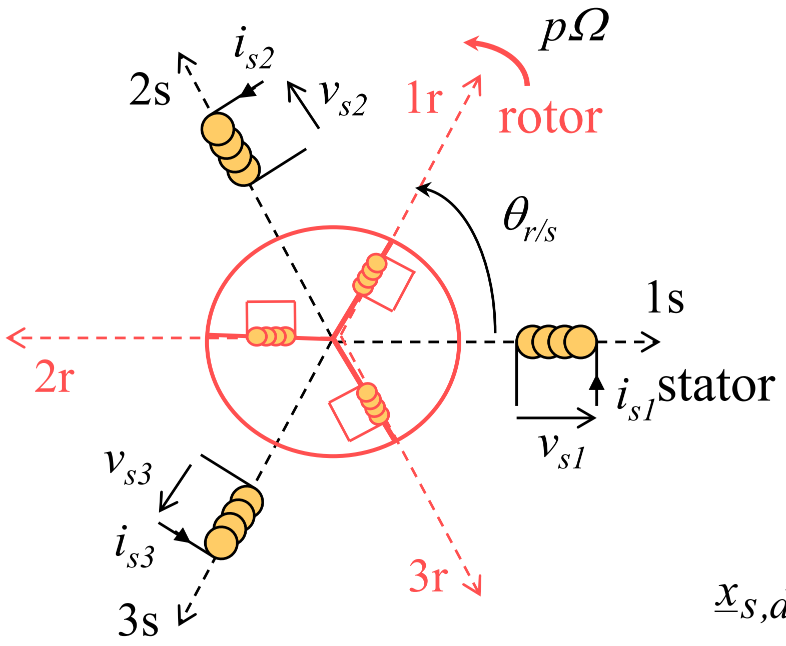




2. merging

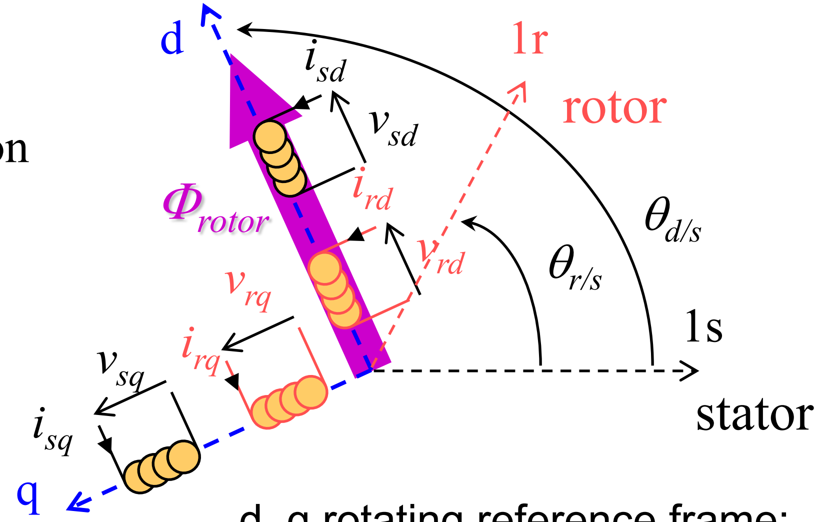
$$J_{eq} = J_1 + \frac{J_2}{k^2}$$

1 – IM: difficult to control AC currents
2 – strong interaction between the 3 phases



Park's transformation

New d,q frame attached to the rotor flux



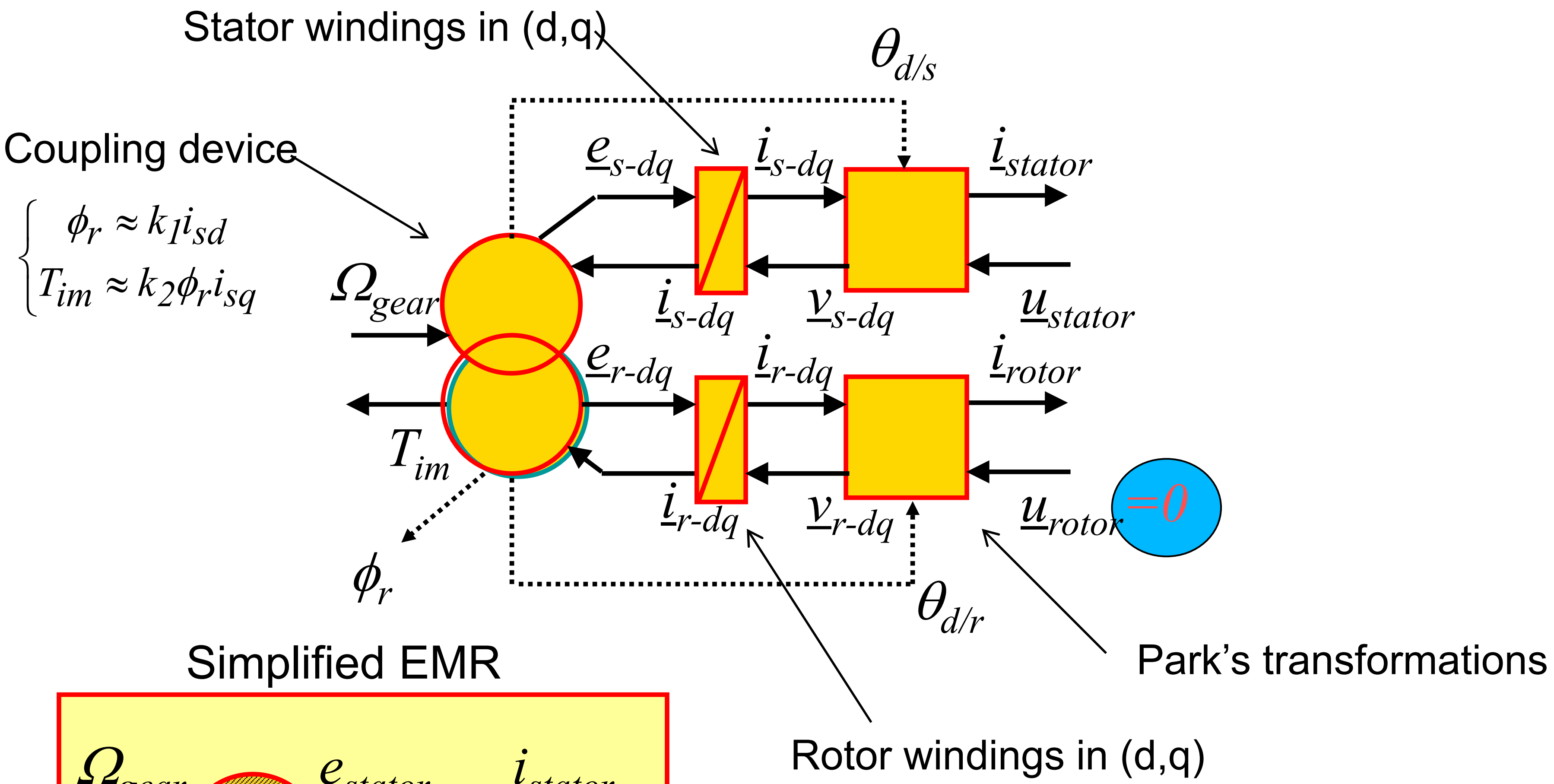
d, q rotating reference frame:
- DC current
- interaction simplification

$$\underline{x}_{s,dq} = [P(\theta_{d/s})]\underline{x}_{s,123}$$

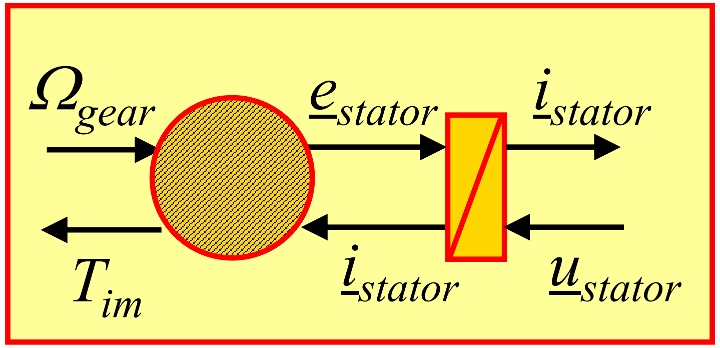
$$\underline{x}_{r,dq} = [P(\theta_{d/r})]\underline{x}_{r,123}$$

Modelling simplifications: $\begin{cases} \phi_r \approx k_1 i_{sd} \\ T_{im} \approx k_2 \phi_r i_{sq} \end{cases}$

EMR of a squirrel cage induction machine

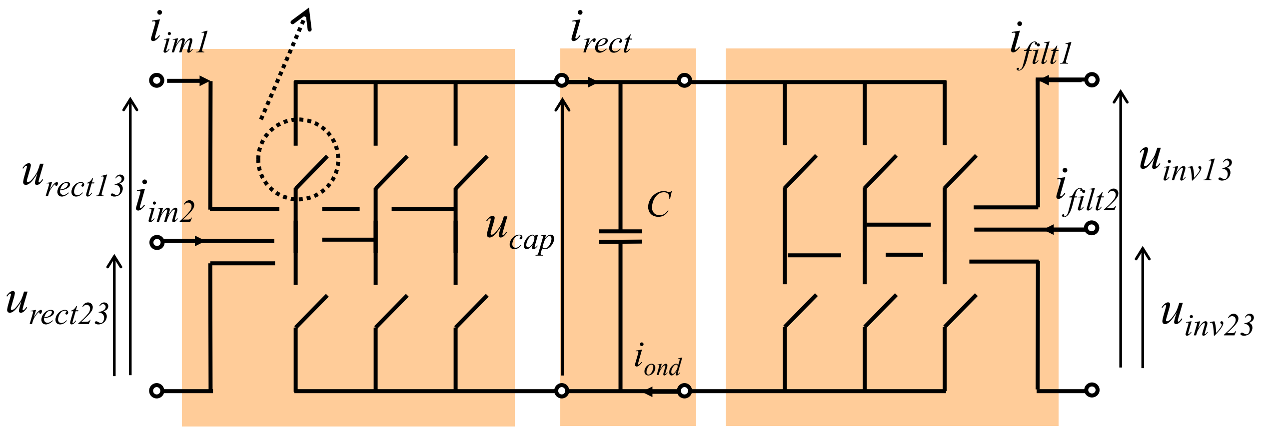


Simplified EMR



EMR of the back-to-back Voltage Source Inverter

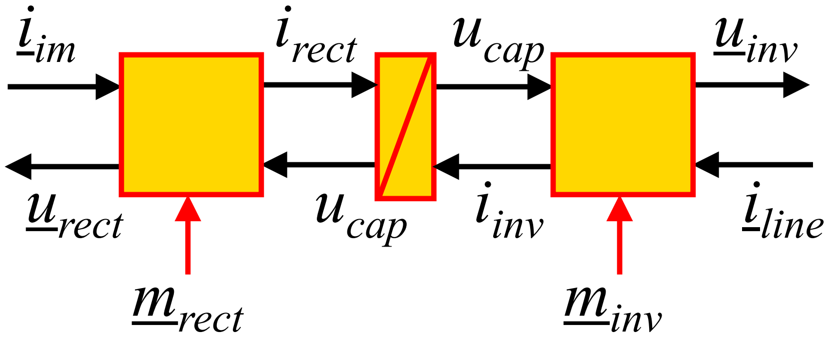
$$s_{11} = \begin{cases} 1\,(closed) \\ 0\,(open) \end{cases}$$



$$\underline{m}_{rect} = \begin{bmatrix} s_{11} - s_{13} \\ s_{12} - s_{13} \end{bmatrix}$$

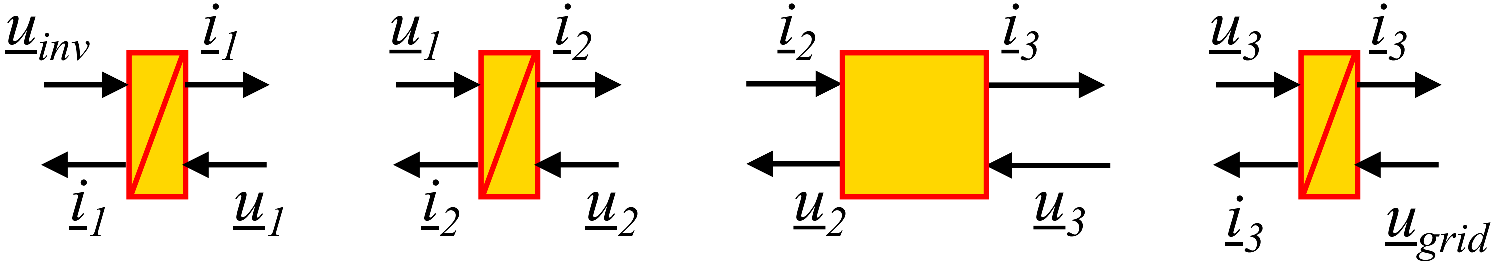
$$\begin{cases} \underline{u}_{rect} = \underline{m}_{rect} u_{cap} \\ i_{rect} = \underline{m}_{rect}^{t} \underline{i}_{im} \end{cases}$$

$$C \frac{d}{dt} u_{cap} = i_{rect} - i_{inv}$$



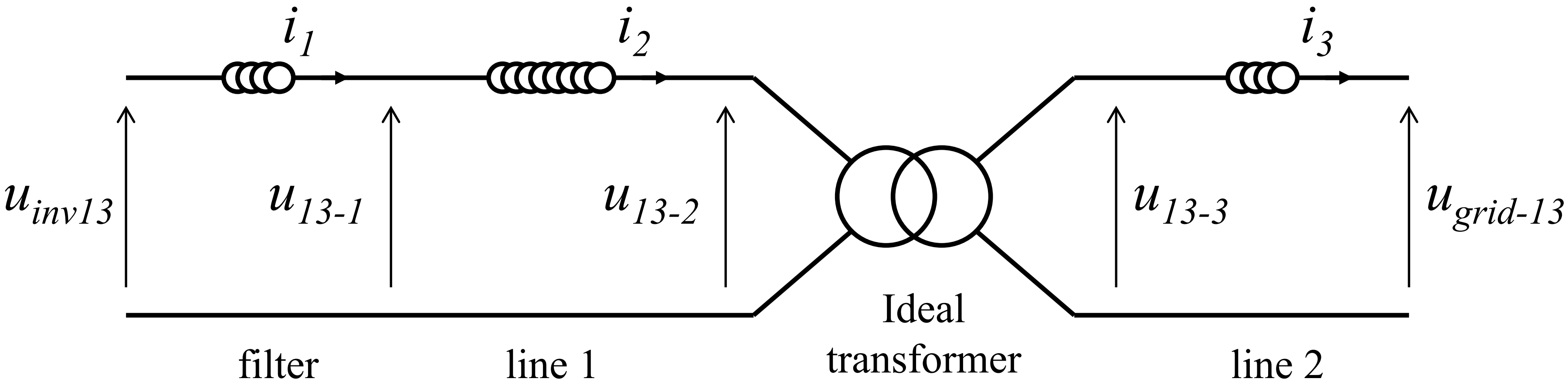
$$L_1 \frac{d}{dt}\underline{i}_1 + R_3 \underline{i}_1 = \underline{u}_{inv} - \underline{u}_1$$

$$\begin{cases} \underline{u}_2 = m_{trans}\underline{u}_3 \\ \underline{i}_3 = m_{trans}\underline{i}_2 \end{cases}$$



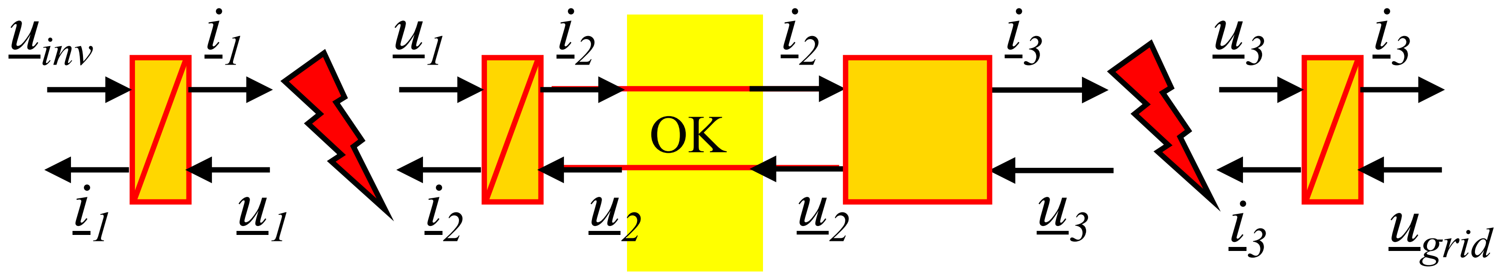
$$L_2 \frac{d}{dt}\underline{i}_2 + R_3 \underline{i}_2 = \underline{u}_1 - \underline{u}_2$$

$$L_3 \frac{d}{dt}\underline{i}_3 + R_3 \underline{i}_3 = \underline{u}_3 - \underline{u}_{grid}$$



Conflict of association

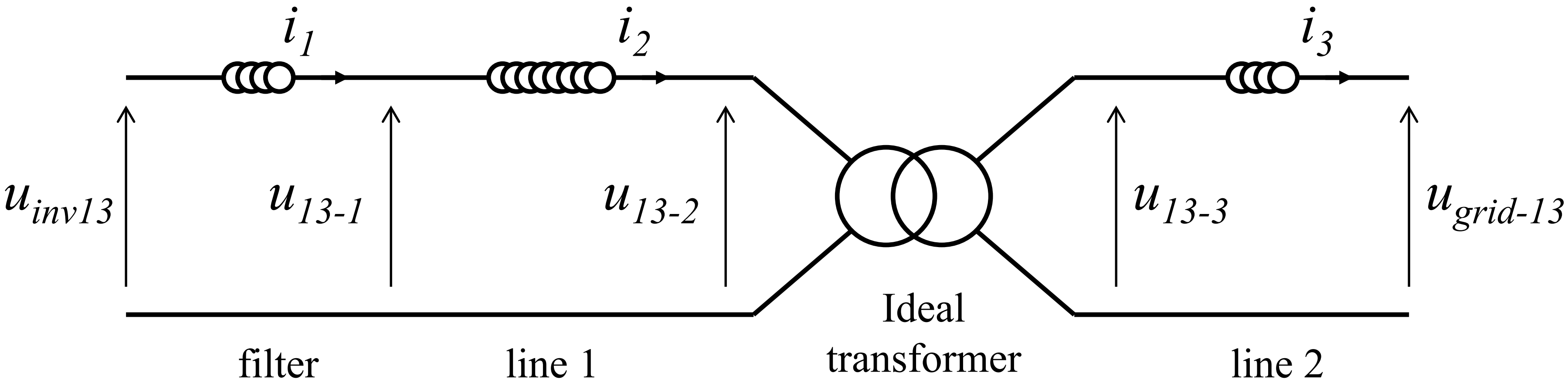
$$\begin{cases} \underline{u}_2 = m_{trans}\underline{u}_3 \\ \underline{i}_3 = m_{trans}\underline{i}_2 \end{cases}$$



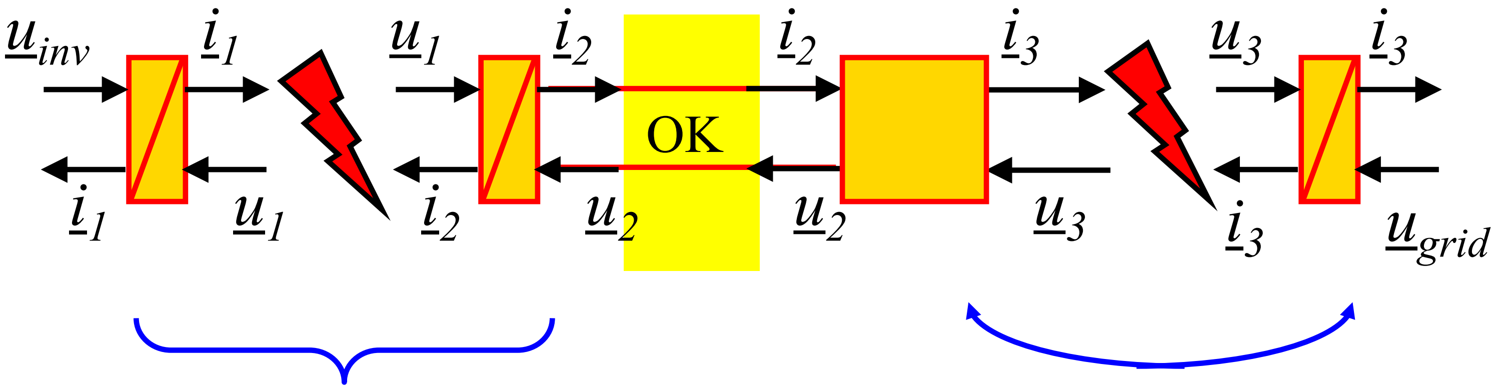
$I_1 = i_2$ series connection

$i_3 = m\ i_2$ transformer ratio

⇨ currents cannot be independent

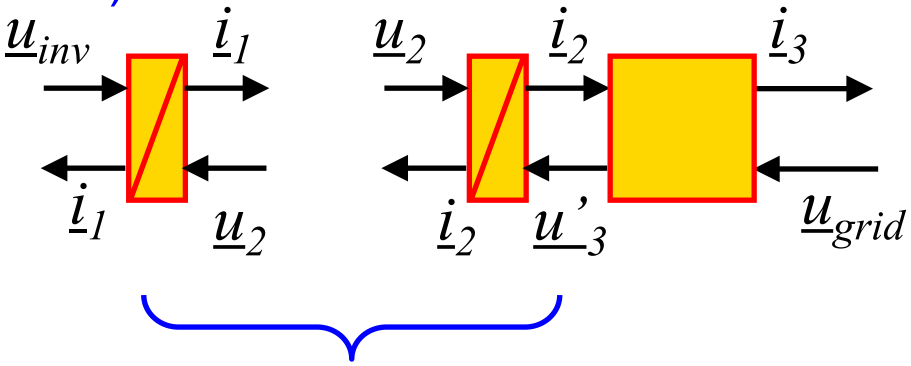


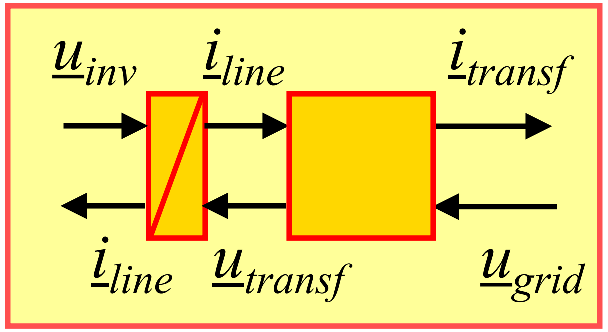
$$\begin{cases} \underline{u}_2 = m_{trans}\underline{u}_3 \\ \underline{i}_3 = m_{trans}\underline{i}_2 \end{cases}$$



1. merging (equiv. Coil)

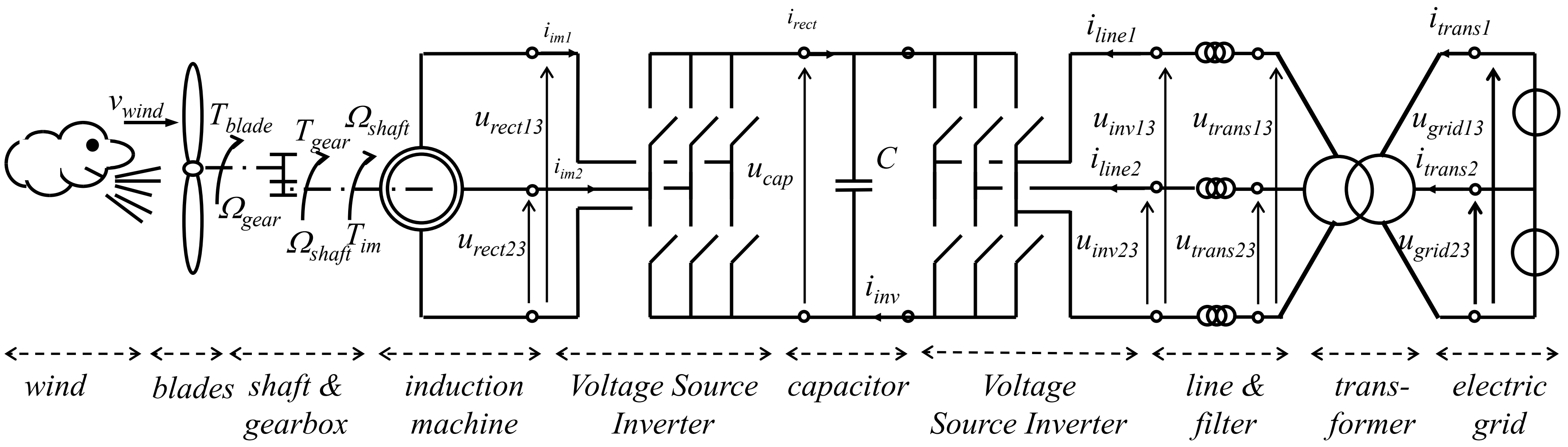
2. Permutation (bring *L3* to primary side)

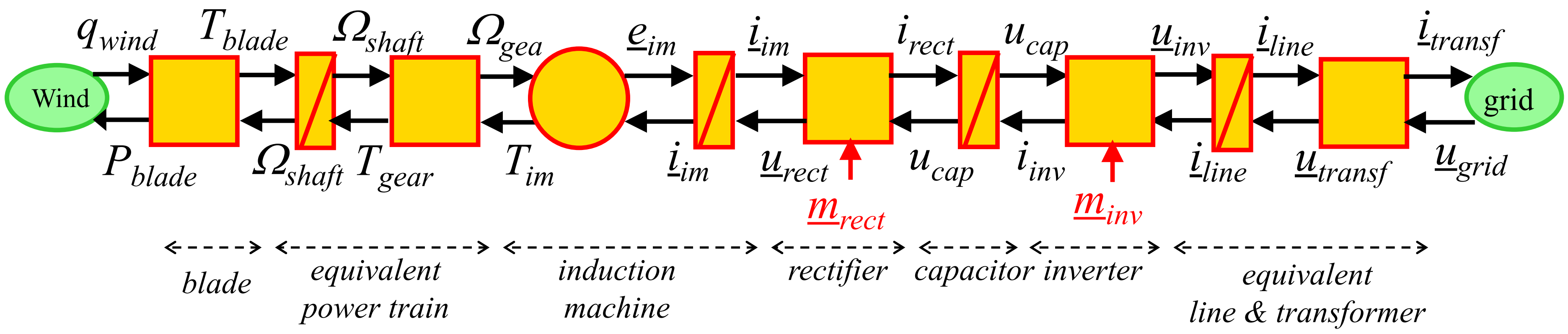




3. merging (equiv. Coil)

$$L_{eq} = L_1 + L_2 + \frac{L_3}{m_{trans}^2}$$


wind
blades
shaft & gearbox
induction machine
Voltage Source Inverter
capacitor
Voltage Source Inverter
line & filter
trans-former
electric grid


Wind
grid
blade
equivalent power train
induction machine
rectifier
capacitor
inverter
equivalent line & transformer

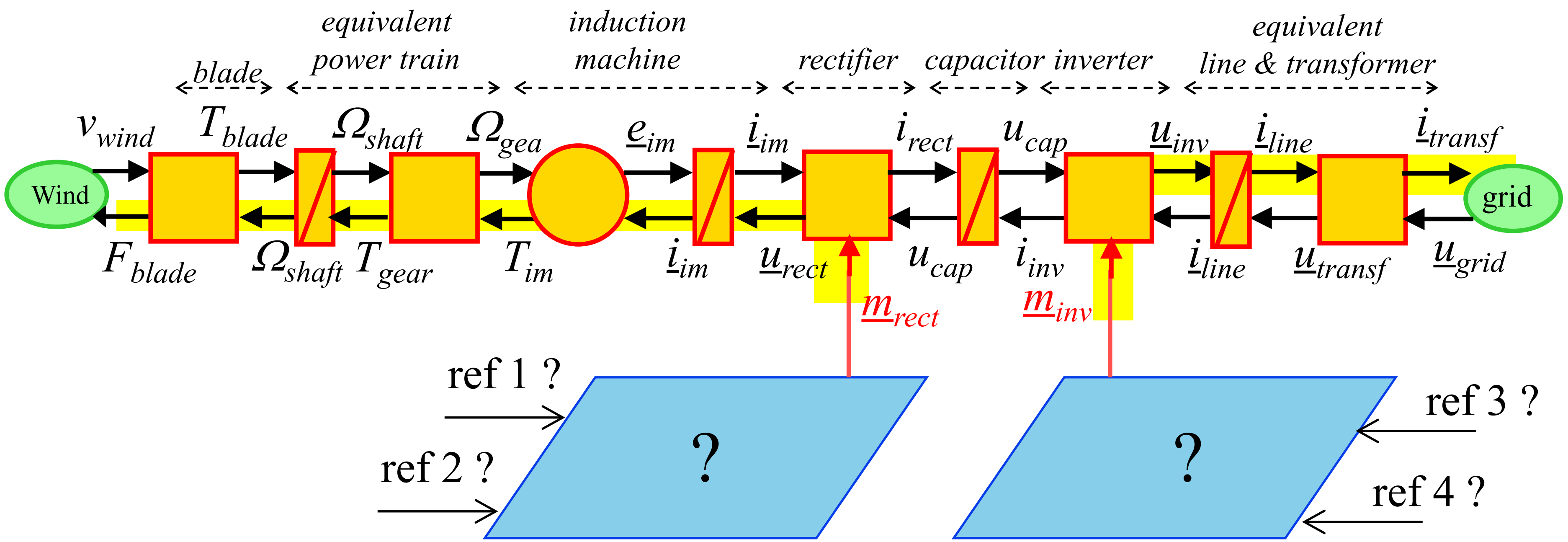
1 Wind Energy

2 EMR of a WECS

3 Control of a WECS

4 MPPT strategy

Tuning paths

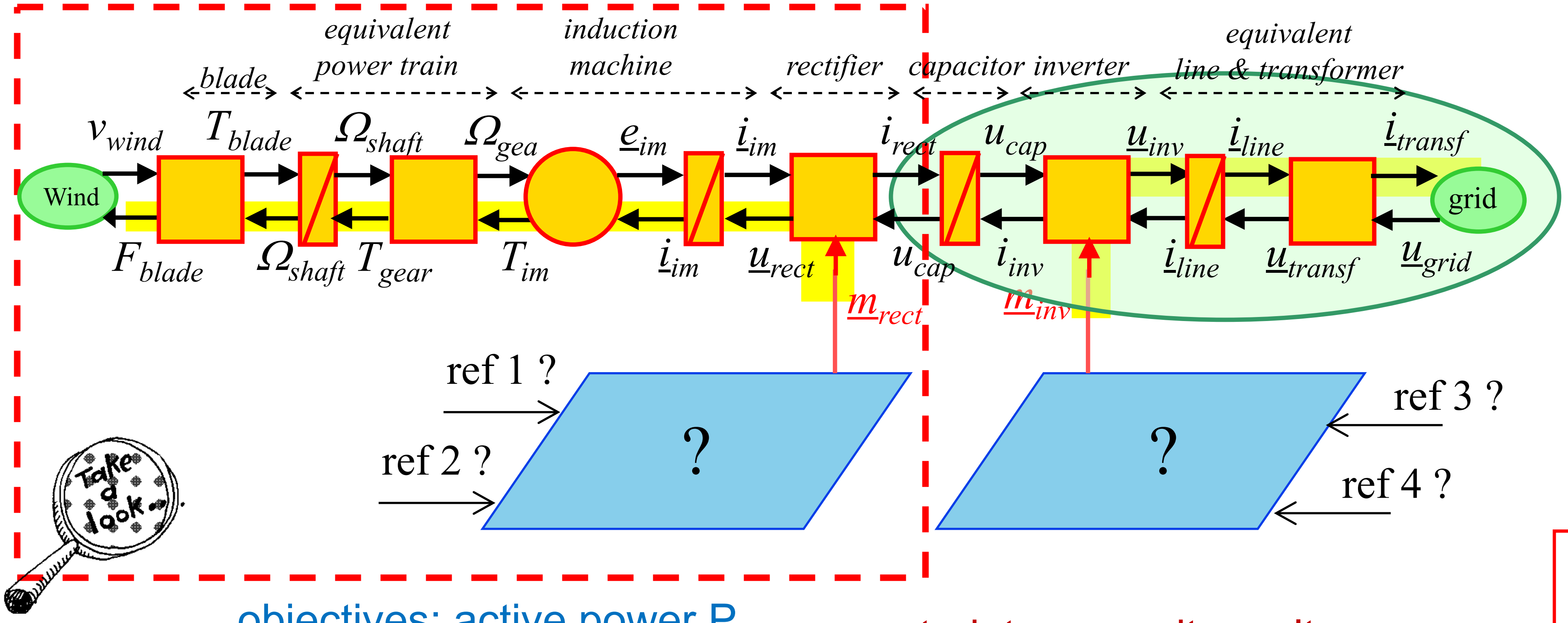


objectives: active power P
reactive power Q

constraints: capacitor voltage
machine flux

$$m_{rect} = \begin{bmatrix} m_{13} \\ m_{23} \end{bmatrix} \Rightarrow \text{2 degrees of freedom}$$

$$m_{inv} = \begin{bmatrix} m'_{13} \\ m'_{23} \end{bmatrix} \Rightarrow \text{2 degrees of freedom}$$



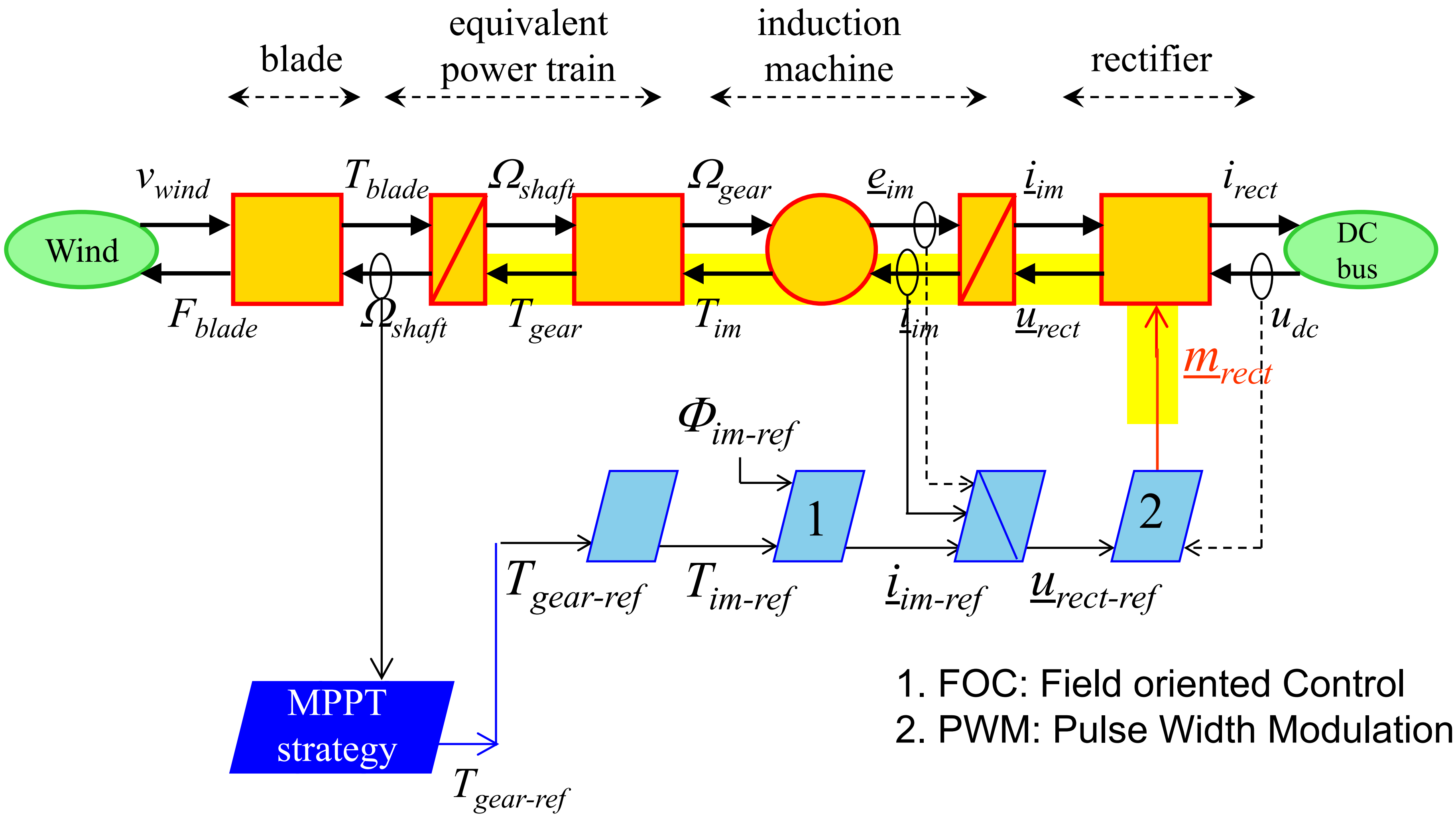
Divide & Conquer!

objectives: active power P
reactive power Q

constraints: capacitor voltage
machine flux

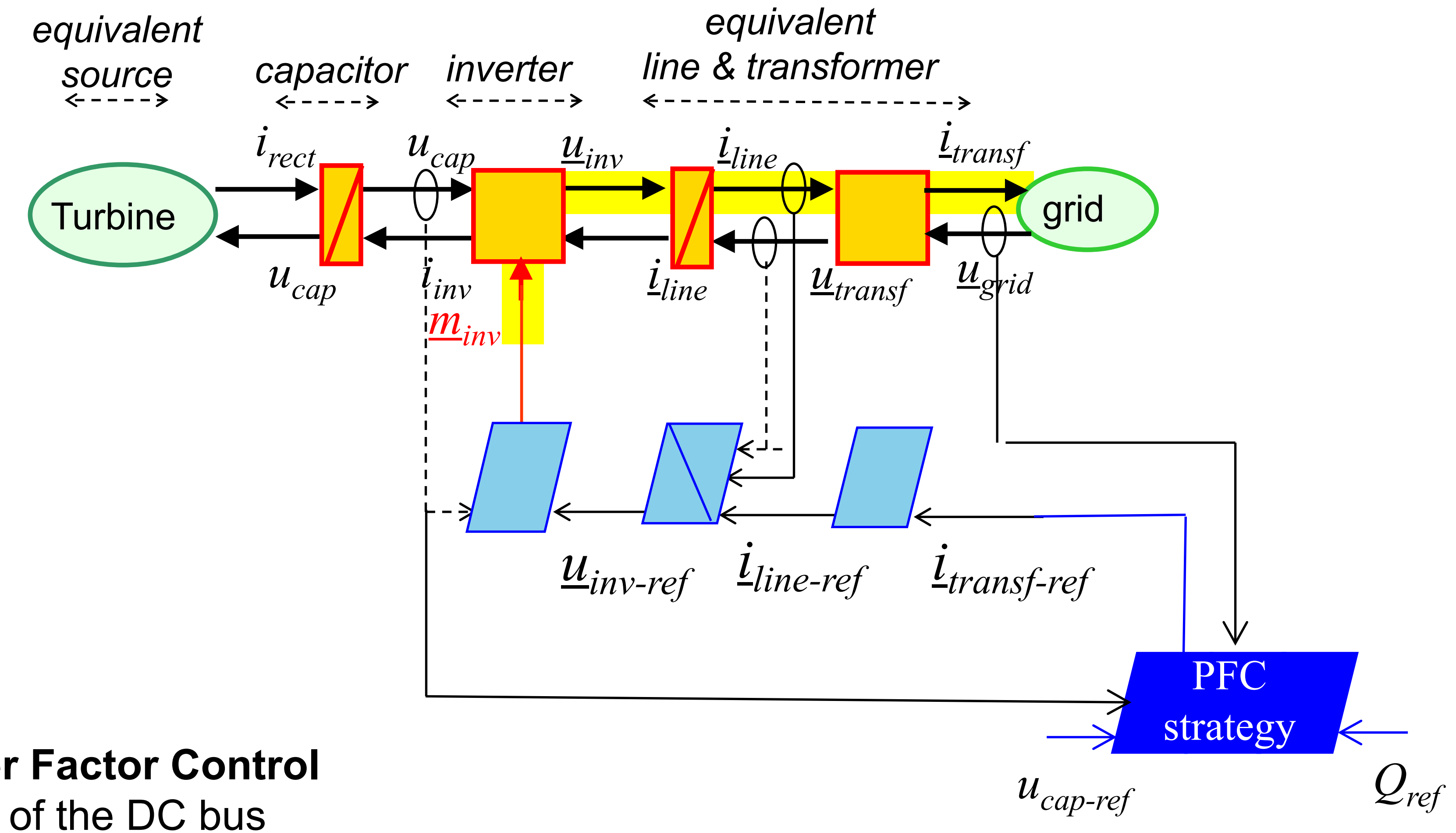
$$m_{rect} = \begin{bmatrix} m_{13} \\ m_{23} \end{bmatrix} \Rightarrow \text{2 degrees of freedom}$$

$$m_{inv} = \begin{bmatrix} m'_{13} \\ m'_{23} \end{bmatrix} \Rightarrow \text{2 degrees of freedom}$$



1. FOC: Field oriented Control
2. PWM: Pulse Width Modulation

MPPT = Maximum Power Point Tracking



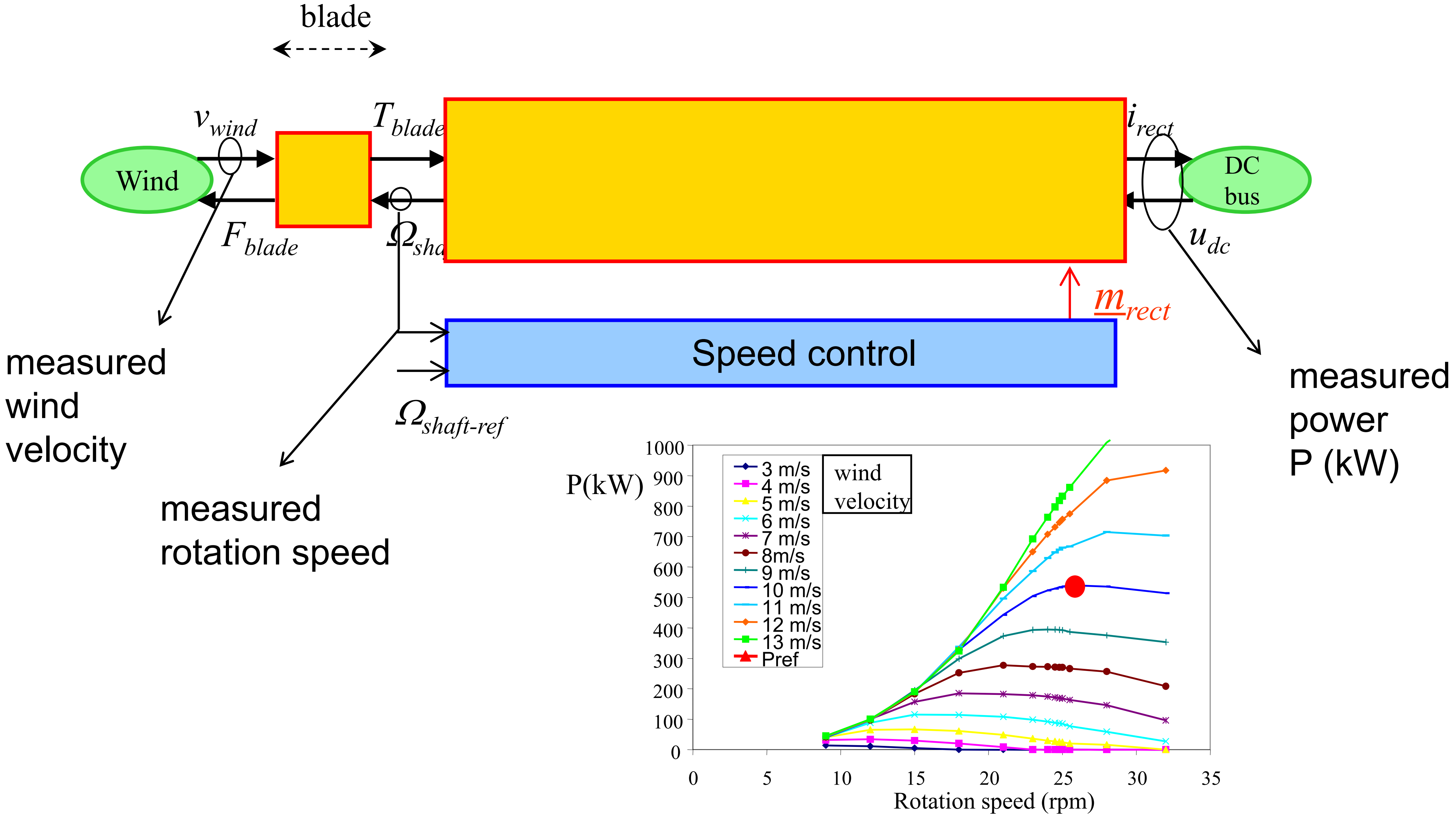
PFC = Power Factor Control

- regulation of the DC bus
- Control of the reactive power

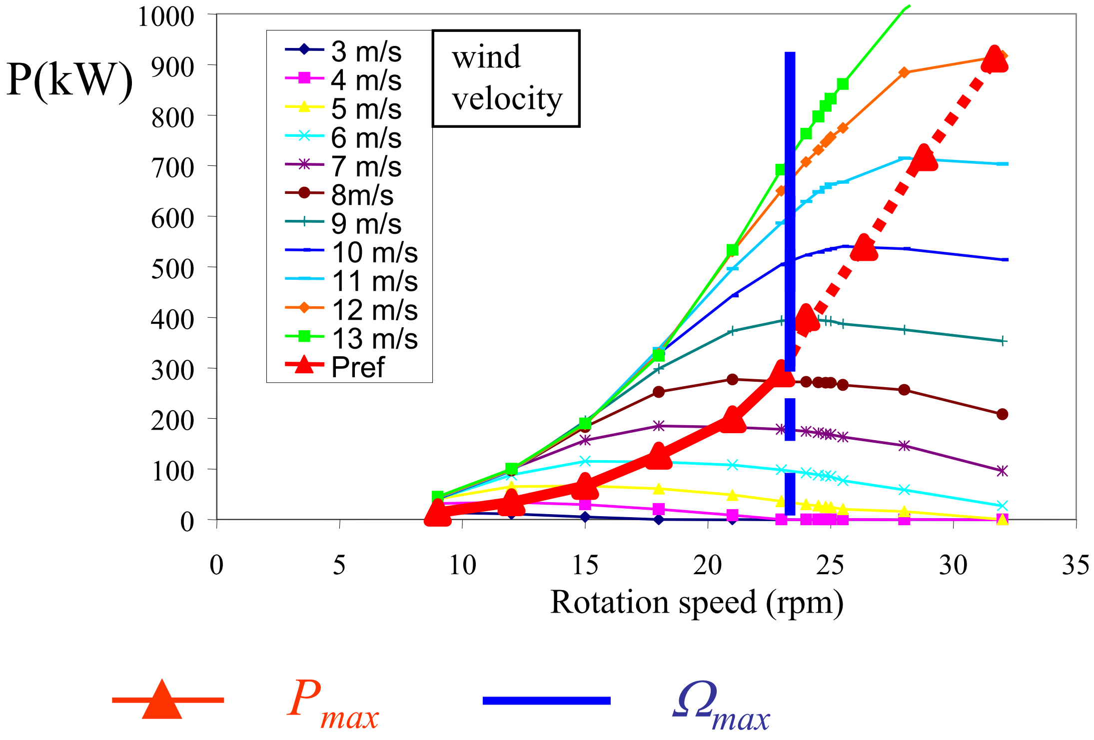
(well-know in power electronics)

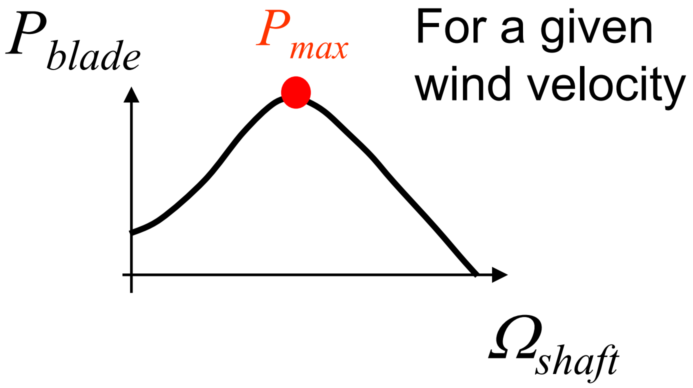
1. Wind Energy
2. EMR of a WECS
3. Control of a WECS
4. **MPPT strategy**

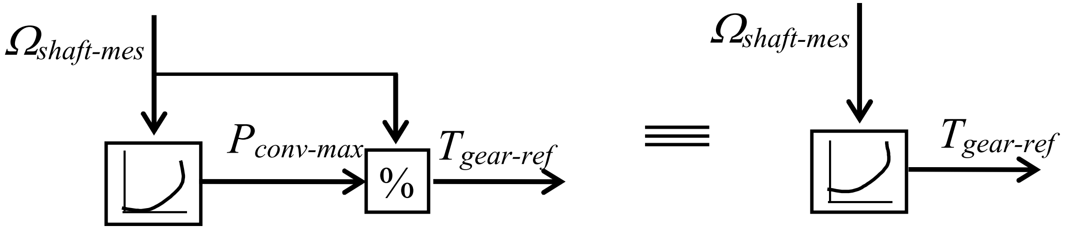
Stress test in wind tunnel

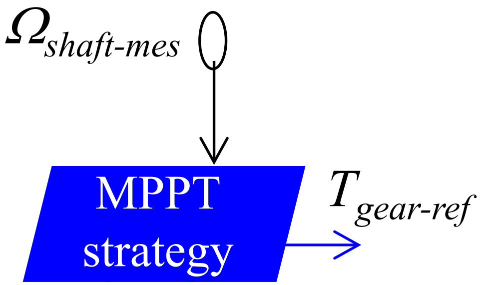


MPPT strategy



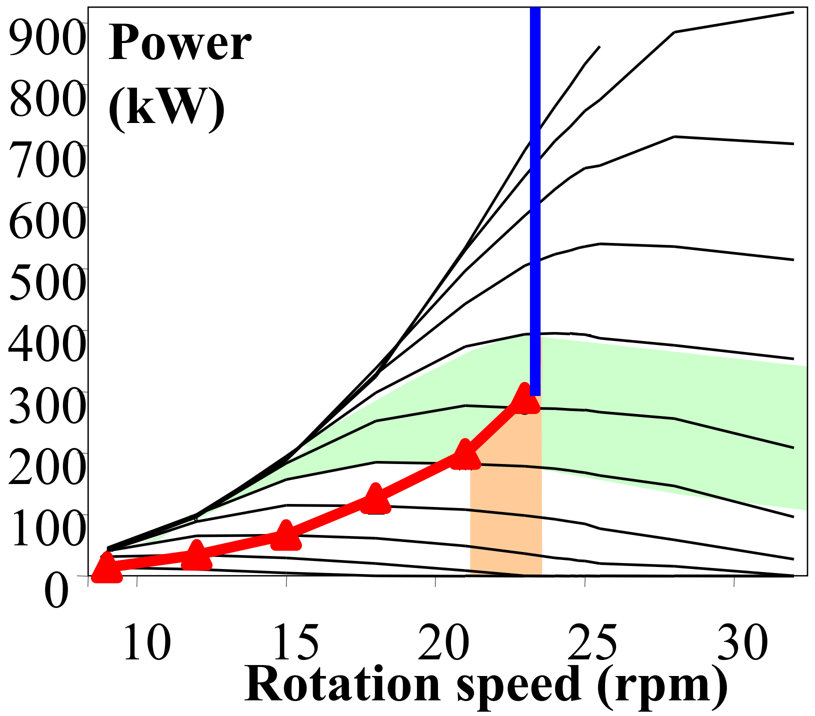


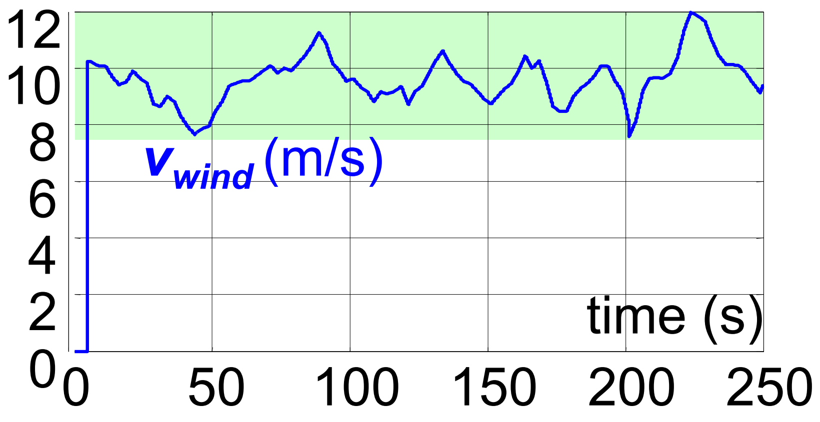




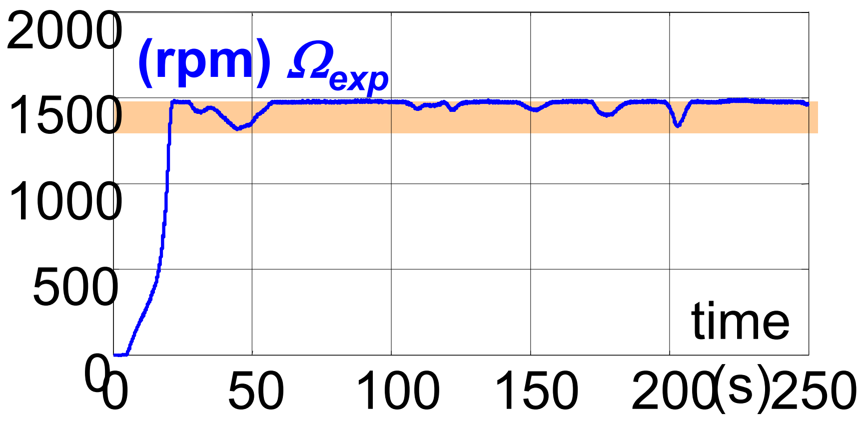
MPPT = Maximum Power Point Tracking

+ speed limitation (safety)





wind velocity



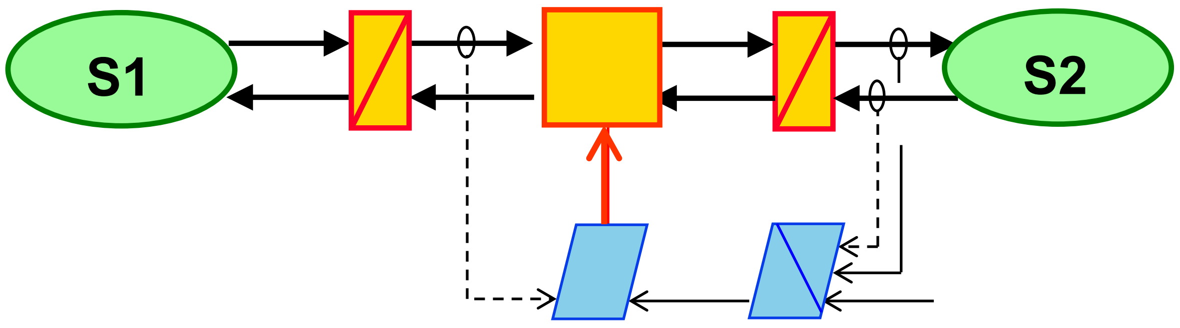
Rotation speed

Conclusion

Wind Energy is developing more and more
for renewable energy production

WECS is a complex system
composed of different subsystems in interactions

WECS control can be deduced from EMR
local controf (MCS) and strategies (MPPT and PFC)



[Bouscayrol 2005] A. Bouscayrol, P. Delarue, X. Guillaud, “Power strategies for Maximum Control Structure of a wind energy conversion system with a synchronous machine", Renewable Energy, vol. 30, May 2005, pp. 2273-2288.

[Bouscayrol 2009] A. Bouscayrol, X. Guillaud, P. Delarue, B. Lemaire-Semail, “Energetic Macroscopic Representation and inversion-based control illustrated on a wind energy conversion systems using Hardware-in-the-loop simulation”, IEEE trans. on Industrial Electronics; vol. 56, no. 12, pp. 4826-4835, December 2009.

[Bouscayrol 2012] A. Bouscayrol, J. P. Hautier, B. Lemaire-Semail, "Graphic Formalisms for the Control of Multi-Physical Energetic Systems", Systemic Design Methodologies for Electrical Energy, tome 1, Analysis, Synthesis and Management, Chapter 3, ISTE Willey editions, October 2012, ISBN: 9781848213883.

[Bouscayrol 2023] A. Bouscayrol, B. Lemaire-Semail, "Energetic Macroscopic Representation and Inversion-Based Control", *Encyclopedia of electrical and electronic power engineering*, Vol. 3, pp 365-375, Elsevier, DOI : 10.1016/B978-0-12-821204-2.00117-3, ISBN : 978-0-12-823211-8, 2023.

[Delarue 2003] P. Delarue, A. Bouscayrol, A. Tounzi, X. Guillaud, G. Lancigu, “Modelling, control and simulation of an overall wind energy conversion system”, Renewable Energy, July 2003, vol. 28, no. 8, p. 1159-1324 (common paper L2EP Lille and Jeumont SA).

Thanks for your attention!

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