www.weset-project.eu

Mechatronics in Wind conversion process

Module 3.1

Introduction to Mechatronics in Wind conversion process

Co-funded by the
Erasmus+ Programme
of the European Union

Objectives

In this part of the course we will discuss the issues arising in the integration of wind energy process, and how mechatronics plays an essential role in its design and operation

ECTS: 3

EQF level: 7

Co-funded by the
Erasmus+ Programme
of the European Union

Learning Outcomes

Upon completion of this module, Student should be able to :

O1. Explain what is a mechatronic;

O2. List the components of a mechatronic ;

O3. Give examples of real-world mechatronic systems;

O4. Appreciate how mechatronics integrates knowledge from different disciplines in order to realize engineering and consumer products that are useful in everyday ;

O5. Define the main components of the mechatronic and control system in Wind energy Systems.

Co-funded by the
Erasmus+ Programme
of the European Union

www.weset-project.eu

Technical Contents

1) Introduction to Mechatronics

- Definition of mechatronic
- Stages in the development of mechatronics
- Key disciplines used in the design of mechatronic systems

2) Mechatronics in the Wind Conversion Process

- Mechatronics in wind energy
- Mechatronics at the heart of wind turbines

Co-funded by the
Erasmus+ Programme
of the European Union

1) Introduction to Mechatronics

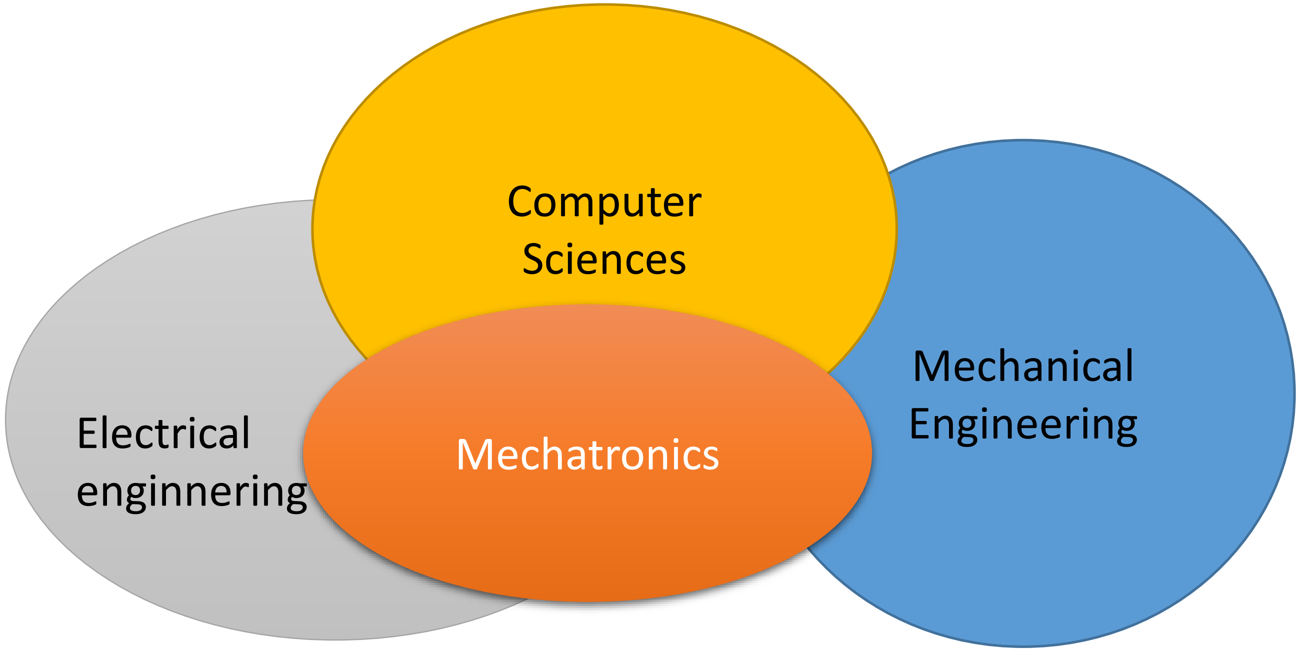
- Definition of mechatronic
- Stages in the development of mechatronics
Key disciplines used in the design of mechatronic systems

2) Mechatronics in the Wind Conversion Process

- Mechatronics in wind energy
- Mechatronics at the heart of wind turbines

Co-funded by the
Erasmus+ Programme
of the European Union

Introduction



Definition :

Approach to the synergy integration of mechanics, electronics, automation and computing in the design and manufacture of a product in order to increase and/or optimize its functionality

Co-funded by the Erasmus+ Programme of the European Union

What is mechatronics?

Definition 1: Mechatronics is the integration of: Electronics-automatic-Computers (microcontrollers, DSPs, etc) in order to control different mechanisms ranging from nano to macro.

Definition 2: Mechatronics is the integration of: Electronics-control-Information Technology to solve mechanical engineering problems. It consists of a bonding between mechanical engineering and electronic control

Definition 3: Mechatronics is the science that integrates mechanical components with electronic control

Co-funded by the Erasmus+ Programme of the European Union

History

- Word coined in 1969 by an engineer from the Japanese company, YASKAWA Electric corporation
- Combination of MECA (mechanical or mechanical and TRONIC (electronic)
- All rights to this word are granted to this company in 1971
- In 1982, YASKAWA abandoned its rights to the name in order to allow and encourage its use

Co-funded by the Erasmus+ Programme of the European Union

Stages in the development of mechatronics

- **Step 1** corresponds to the beginnings of the introduction of mechatronics (1969)

- **Step 2** corresponds to the early 80s.Emergence of the integration of different technologies

Example introduction of opto-electronics and some designs using software/hardware integration

- **Step 3** corresponds to the early 90s with miniaturization of components.

Notable developments include:

The development of smart machines

Miniaturization of components (micro-actuators, micro-sensors)

Co-funded by the Erasmus+ Programme of the European Union

Multidisciplinary Approaches to Design

Mechatronics can be defined as the integration of:

- Sensors and measurement systems;
- Actuators
- Analysis of system behaviour
- Control Systems
- Electronics
- Microprocessor-based systems
- etc

Mechatronics refers to an interdisciplinary approach to engineering that deals with the design of products whose functions are based on the integration of mechanical, electrical and electronic components, connected by an architecture of Command

Co-funded by the Erasmus+ Programme of the European Union

Key disciplines used in the design of mechatronic systems

- Mechanics
- Electronics
- Control
- Computer science

In order for the design to conform to the intended objective, the designer of a mechatronic system must assemble

-Analog and digital circuits

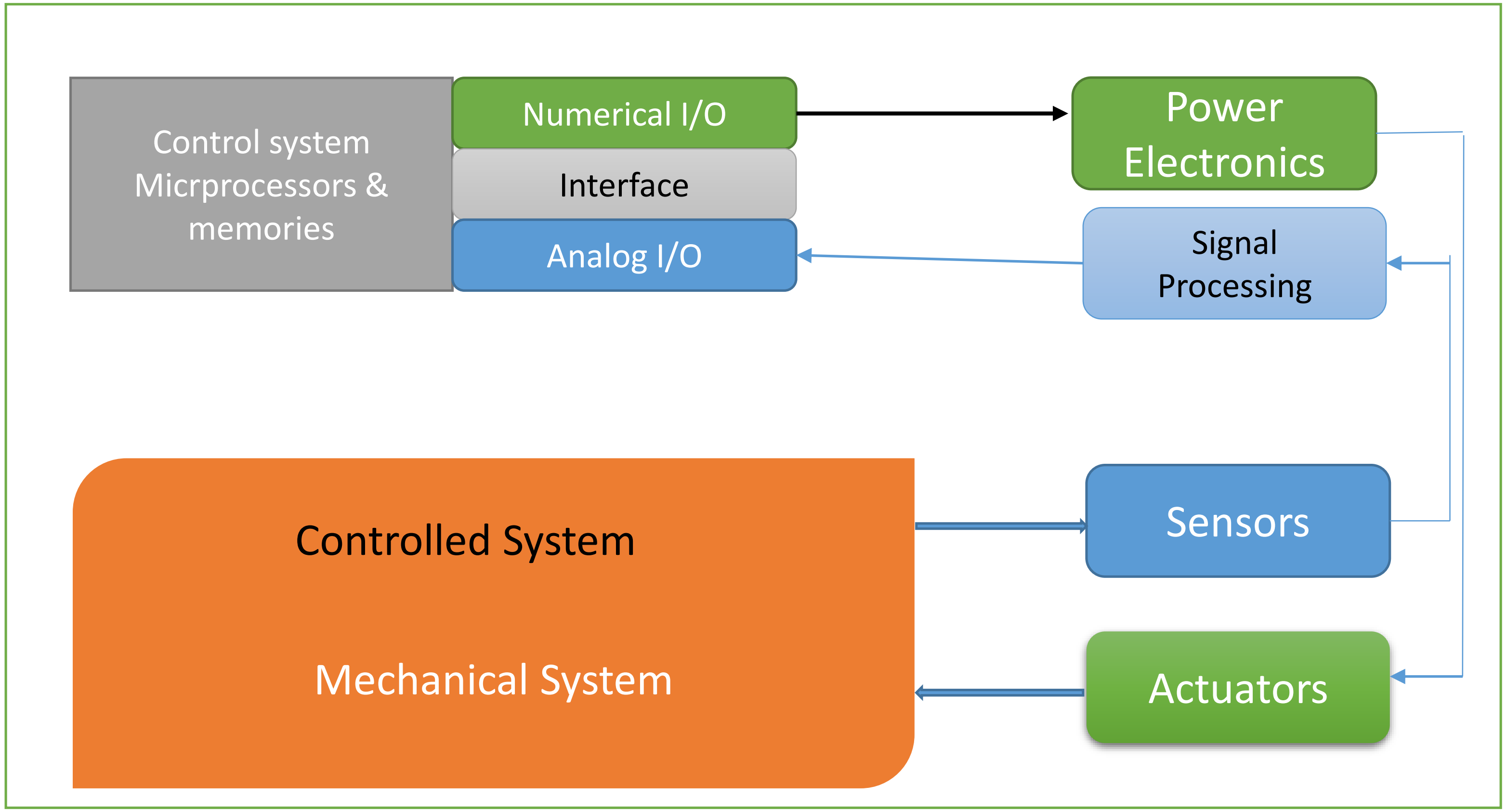
-Microprocessors, microcontrollers, computers, etc.

-Sensors and actuators

-Control algorithms

Co-funded by the Erasmus+ Programme of the European Union

General configuration of a mechanical system



Co-funded by the
Erasmus+ Programme
of the European Union

General configuration

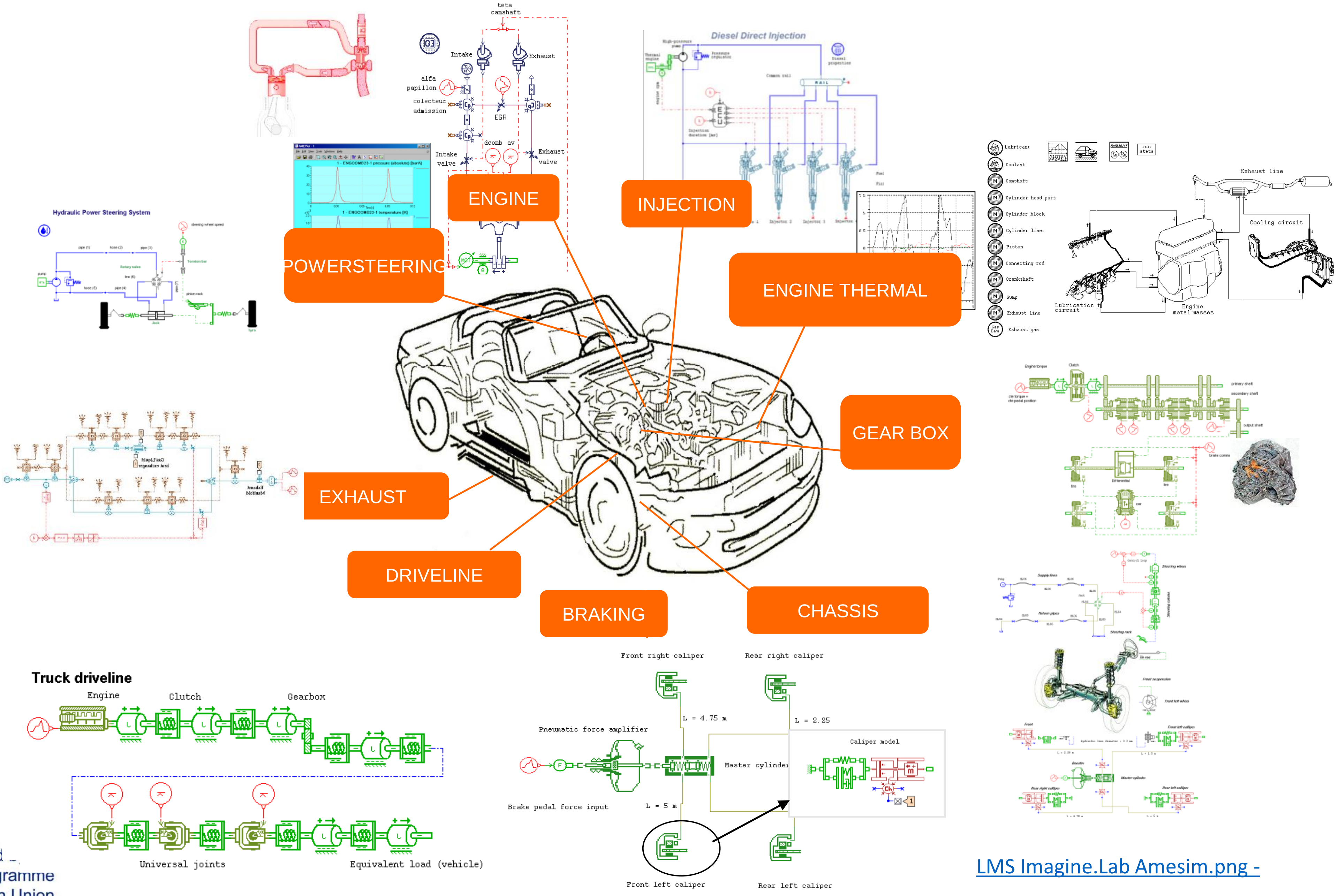
- **Controlled system**: mechanical component generally controlled and in contact with the environment by all its sensors and actuators

- **Control system**: this is the essential organ of the mechanical system. Its role is to exploit the information from the sensors to provide the decisions to the system ordered for the completion of the desired task. It has three main components:
  - -Perception
  - -Representation of knowledge
  - -Control planning

Mechatronics is at the heart of the success of the various products: cameras, televisions, etc…

Co-funded by the Erasmus+ Programme of the European Union

www.weset-project.eu



LMS Imagine.Lab Amesim.png -

Co-funded Erasmus+ Programme of the European Union

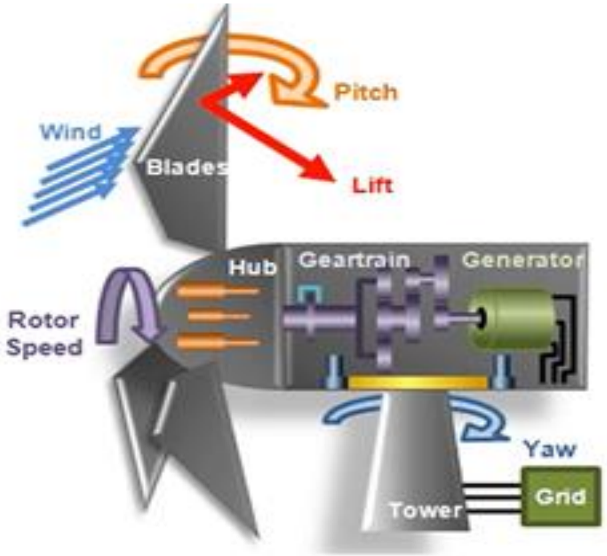
Mechatronics in wind energy 1/2

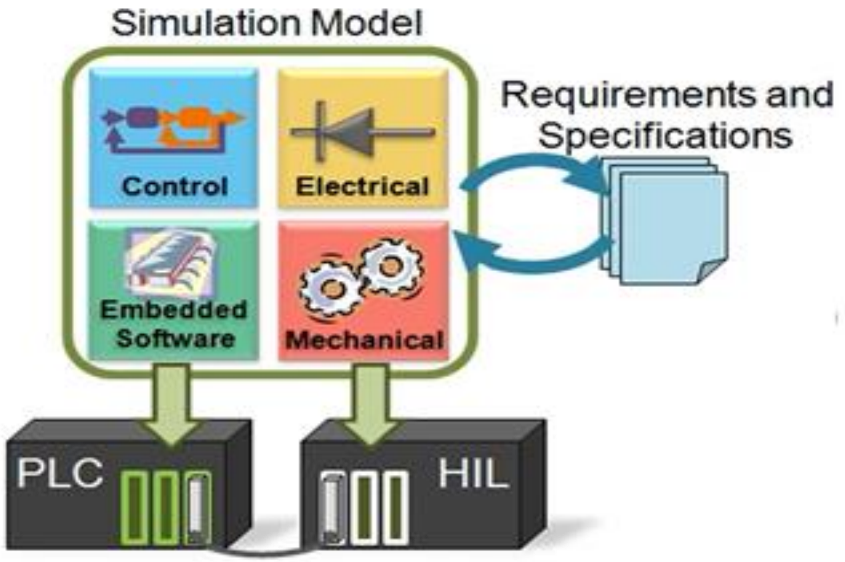
- Applications where mechatronics play an essential role include wind turbine. This is a combination of the aerodynamics of rotor design, the mechanics of the speed reduction system, the electromagnetism of the electric generator, the electronic power system for power conditioning of release and synchronization of the power provided to the network.

- Each part of the system must be designed in conjunction with other systems to achieve the overall objectives of an efficient conversion of the energy produced, taking into account both hardware and efficiency constraints.

Co-funded by the Erasmus+ Programme of the European Union

Mechatronics in wind energy 2/2





- *Matlab : Model based design of a wind Turbine by Steve Miller, Technical Marketing, physical Modeling tools, the Mathworks GmbH, Munich, germay*

Mechatronics at the heart of wind turbines 1/3

Wind control, rotational speed, temperature, etc
Mechatronics not only improves the operation of wind turbines, but also their design and maintenance

https://cdn.arstechnica.net/wp-content/uploads/sites/3/2017/05/5-Offshore-wind-OM-Siemens.jpg

Intelligent systems on board wind turbines allow preventive maintenance to be carried out. The response time of technicians on site is thus reduced.

Co-funded by the
Erasmus+ Programme
of the European Union

Mechatronics at the heart of wind turbines 2/3

One of the main challenges of the wind industry

- To reduce the costs of electricity generation,. by increasing the performance and reliability of the machines to optimize their maintenance and their lifespan .

- To use advanced technology development :

    - *Blade construction*
    - *Aerodynamic optimization*
    - *Advanced load control*
    - *Power electronics*
    - *Advanced material development*
    - *Wind sensing*
    - *Compact drivetrains*
    - *Advanced generators*
    - *Wind Farm Management*
    - *Advanced tower design*
    - …

    - **Possibilities are endless**

Co-funded by the
Erasmus+ Programme
of the European Union

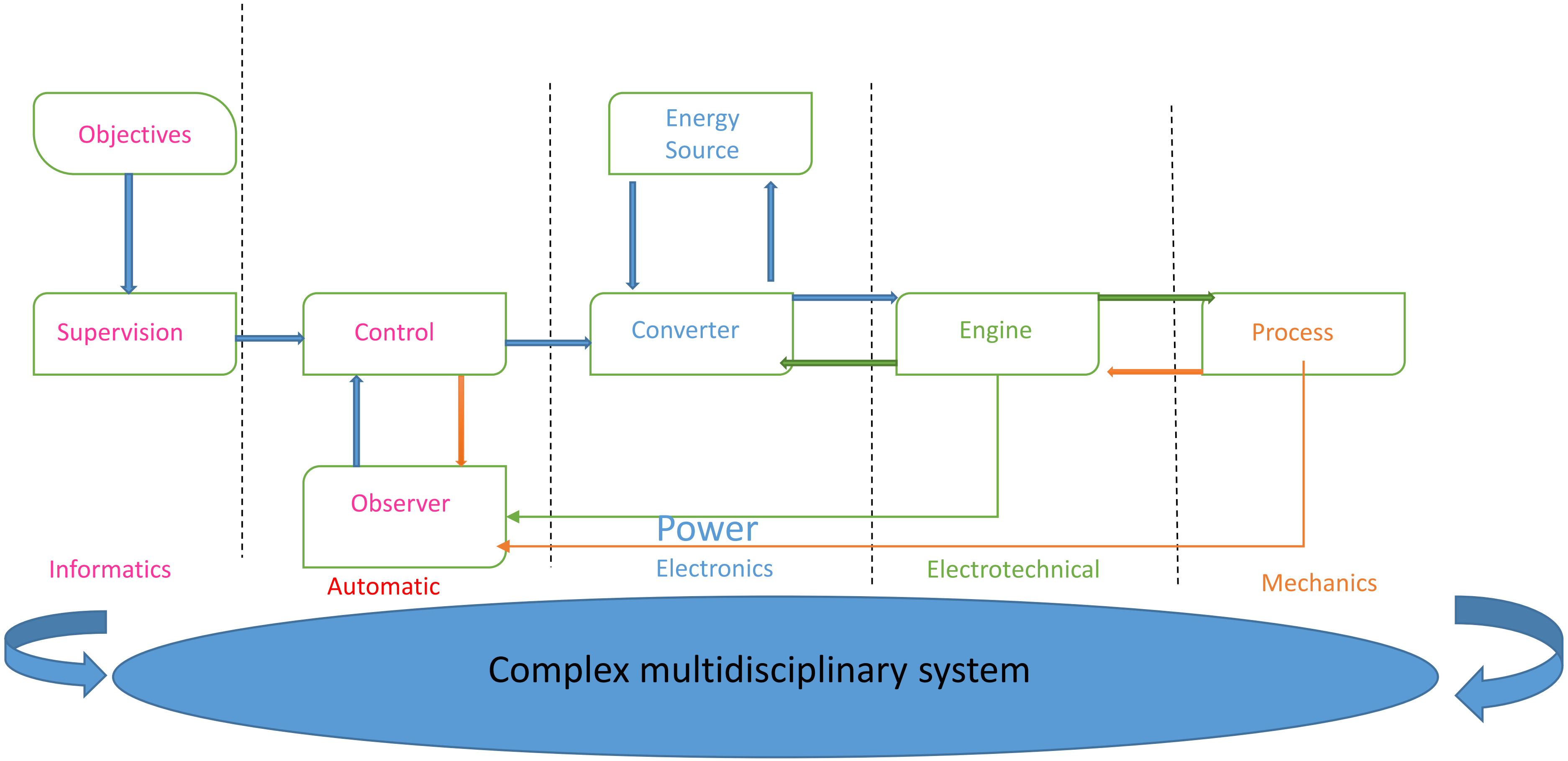
Mechatronics at the heart of wind turbines 3/3

- When a sensor detects an anomaly, such as an abnormal rise in temperature of an internal component, a brake is frequently applied to completely stop the rotation.

- Other hazards can be solved automatically. This is the case of frost that settles on the blades. Its detection is not provided directly, but by the appearance of a clam (unbalance) at the blades. The control center will then operate a heating system integrated into the blades.

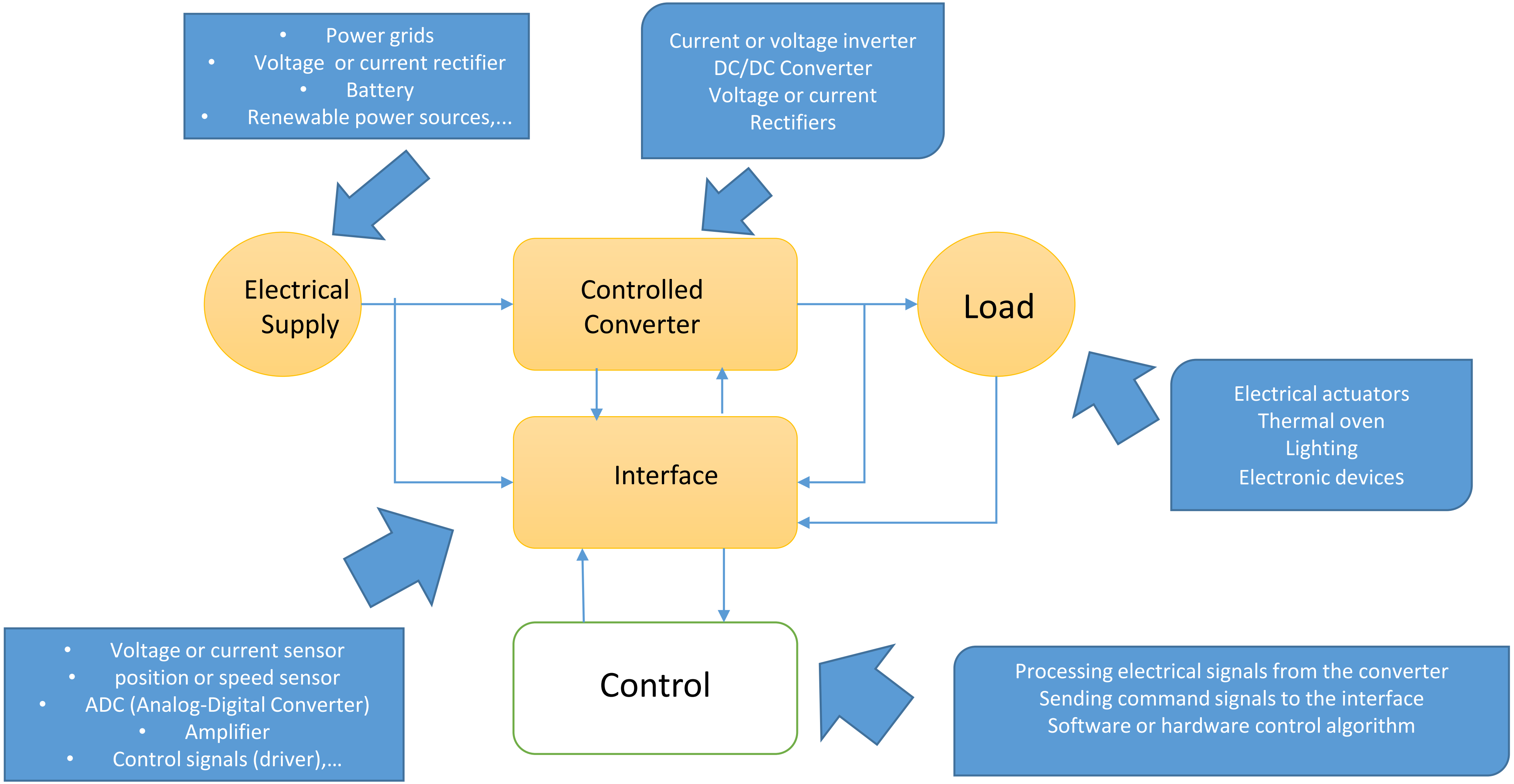
Co-funded by the
Erasmus+ Programme
of the European Union

Mechatronic system approach 1/2



Co-funded by the
Erasmus+ Programme
of the European Union

Mechatronic System approach 2/2



Co-funded by the
Erasmus+ Programme
of the European Union

Key elements of Mechatronics System

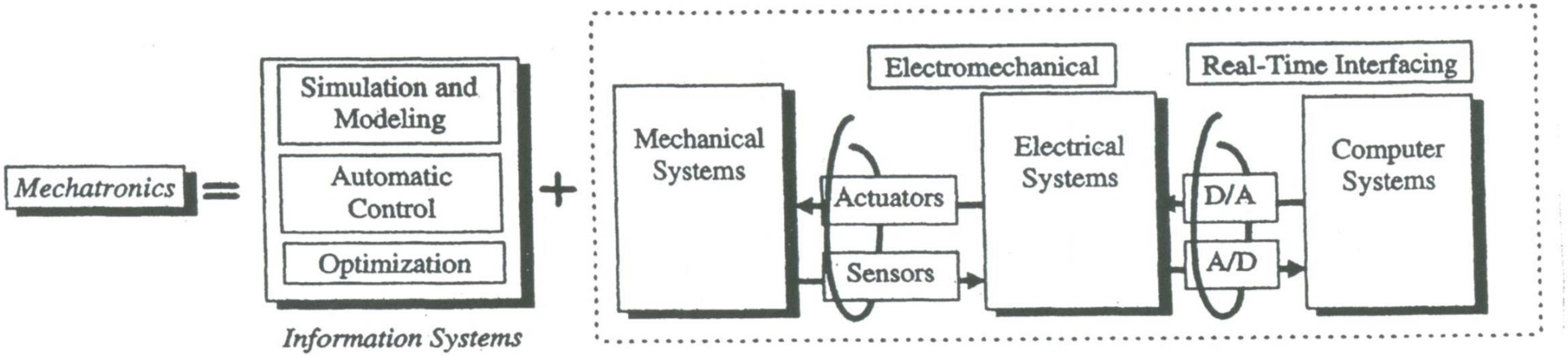


Illustration courtesy of National Instruments

Co-funded by the Erasmus+ Programme of the European Union

Conclusions

Mechatronics:

- Crossroads of different engineering specialties
- Recognized as a discipline in its own right
- Difficulty in transferring jurisdiction between different specialties
- Real needs in the industrial world
- Medium: simulation tools (AMESIM - LMS for example)

Applications: automotive, aeronautics, aerospace, wind , etc

Co-funded by the
Erasmus+ Programme
of the European Union

Recommended literature

Books:

1. Mechatronics: Principles and Applications, G. Onwubolu (Elsevier Science, 2005);

2• Mechatronics and Measurement Systems, D. Alciatore and M. Histland (McGraw-Hill, 2003);

3• Mechatronic Systems: Modeling and Simulation with HDLs, G. Pelz (Wiley, 2003);

4• Mechatronics: Electronic Control Systems in Mechanical and Electrical Engineering, 2nd Edition,

5. W. Bolton (Addison Wesley Longman Ltd, 1999);

6• Mechatronics System Design, D. Shetty and R. Kolk, (PWS Publishing Comp., 1997);

7• Mechatronics: Mechanical System Interfacing, D. Auslander and C. Kempf (Prentice Hall, 1996);

8• Mechatronics: Electromechanics & Contromechanics, by D. Miu (Springer Verlag, 1993).

Review articles:

[1]. Condition Diagnostic for Wind Parks, Rovsing Dynamics, Nov. 2008.

[2].Matlab [15]: Model based design of a wind Turbine by Steve Miller, Technical Marketing, physical Modeling tools, the Mathworks GmbH, Munich, germay

Co-funded by the
Erasmus+ Programme
of the European Union

Thank You for Your Attention!

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Contact: info@weset-project.eu weset.erasmusplus@uva.es

Co-funded by the Erasmus+ Programme of the European Union

Mechatronics in Wind conversion process

Module 3.2

Introduction to Modelling and Simulation for Wind Energy :

Bond Graph Modelling Approach

Co-funded by the
Erasmus+ Programme
of the European Union

Objectives

This part of the course is a complement to the course on multiphysical modeling. it is intended for those who wish to deepen the concepts of modeling and simulation based on the Bond Graph approach.

ECTS: 3

EQF level: 7

Co-funded by the
Erasmus+ Programme
of the European Union

Learning Outcomes

Upon completion of this module, Student should be able to :

O1. Understand the Bond Graph ;

O2. To use the different BG element;

O3. To understand and use the causality concept in BG;

O4. To see how to use of BG in Wind Turbine modelling

05. To use the 20 sim software for WT simulation

.

Co-funded by the
Erasmus+ Programme
of the European Union

www.weset-project.eu

Contents

Co-funded by the Erasmus+ Programme of the European Union

This part of the course is a complement to the course on multiphysical modeling. it is intended for those who wish to deepen the concepts of modeling and simulation based on the Bond Graph approach.

Co-funded by the Erasmus+ Programme of the European Union

Introduction

- Bond graph is an explicit graphical tool for capturing the common energy structure of systems. It increases one's insight into systems behavior. In the vector form, they give concise description of complex systems. Moreover, the notations of causality provides a tool not only for formulation of system equations, but also for intuition based discussion of system behavior, viz. controllability, observability, fault diagnosis, etc.

- By this approach, a physical system can be represented by symbols and lines, identifying the power flow paths. The lumped parameter elements of resistance, capacitance and inertance are interconnected in an energy conserving way by bonds and junctions resulting in a network structure. From the pictorial representation of the bond graph, the derivation of system equations is so systematic that it can be algorithmized

Co-funded by the
Erasmus+ Programme
of the European Union

Power variables of Bond Graphs

The language of bond graphs aspires to express general class physical systems through power interactions. The factors of power i.e., Effort and Flow, have different interpretations in different physical domains. Yet, power can always be used as a generalized co-ordinate to model coupled systems residing in several energy domains.

One such system may be an electrical motor driving a hydraulic pump or an thermal engine connected with a muffler; where the form of energy varies within the system. In the following table, effort and flow variables in some physical domains are listed

Systems	**Effort (e)**	**Flow (f)**
Mechanical	Force (F)	Velocity (v)
	Torque (τ)	Angular velocity (ω)
Electrical	Voltage (V)	Current (i)
Hydraulic	Pressure (P)	Volume flow rate (dQ/dt)
Thermal	Temperature (T)	Entropy change rate (ds/dt)
	Pressure (P)	Volume change rate (dV/dt)
Chemical	Chemical potential (μ)	Mole flow rate (dN/dt)
	Enthalpy (h)	Mass flow rate (dm/dt)
Magnetic	Magneto-motive force (e_m)	Magnetic flux (φ)

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Why ?

- ✓ Powerful modeling tool
- ✓ Makes it possible to understand power transfers
- ✓ Can be traced without writing and solving equations
- ✓ Possible deduction of block diagrams, state equations, transfer functions for linear cases,...
- ✓ Identical graphics regardless of domain
- ✓ Allows analogies between domains
- ✓ Many examples treated in mechatronics
- ✓ Simulations directly possible

Co-funded by the
Erasmus+ Programme
of the European Union

www.weset-project.eu

Energy is an essential (not to say ""the") concept in describing the evolution of technological systems. It is found in all areas: it is the link between them. With this in mind, Henry M. Paynter (1923-2002) introduced the concept of bond graph (BG) in 1961.

Co-funded by the Erasmus+ Programme of the European Union

Pioneers of Bond graphs: Henry Paynter (MIT Boston)
1st book: 1961

Arrival in Europe: the end of the 70s
Netherlands (TwenteUniv.)
France (Alsthom

R.Rosenberg H. Paynter D. Karnopp D. Margolis

International Conference on Bond Graph Modelling
Phoenix, Arizona, Janvier 2001

The BG method applies to all systems in all fields (linear, non-linear, continuous, sampled, digital, electronic, hydraulic, mechanical, thermal, etc.).

The BG method allows the processing of energy and information chains.

What is a bond graph?

It is a oriented graph, showing dynamic variables,
which reflect the transfer of energy between systems. They are based on power links.

Real system → **Represent Graphically the articulation of energy transfers** → Operational and functional representation of energy transfers within the system

Bond Graph

Co-funded by the
Erasmus+ Programme
of the European Union

Objectives

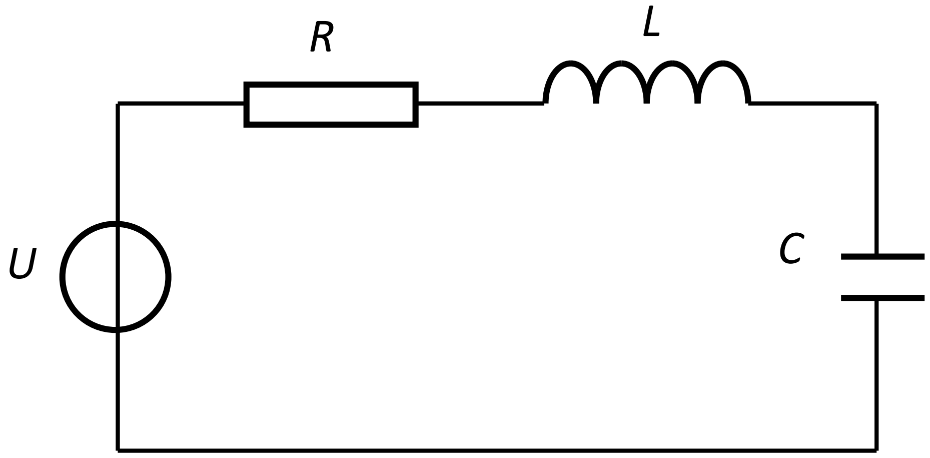
The Bond graph language allows you to:

- Understanding energy transfers (topology of exchanges);
- Pay particular attention to the structural properties of systems;
- Free yourself from the vicissitudes of mathematical modeling - provide a graph-associated computational pattern;
- Highlight causality in the resulting model;
- Simply simulate a multi-technical system

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

First example: an electrical system



Power variables

Electric voltage U
Electrical intensity I

⇓

Electrical power

P = U I

Constituent Laws

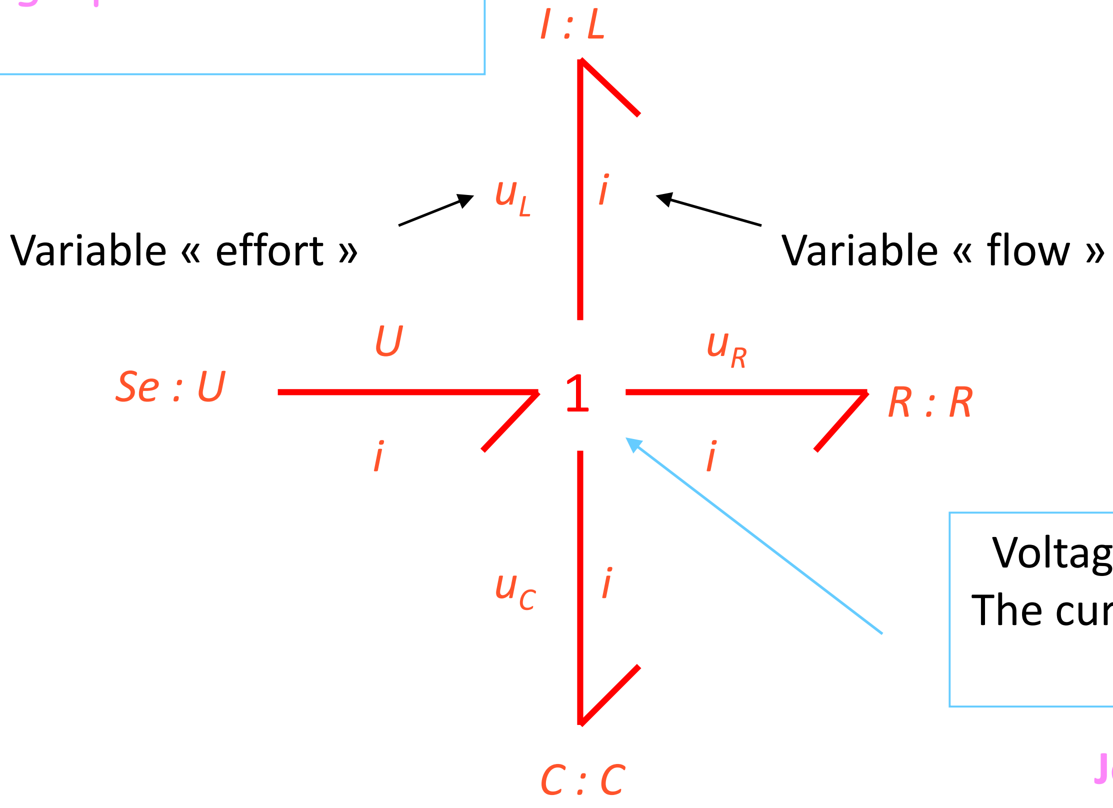
$$u_R = RI \qquad u_c = \frac{1}{C}\int i\mathrm{d}t \qquad u_L = L\frac{\mathrm{d}i}{\mathrm{d}t}$$

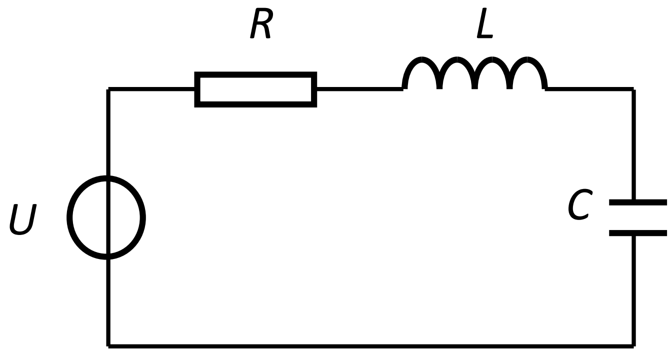
Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

First example: an electrical system

Bond graph of the circuit





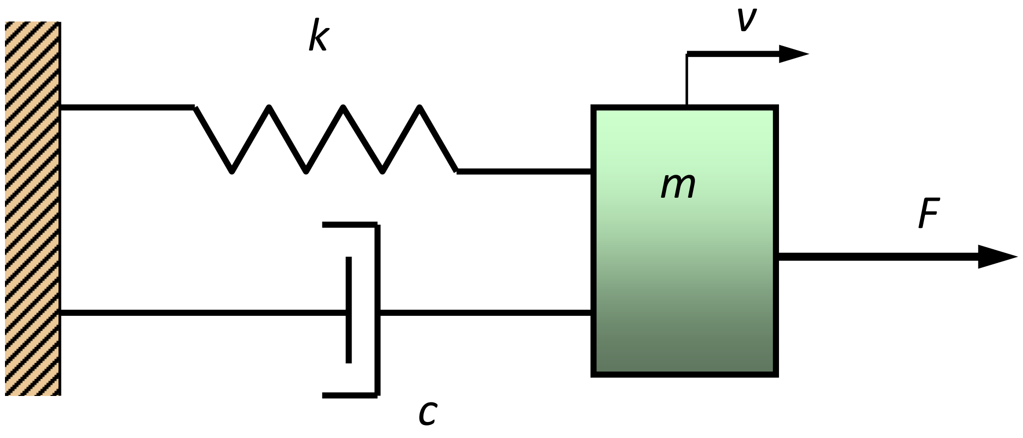
Voltages are different
The current is the same

Jonction 1

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Second example : mechanical system



Power variables

↳ **Force *F***
↳ **Linear speed v**

Mechanical power

$$P = F v$$

Constituent Laws

$$F_r = k\int v\,dt \qquad F_a = cv \qquad F_m = m\frac{dv}{dt}$$

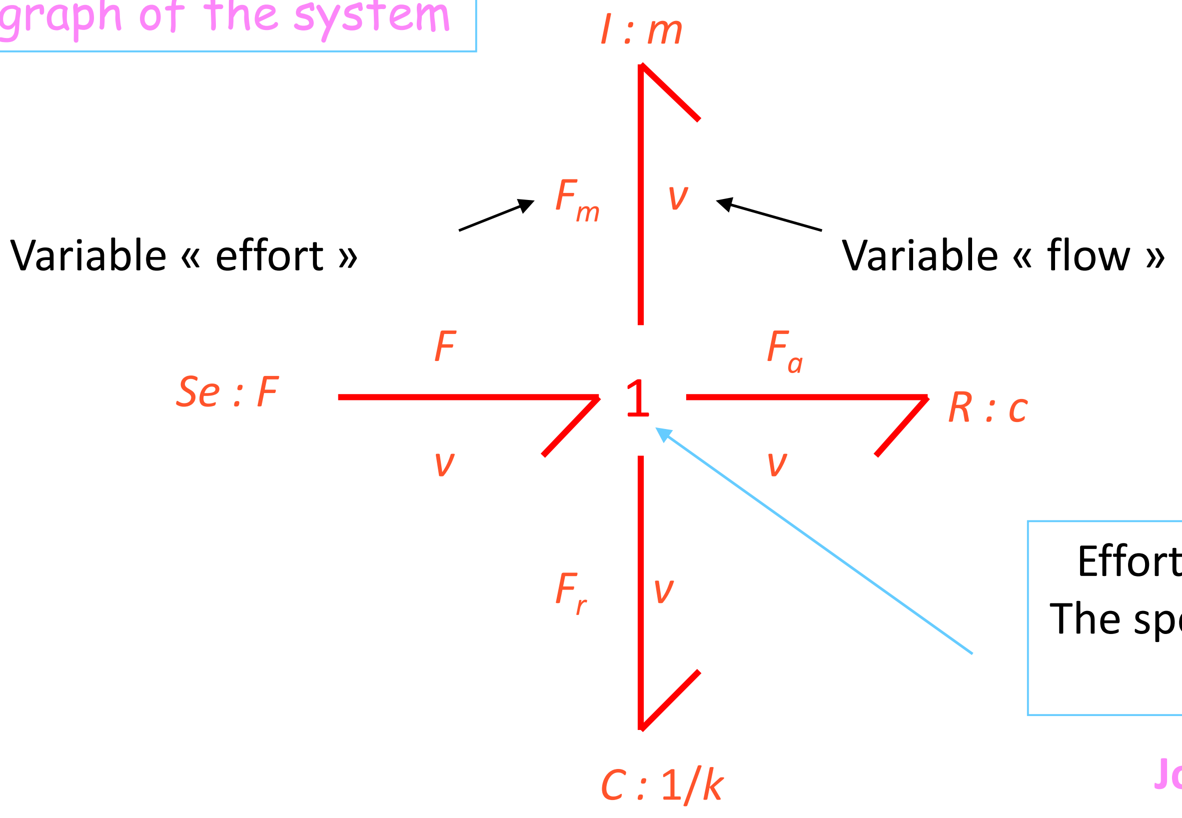
Co-funded by the
Erasmus+ Programme
of the European Union

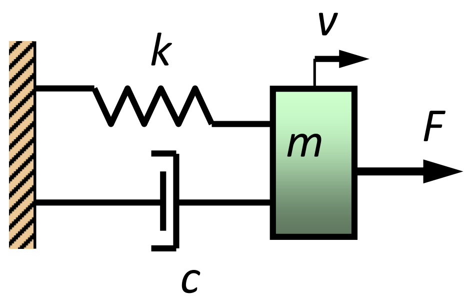
www.weset-project.eu

Bond Graphs

Second example : mechanical system

Bond graph of the system





Efforts are different
The speed is the same

Jonction 1

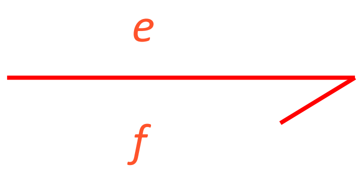
Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Energy & Power variables

Effort $e(t)$

Flow $f(t)$



$$P = e \times f$$

bond graph Link

Integration of Power Variables

Generalised moment $p(t) = p_0 + \int_{t_0}^{t} e(\tau)\mathrm{d}\tau$

Generalised displacement $q(t) = q_0 + \int_{t_0}^{t} f(\tau)\mathrm{d}\tau$

Co-funded by the
Erasmus+ Programme
of the European Union

Systems	Effort (e)	Flow (f)
Mechanical	Force (F)	Velocity (v)
	Torque (τ)	Angular velocity (ω)
Electrical	Voltage (V)	Current (i)
Hydraulic	Pressure (P)	Volume flow rate (dQ/dt)
Thermal	Temperature (T)	Entropy change rate (ds/dt)
	Pressure (P)	Volume change rate (dV/dt)
Chemical	Chemical potential (μ)	Mole flow rate (dN/dt)
	Enthalpy (h)	Mass flow rate (dm/dt)
Magnetic	Magneto-motive force (e_m)	Magnetic flux (φ)

Co-funded by the Erasmus+ Programme of the European Union

Bond Graphs

Physical domains & variables

Domain	Effort *e*	Flow *f*	*p*	*q*
Electricity	Voltage u	Current i	Magnetic flow λ	Charge q
Translation Mechanics	Force F	Speed v	Quantité de mouvement p	displacemet x
Rotation Mechanics	Couple C	Taux de rotation ω	Kinetic moment σ	Angle θ
Hydraulic - pneumatic	Pression P	Volume flow q_v	Impulsion p	Volume V
Thermal	Temperature T	Entropy flow q_S		Entropy S
Chemistry	Chemical potential μ	Molar Flow q_m		Numbers of moles N

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Nine basic elements of language

R : modeling element of a physical phenomenon linking the effort variable to the flow variable

I: modeling element of a physical phenomenon linking the effort flow to the variable p.

C: modeling element of a physical phenomenon linking the effort variable to the variable q

Se, Sf : source of effort and source of flow independent of their complementary variable respectively

0, 1 : junction 0 is used to couple elements subject to the same effort, junction 1 is used to couple elements traversed by the same flow

TF : transformer (examples: electrical transformer, gear train,...)

GY : gyrator (e.g. electric motor, centrifugal pump,...)

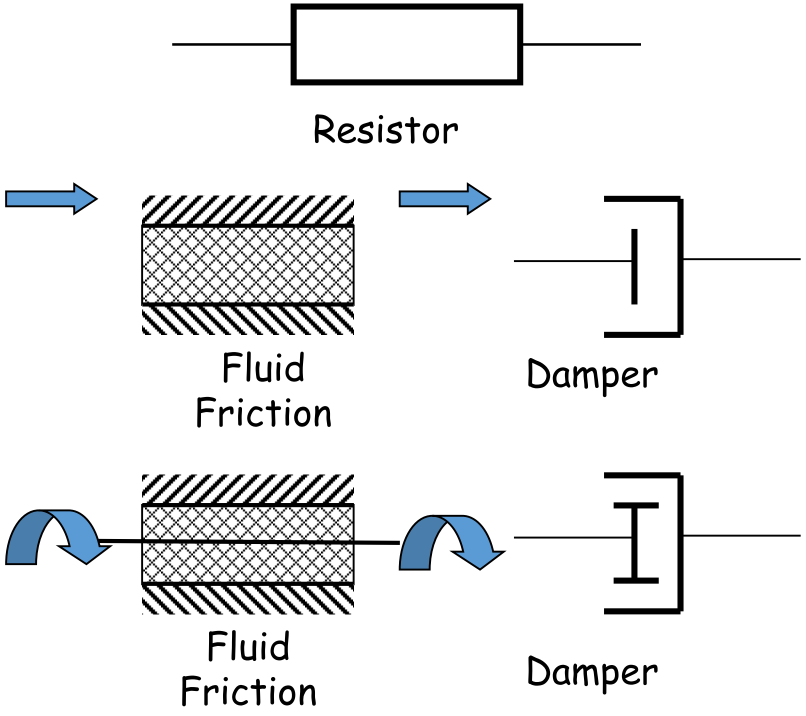
Co-funded by the
Erasmus+ Programme
of the European Union

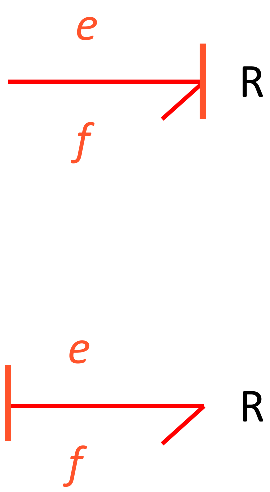
Bond Graphs

Passive elements 1-port

Élément R

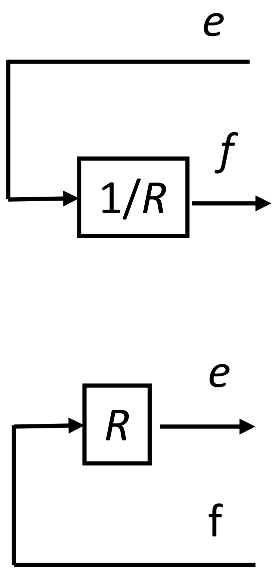
symbols | BG Element | Law | Block-scheme





$$f = \frac{1}{R} e$$

$$e = Rf$$



R : energy sink element

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

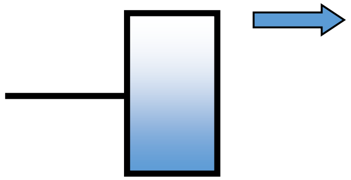
Passive elemnt 1-port

Élément I

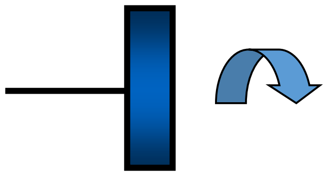
Symbols	BG elemnt	Law	Block-scheme

Symbols

Inductance

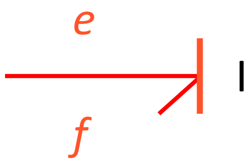


Mass



Inertia

BG elemnt

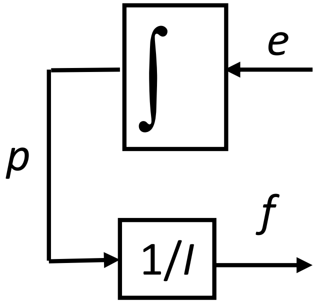


Law

$$f = \frac{1}{I} p$$

$$p(t) = p_0 + \int_{t_0}^{t} e(\tau) d\tau$$

Block-scheme



I : storage element for generalized effort

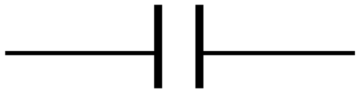
Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

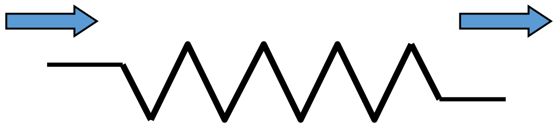
Passive element 1-port

Élément C

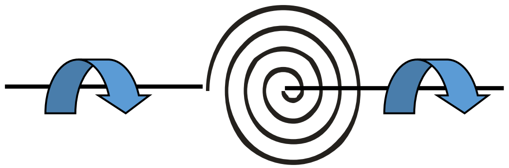
symbols



Capacitor

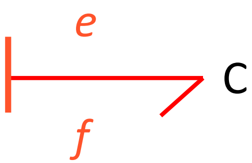


Linear Spring



Twisted soring

BG Element

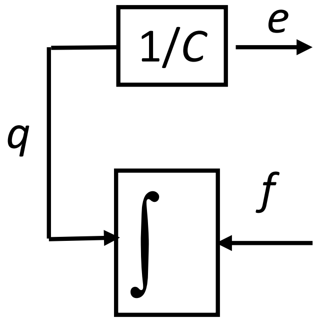


Law

$$e = \frac{1}{C} q$$

$$q(t) = q_0 + \int_{t_0}^{t} f(\tau) \mathrm{d}\tau$$

Block Scheme



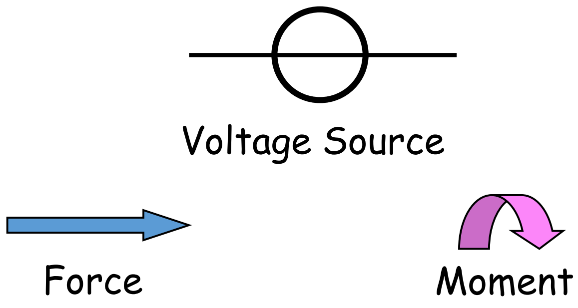
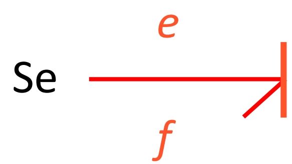
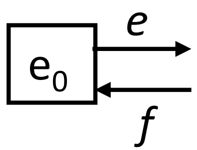
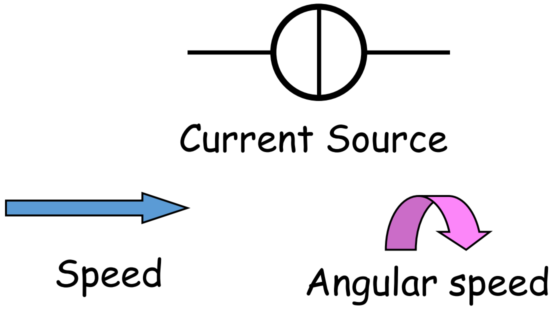
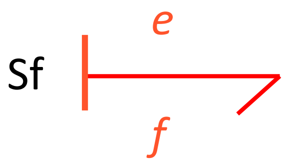
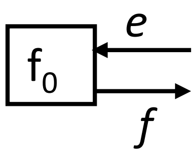
C : Storage element for generalized displacement

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Active Element 1-port

Éléments Se & Sf

symbols	BG Element	Law	Block -Sheme
		$e = e_0$	
		$f = f_0$	

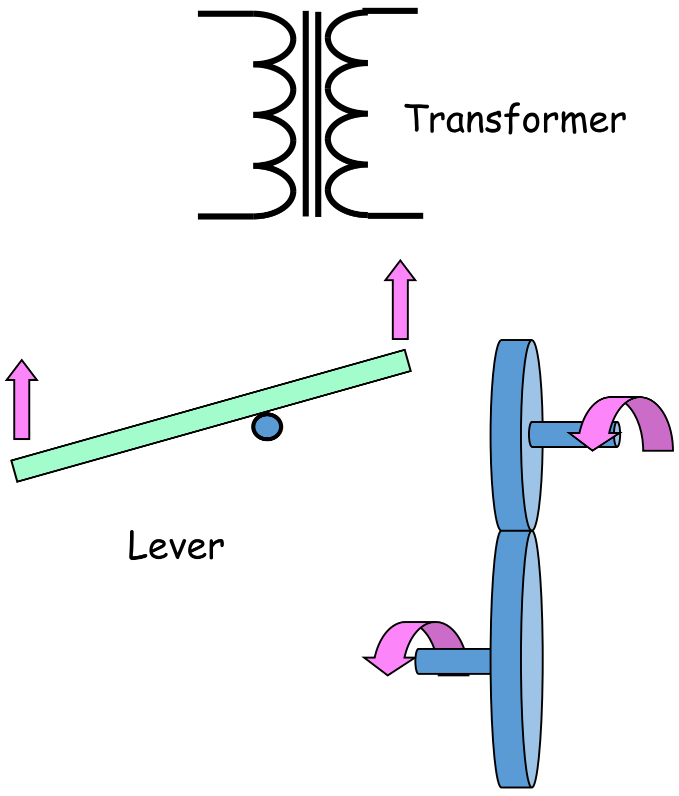
Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

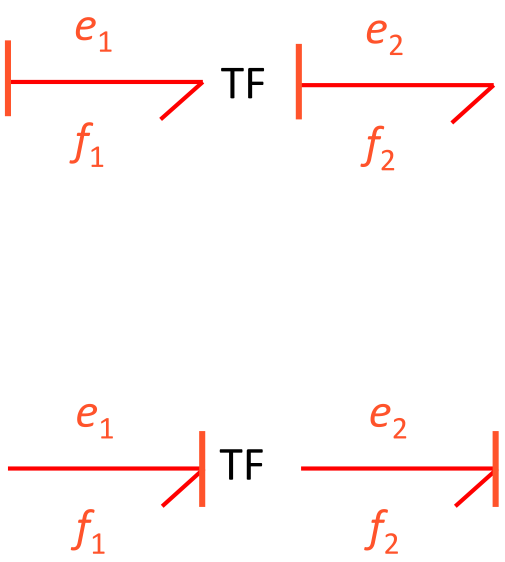
Junction elemnts

Élément TF

symbols



BG Element

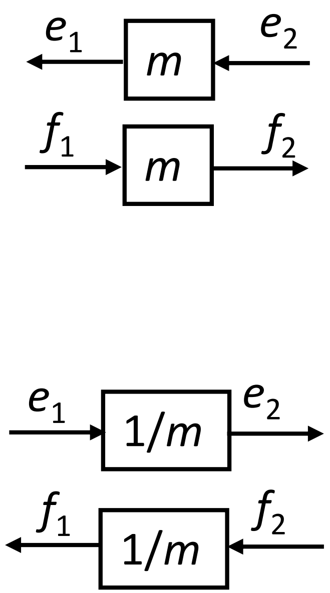


Law

$$e_1 = me_2$$
$$f_2 = mf_1$$

$$e_2 = \frac{e_1}{m}$$
$$f_1 = \frac{f_1}{m}$$

Block-scheme

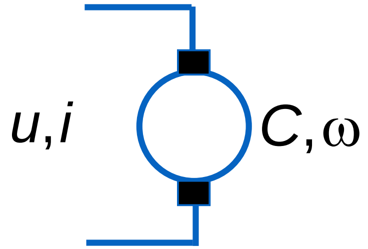
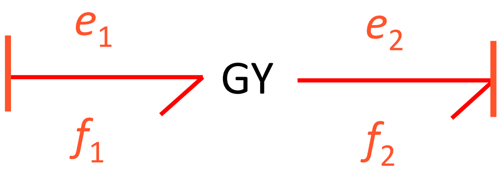
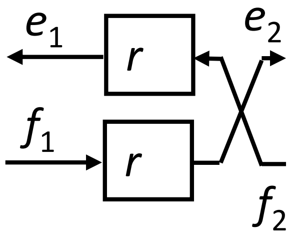
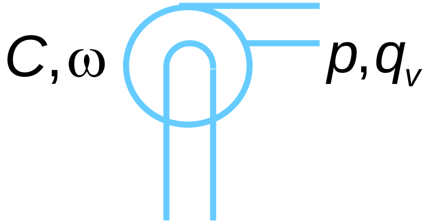
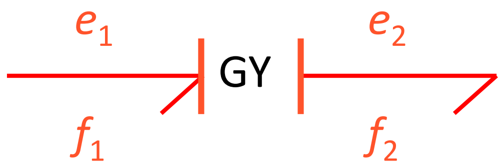
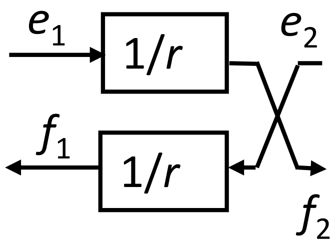


Co-funded by the
Erasmus+ Programme

Bond Graphs

Junction element

Élément GY

Symbols		BG Element	Law	Block scheme
	Engine Generator		$e_2 = rf_1$ $e_1 = rf_2$	
	Pump Turbine		$f_2 = \frac{e_1}{r}$ $f_1 = \frac{e_2}{r}$	

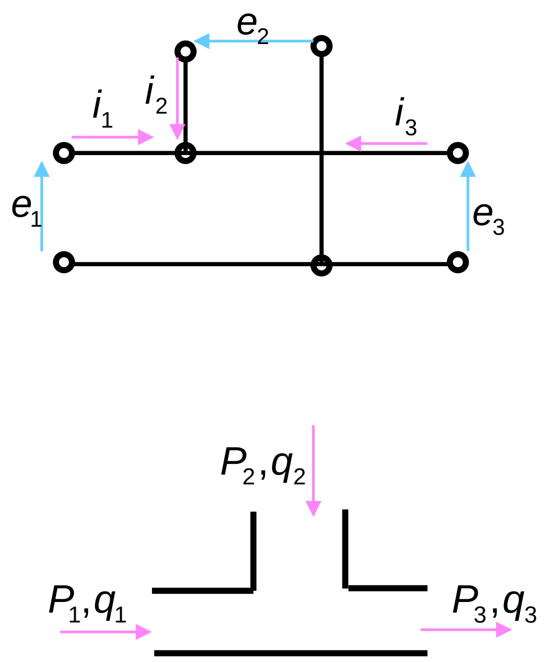
Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

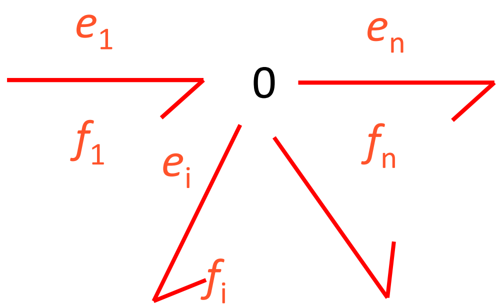
Junction elements

Jonction 0

symbols



BG element



Laws

$$e_1 f_1 - e_i f_i - \ldots - e_n f_n = 0$$

Power conservation

$$e_1 = e_i = \ldots = e_n$$

$$f_1 - f_i - \ldots - f_n = 0$$

The direction of the arrows gives the sign of the flow

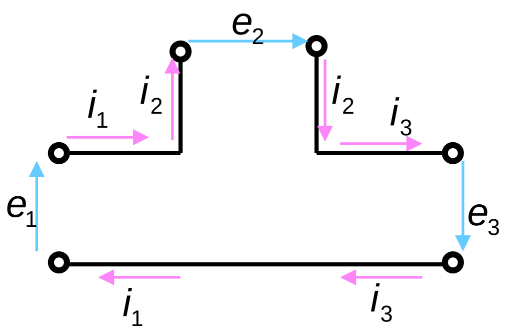
Co-funded by the
Erasmus+ Programme
of the European Union

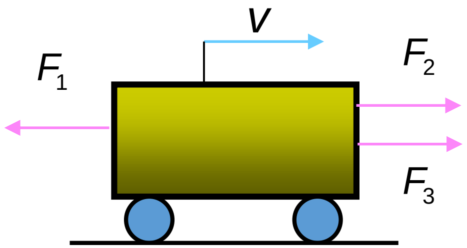
Bond Graphs

Junction elemnts

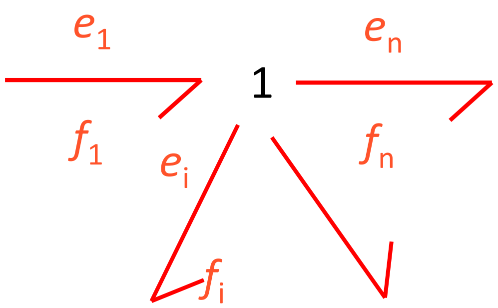
Jonction 1

symbols





BG Elemnt



LAws

$$e_1 f_1 - e_i f_i - \ldots - e_n f_n = 0$$

Power conservation

$$f_1 = f_i = \ldots = f_n$$

$$e_1 - e_i - \ldots - e_n = 0$$

The meaning of the arrows gives the sign of effort

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

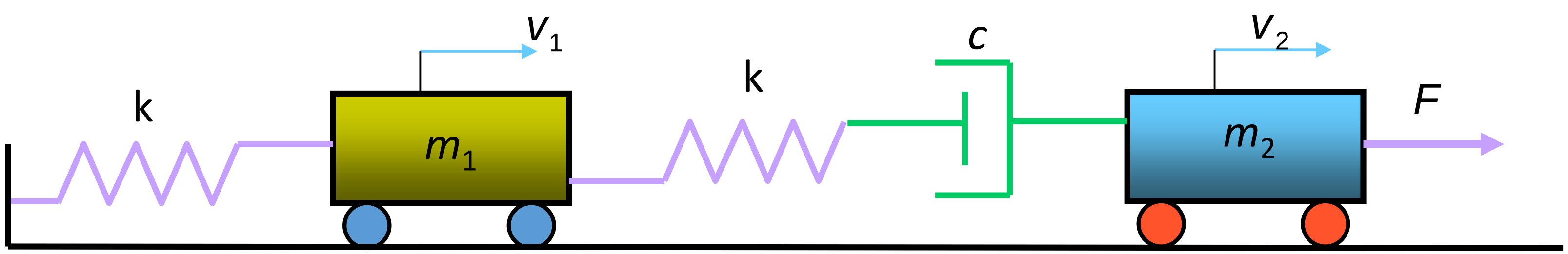
Translation mechanics

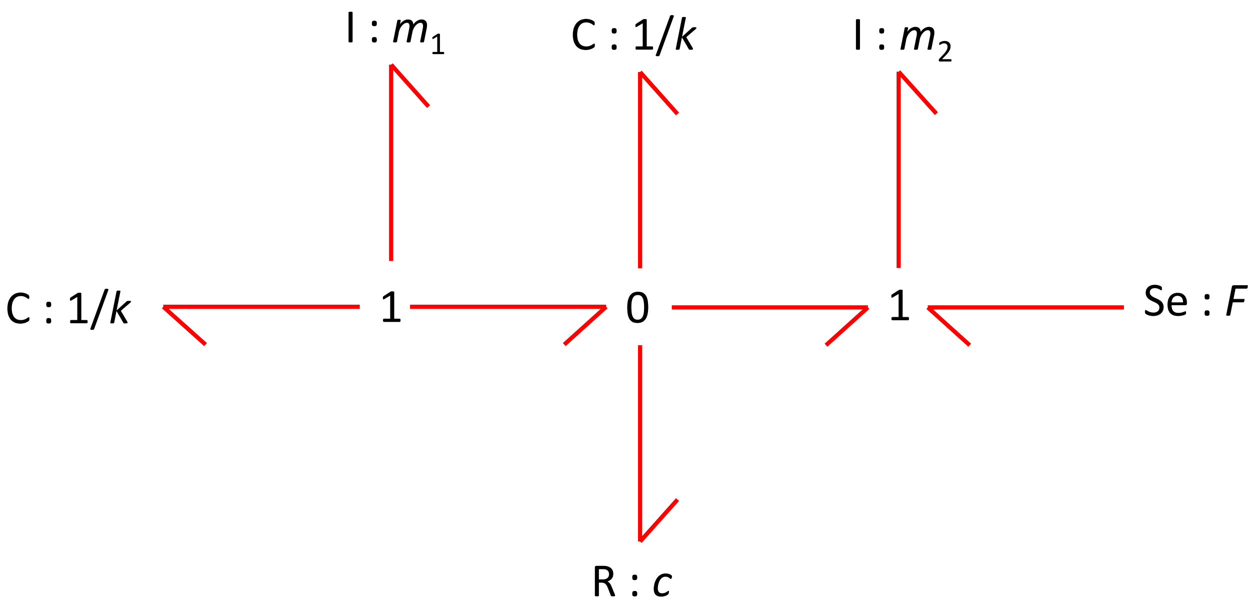
variable	notation	translation
Effort	$e(t)$	force F
Flow	$f(t)$	Speed v
Moment	$p(t) = \int e(t)\mathrm{d}t$	Impulsion p
displacement	$q(t) = \int f(t)\mathrm{d}t$	distance x
Power	$P(t) = e(t) \times f(t)$	$F(t) \times v(t)$
Eneergy	$E(p) = \int f\mathrm{d}p \; ; \; E(q) = \int e\mathrm{d}q$	$E_c = \int v\mathrm{d}p \quad E_p = \int F\mathrm{d}x$

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

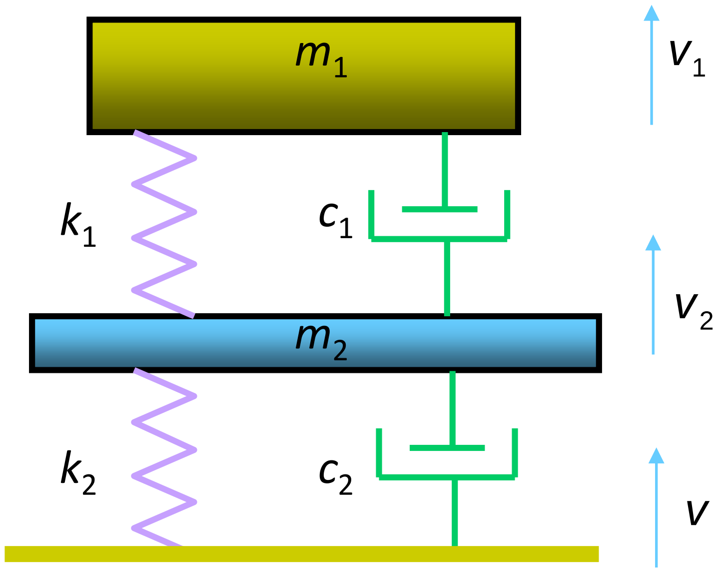
Translation mechanics

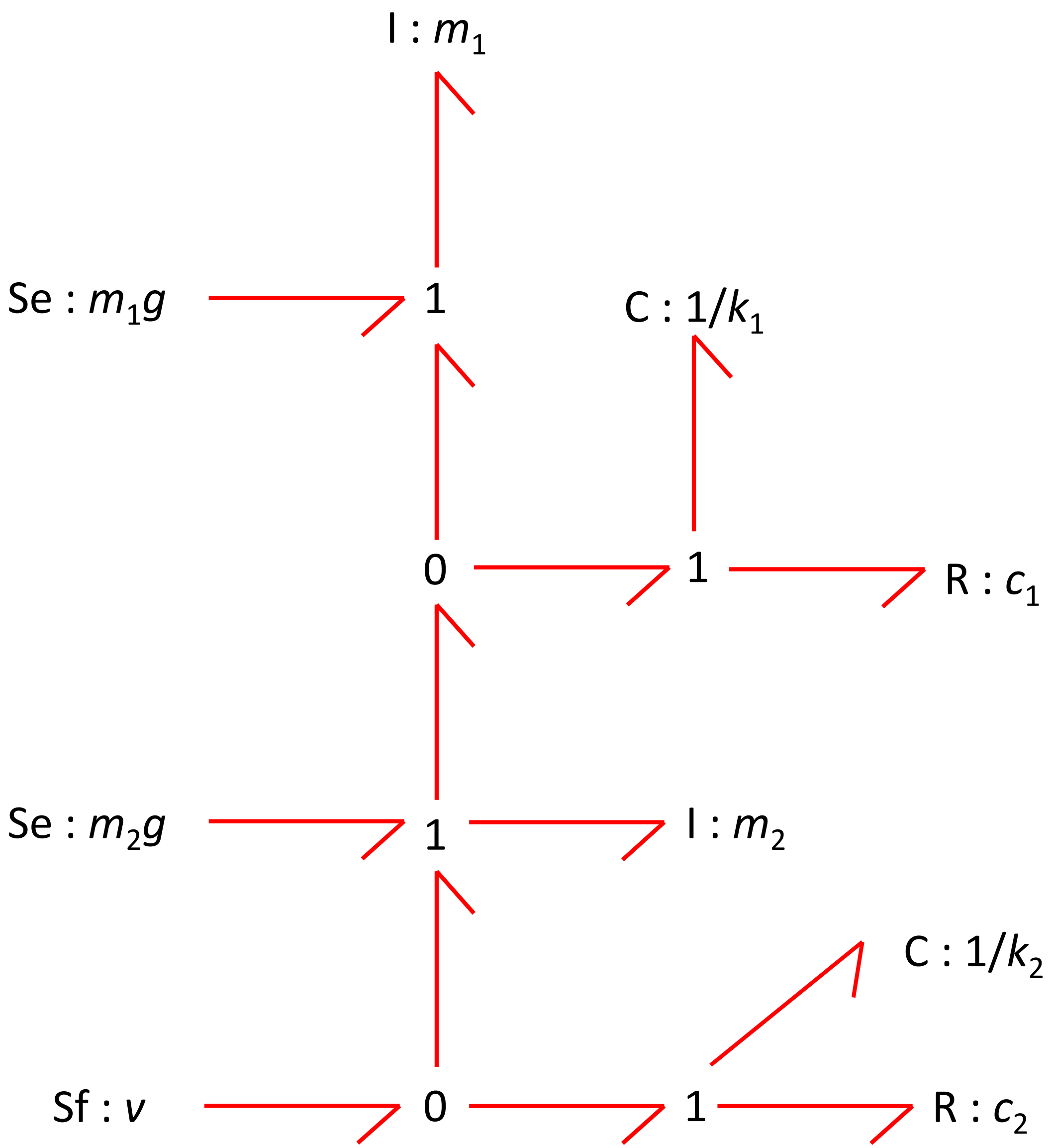




Bond Graphs

Translation mechanics





Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

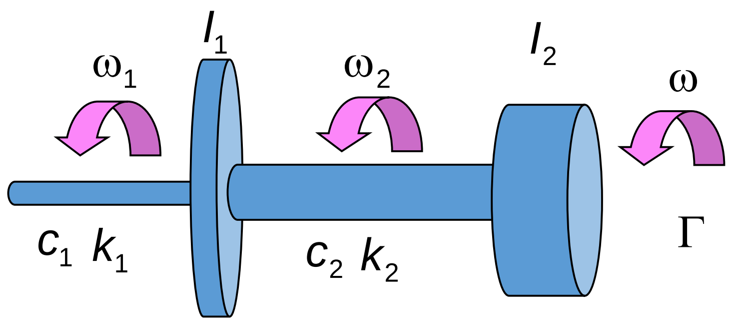
Rotation mechanics

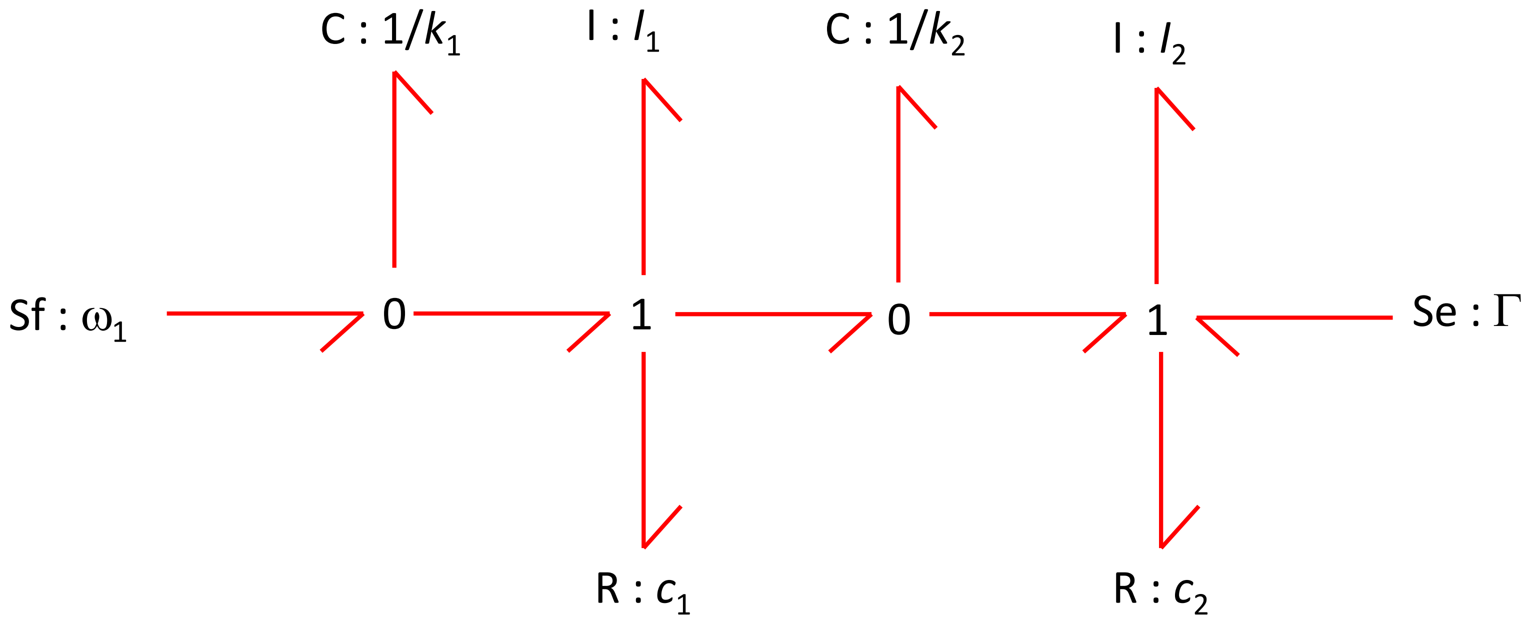
variable	notation	rotation
Effort	$e(t)$	Torque Γ
flow	$f(t)$	angular velocity ω
Moment	$p(t) = \int e(t)dt$	kinetic moment σ
displacement	$q(t) = \int f(t)dt$	Angle θ
Power	$P(t) = e(t) \times f(t)$	$\Gamma(t) \times \omega(t)$
Energy	$E(p) = \int fdp$; $E(q) = \int edq$	$E_c = \int \omega d\sigma$ $E_p = \int \Gamma d\theta$

Co-funded by the Erasmus+ Programme of the European Union

Bond Graphs

Rotation in mechanics

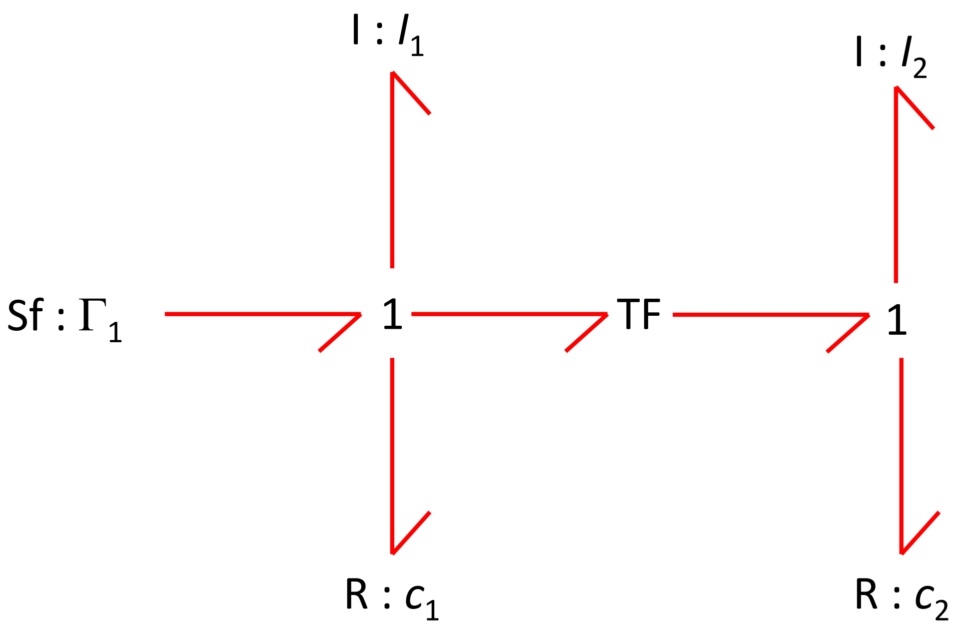


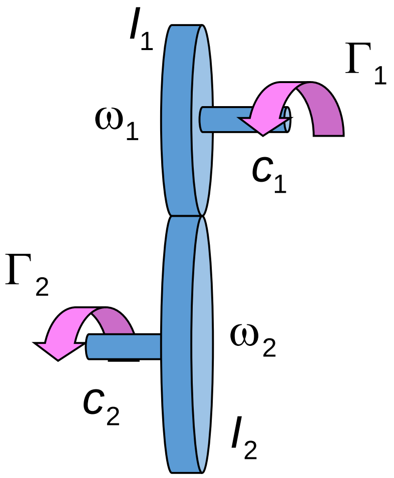


Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Rotation mechanics





Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

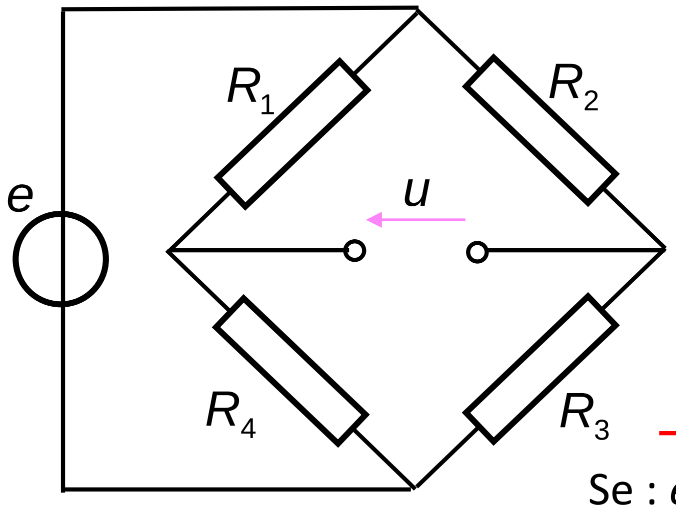
electric

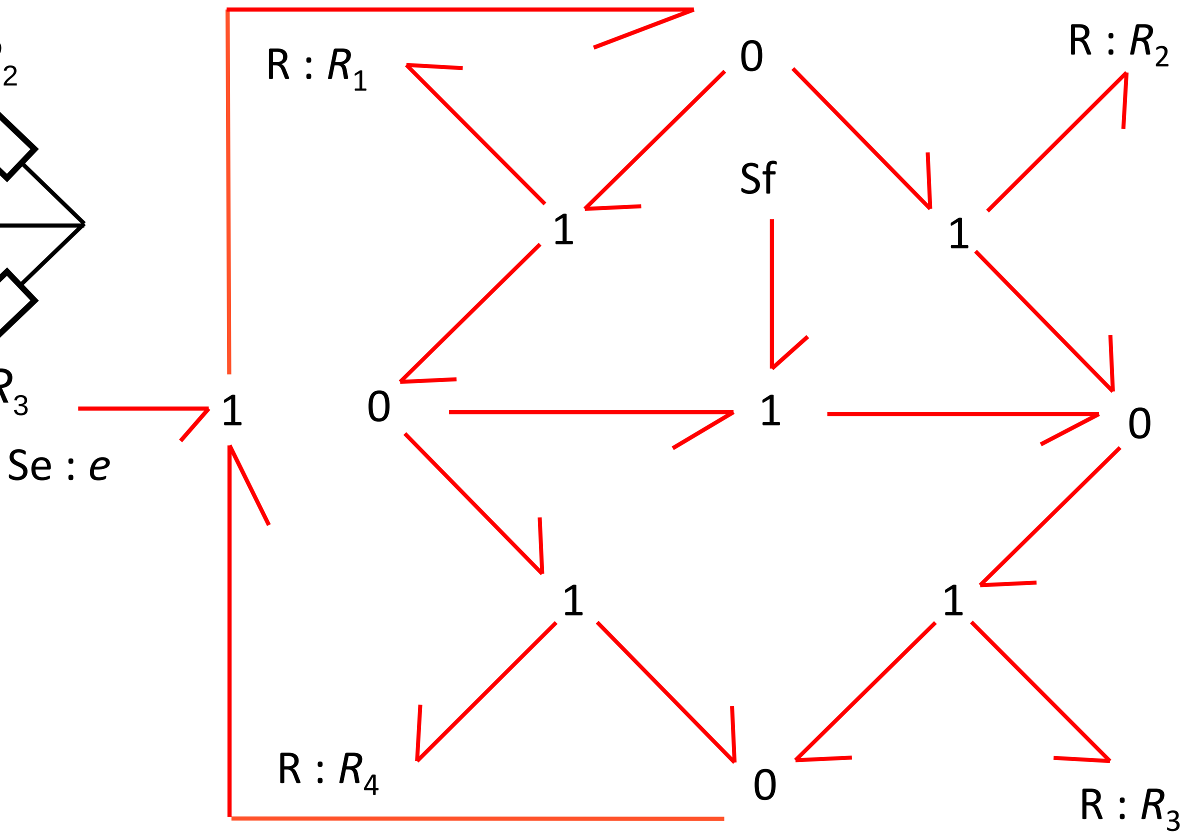
variable	notation	electric
Effort	$e(t)$	voltage U
Flow	$f(t)$	current i
Moment	$p(t) = \int e(t)dt$	Magnetic flow λ
Displacement	$q(t) = \int f(t)dt$	charge q
Power	$P(t) = e(t) \times f(t)$	$U(t) \times i(t)$
Energy	$E(p) = \int fdp$; $E(q) = \int edq$	$E_m = \int id\lambda$ $E_{el} = \int Udq$

Co-funded by the Erasmus+ Programme of the European Union

Bond Graphs

electric

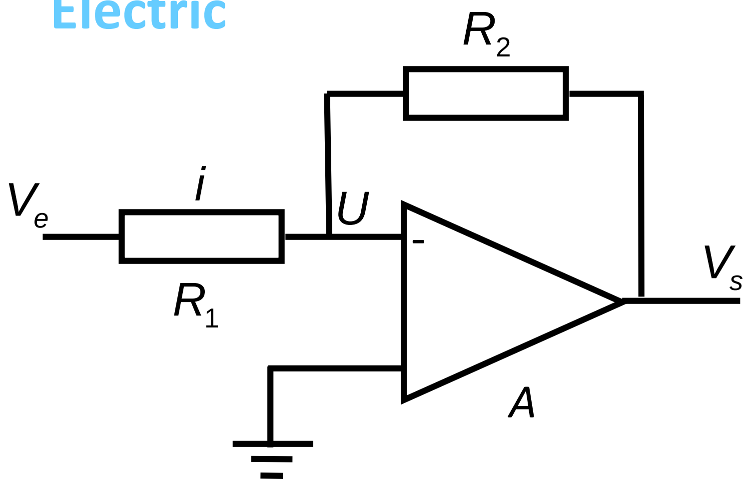


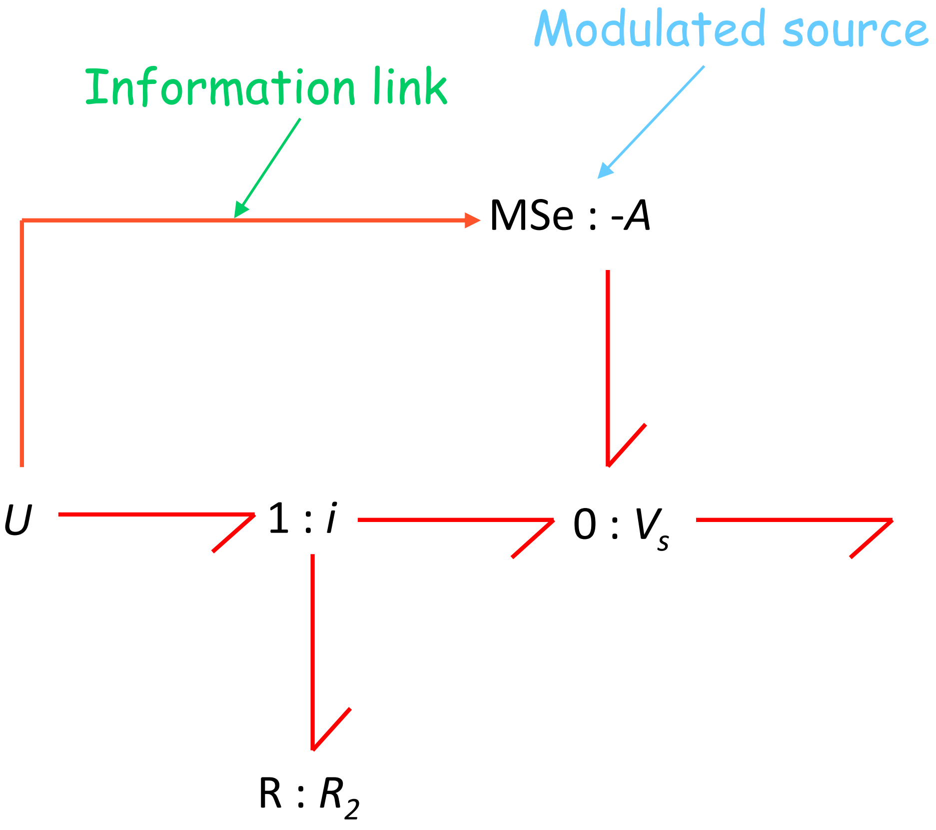


Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Electric





Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Hydraulic

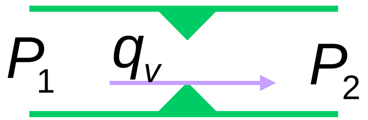
variable	notation	Hydraulic
Effort	$e(t)$	pression P
Flow	$f(t)$	Volume flow q_v
Moment	$p(t)=\int e(t)\mathrm{d}t$	impulsion p
Displacement	$q(t)=\int f(t)\mathrm{d}t$	volume V
Power	$P(t)=e(t)\times f(t)$	$P(t)\times q_v(t)$
Energy	$E(p)=\int f\mathrm{d}p$; $E(q)=\int e\mathrm{d}q$	$E_c=\int q_v\mathrm{d}p$ $E_p=\int P\mathrm{d}V$

Co-funded by the Erasmus+ Programme of the European Union

Bond Graphs

Hydraulic

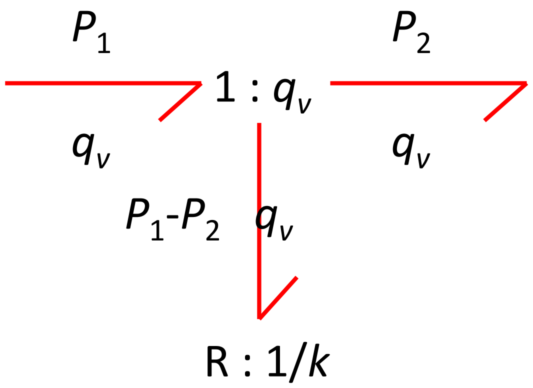
R element



Dissipation of energy in a restriction

For a laminar flow, Re<2000

$$q_v = k\left(P_1 - P_2\right)$$



For a turbulent flow, Re>3000

$$q_v = f\left(P_1 - P_2\right)$$

The f function to be determined for each case

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Hydraulic

Relationship between pressure and flow derived

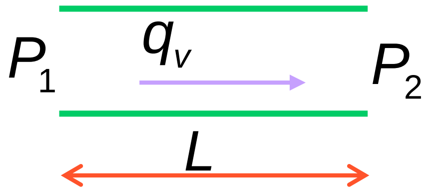
$$q_v = Av \Rightarrow \frac{dq_v}{dt} = A\frac{dv}{dt}$$

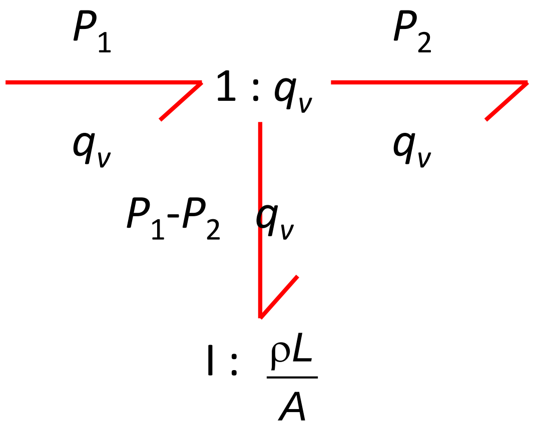
$$F = (P_1 - P_2)A = \rho AL\frac{dv}{dt}$$

$$P_1 - P_2 = \frac{\rho L}{A}\frac{dq_v}{dt}$$

$$I = \frac{\rho L}{A}$$

Element I





Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

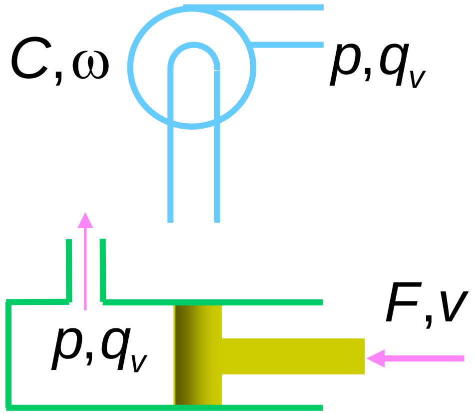
Hydraulic

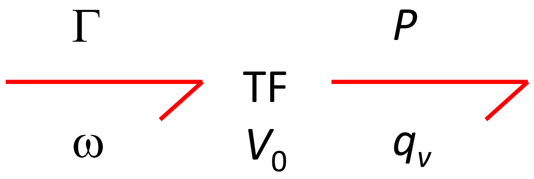
TF Junction

transformer

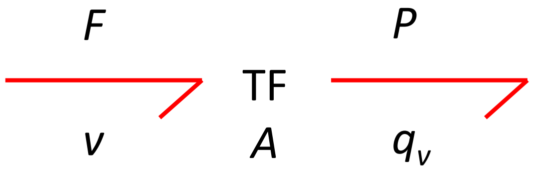
pump

cylinder



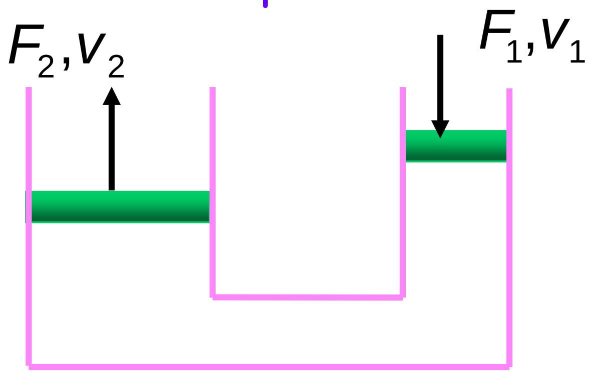


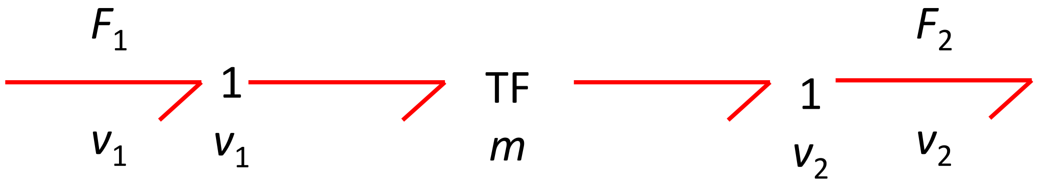
Cylinder capacity V_0



Section A

Pression amplifier





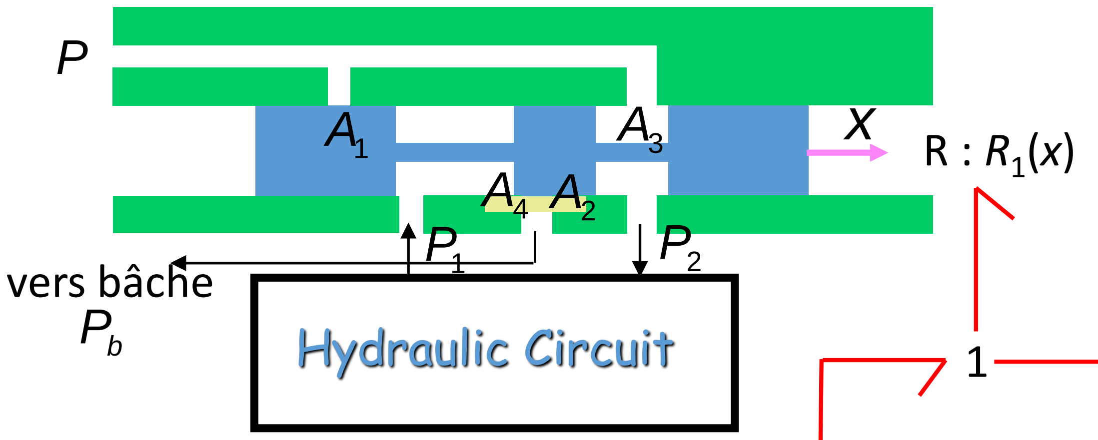
$$m = \frac{A_1}{A_2}$$

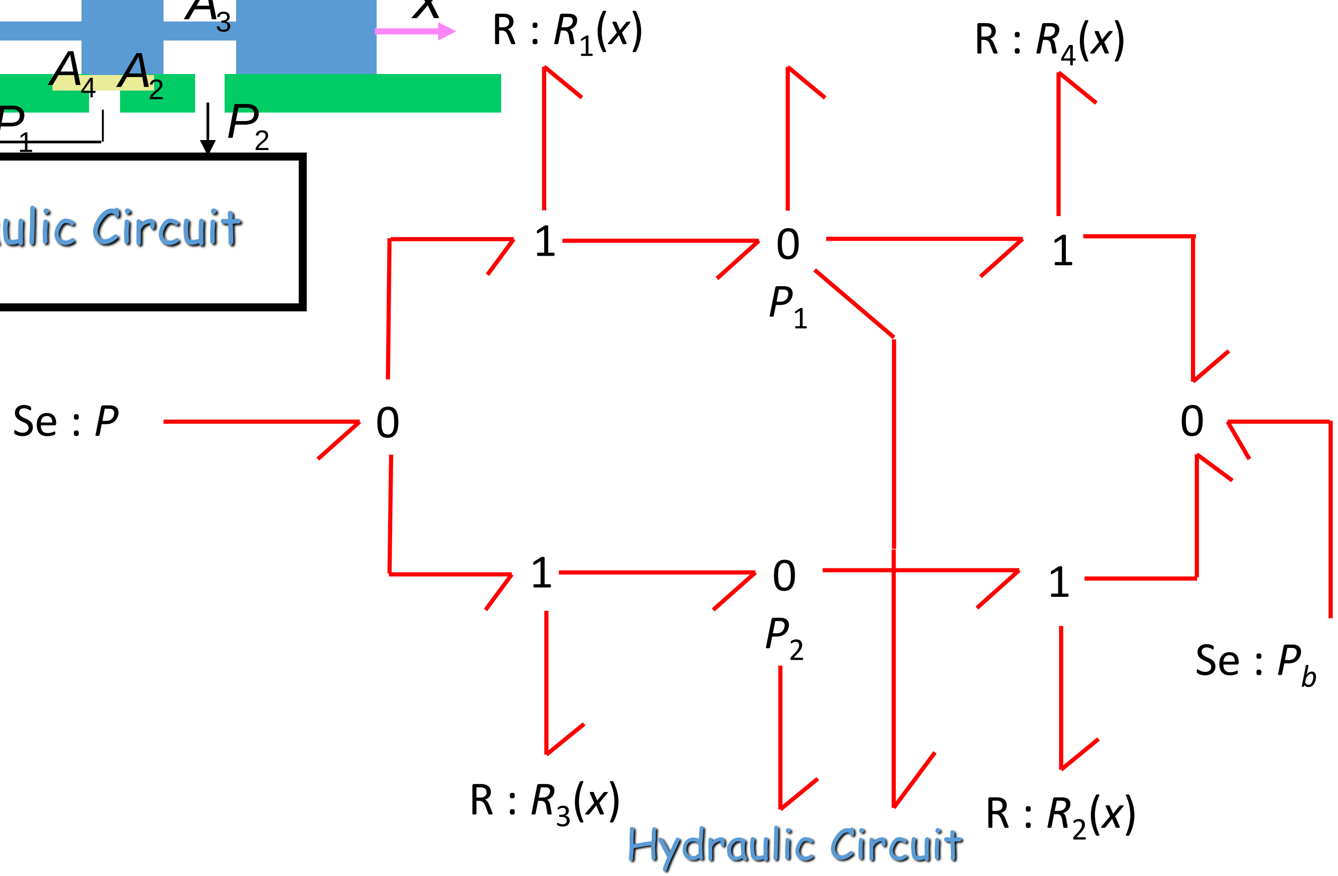
Co-funded by the Erasmus+ Programme of the European Union

Bond Graphs

Hydraulic example

Hydraulic dispenser

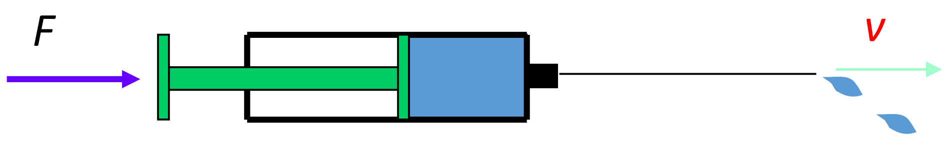


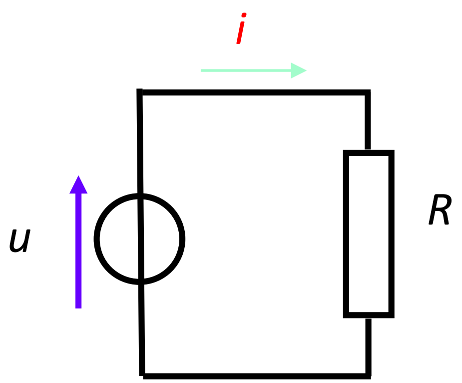


Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Causality





In both cases, there is a cause and effect

The stress applied to the syringe piston generates a speed at which the liquid is released from the syringe and not the other way around

.

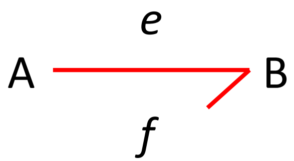
The voltage source imposes the current in the electrical circuit and not the other way around.

Co-funded by the Erasmus+ Programme of the European Union

Bond Graphs

Causality

Be two A-B systems coupled and exchanging P(t) power

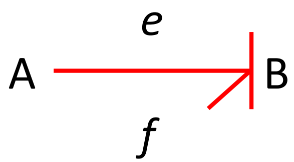


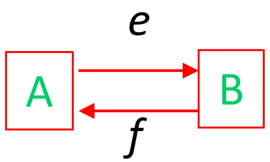
$$P(t) = e(t) \times f(t)$$

Two possible cases

- Applied an effort to B who reacted by returning to A a flow

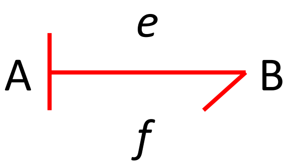
$$f(t) = \Psi_B(e(t))$$

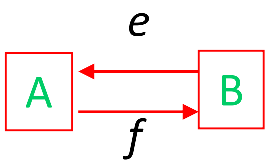




- A applies a f(t) flow to B that reacts by returning to A an effort

$$e(t) = \Phi_B(f(t))$$





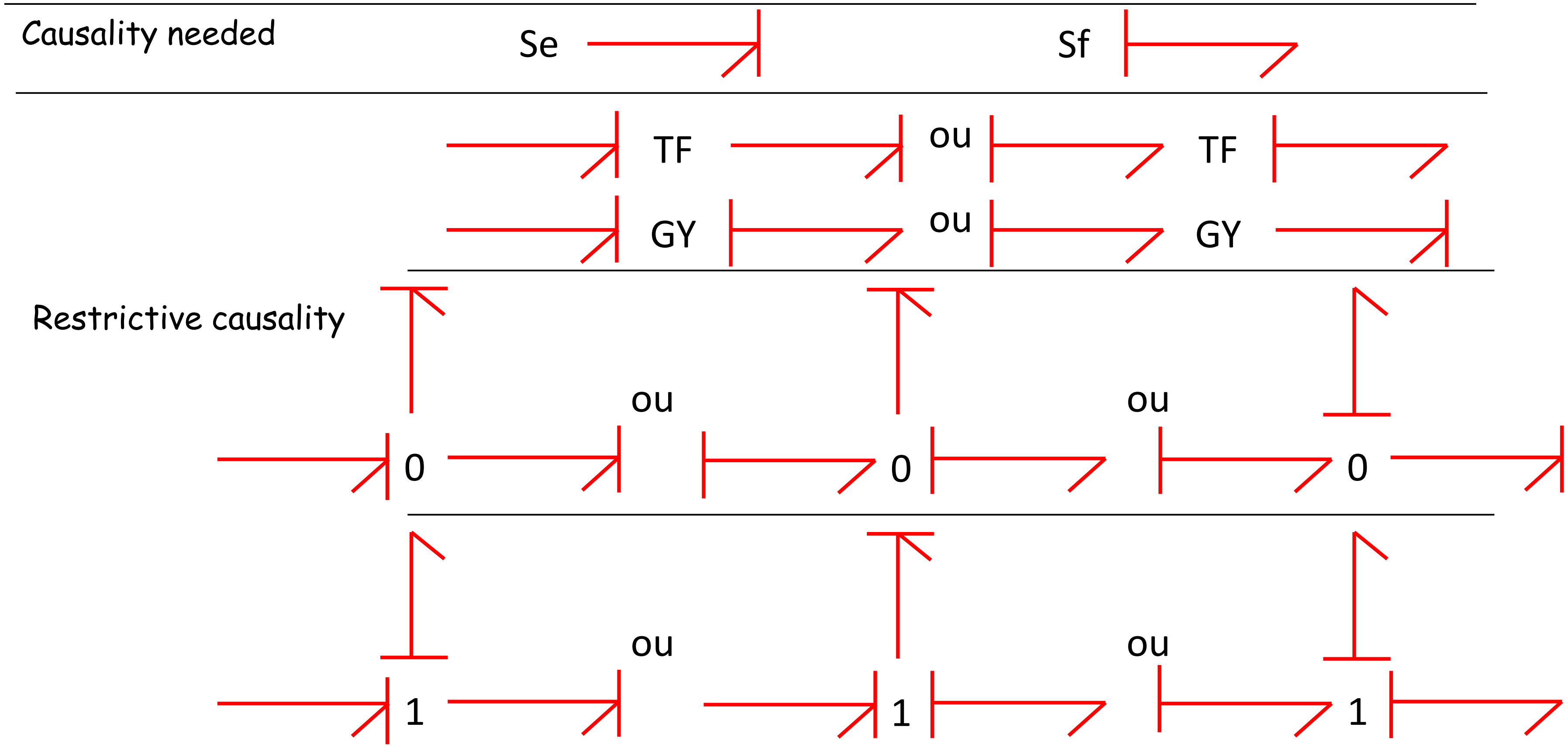
Convention: The causal line is placed on the side of the element on which the effort is imposed.

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Causality

Causal assignment



Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

Causality

Causal assignment

Integral causality	I		C
Derivative causality	I		C
Arbitrary causality (linear case)	R	ou	R

Causal assignment procedure

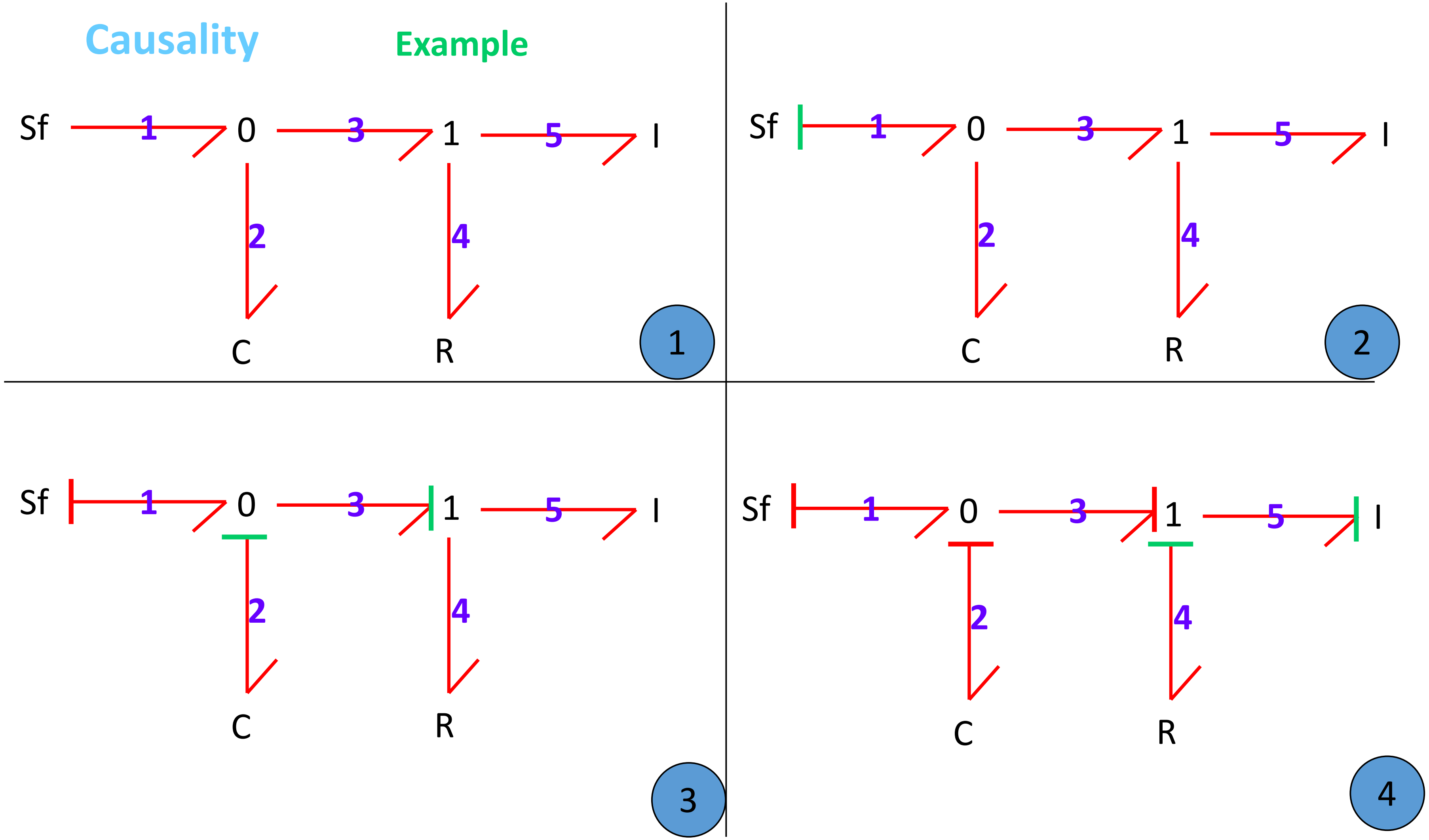
1 - Assign the necessary causalities to the sources and pass on;
2 - Put the I and C in preferential integral causality and pass on;
3 - Assign causality to R-elements by respecting junction restrictions;
4 - In the event of a conflict at a junction search for the element I or C that is the cause and put it into derivative causality; resume in 3.

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

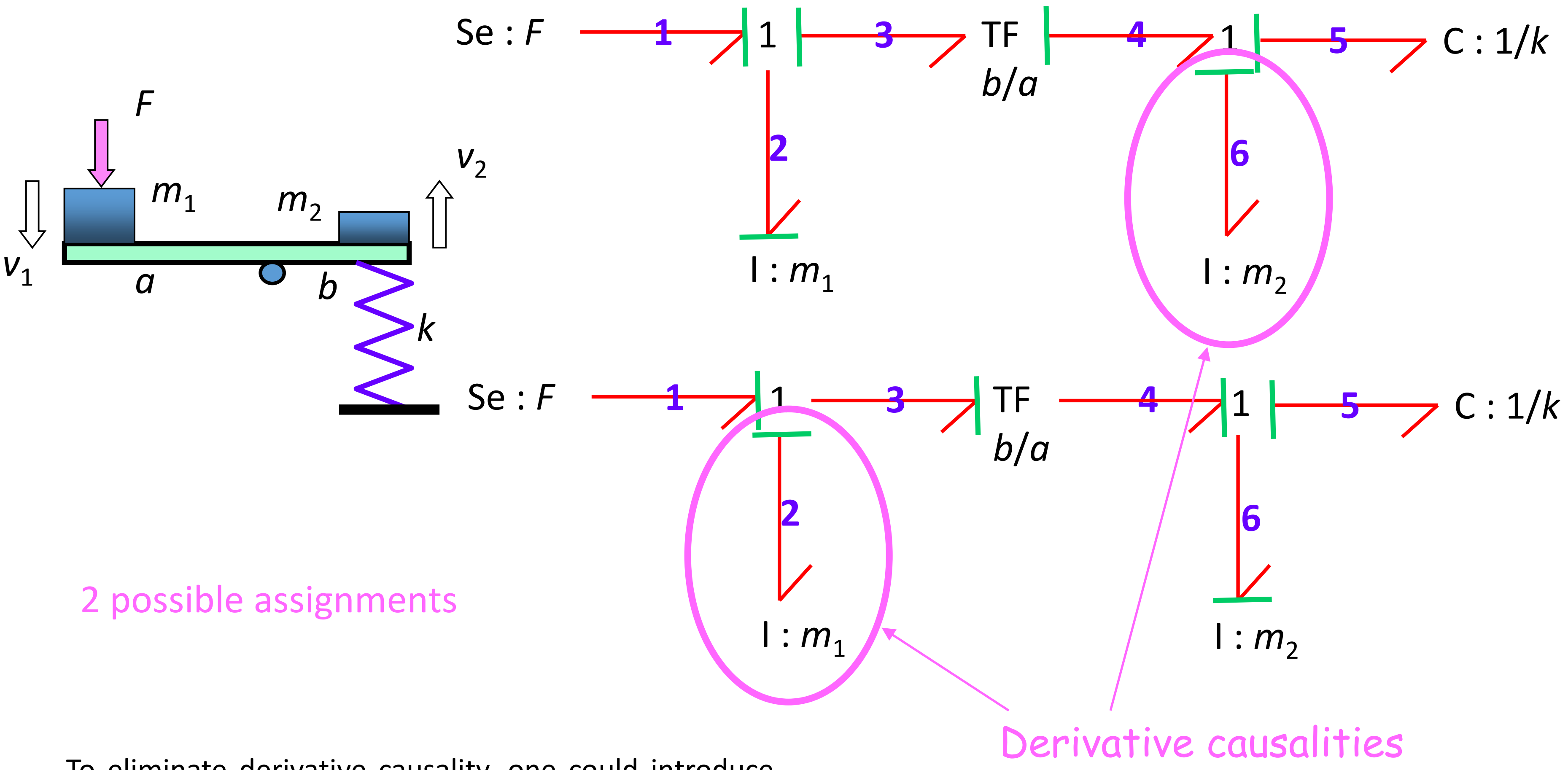
Causality

Example



Bond Graphs

Mixed causality



2 possible assignments

To eliminate derivative causality, one could introduce the flexibility of the lever arm.

Co-funded by the Erasmus+ Programme of the European Union

Bond Graphs

State Equations

Using a BG model, it is possible to deduce the state equations of the system

State variables are the energy variables associated with elements I and C

State Vecor

$$X = \begin{bmatrix} [p_I] \\ [q_C] \end{bmatrix} \Rightarrow \dot{X} = \begin{bmatrix} [e_I] \\ [f_C] \end{bmatrix}$$

If all the elements are in integral causality, the state vector dimension is worth the number of elements I and C.

If among elements I and C, there is nd in derivative causality, then the dimension of the state vector is n-nd

Co-funded by the Erasmus+ Programme of the European Union

Bond Graphs

State Equations

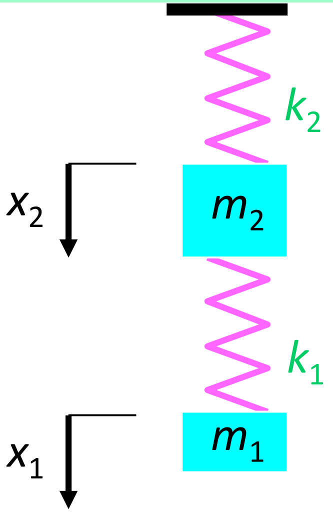
$$\dot{X} = AX + BU$$
$$Y = CX + DU$$

Cases where all elements I and C are in integral causality

U input vector and Y output vector

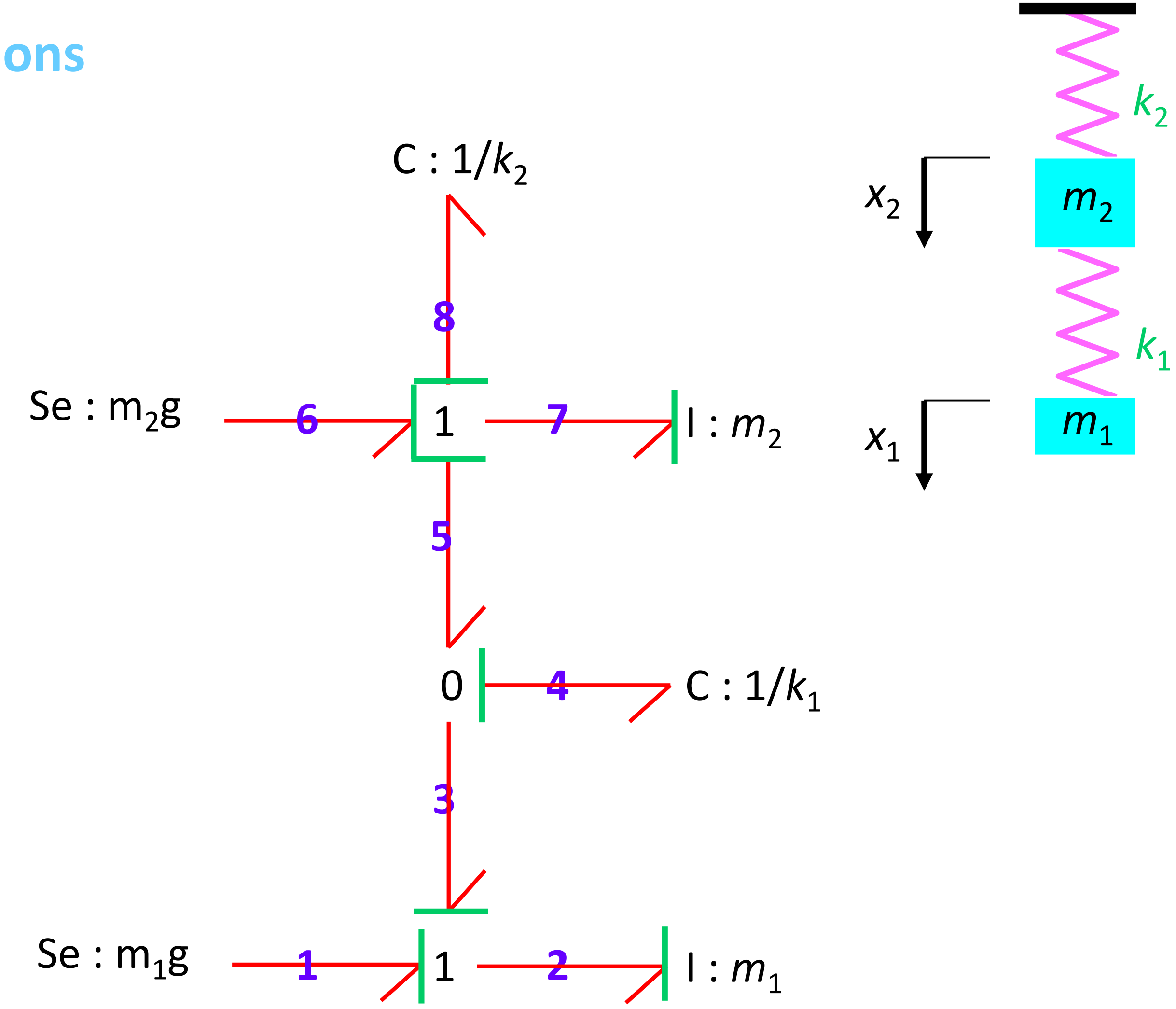
Procedure

Write structure laws at junctions taking causality into account;
Write down the laws associated with the elements taking into account their causality;
Explain the derivatives of state variables based on state variables and inputs.



Bond Graphs

State Equations



Co-funded by the Erasmus+ Programme of the European Union

Bond Graphs

Laws at junctions

$$e_1 + e_3 - e_2 = 0 \qquad f_1 = f_2 = f_3$$
$$f_5 - f_3 - f_4 = 0 \qquad e_3 = e_4 = e_5$$
$$e_6 - e_5 - e_7 - e_8 = 0 \qquad f_5 = f_6 = f_7 = f_8$$

Laws at elements

$$\dot{q}_4 = f_4 \qquad \dot{q}_8 = f_8$$
$$e_4 = k_1 q_4 \qquad e_8 = k_2 q_8$$

$$\dot{p}_2 = e_2 \qquad \dot{p}_7 = e_7$$
$$f_2 = \frac{1}{m_1} p_2 \qquad f_7 = \frac{1}{m_2} p_7$$

Element C

Element I

State Vector

$$X = \begin{bmatrix} p_2 \\ p_7 \\ q_4 \\ q_8 \end{bmatrix}$$

State equations

$$\dot{p}_2 = k_1 x_4 + m_1 g$$
$$\dot{p}_7 = -k_1 x_4 - k_2 x_8 + m_2 g$$
$$\dot{q}_4 = -\frac{1}{m_1} p_2 + \frac{1}{m_2} p_7$$
$$\dot{q}_8 = \frac{1}{m_2} p_7$$

Co-funded by the Erasmus+ Programme of the European Union

www.weset-project.eu

BG tool contributions

- For modeling
- For identification
- For analysis
- For the order
- For the diagnosis of breakdowns
- For the simulation

- the user of the bond graph tool can do nothing without the PHYSICAL knowledge of the system

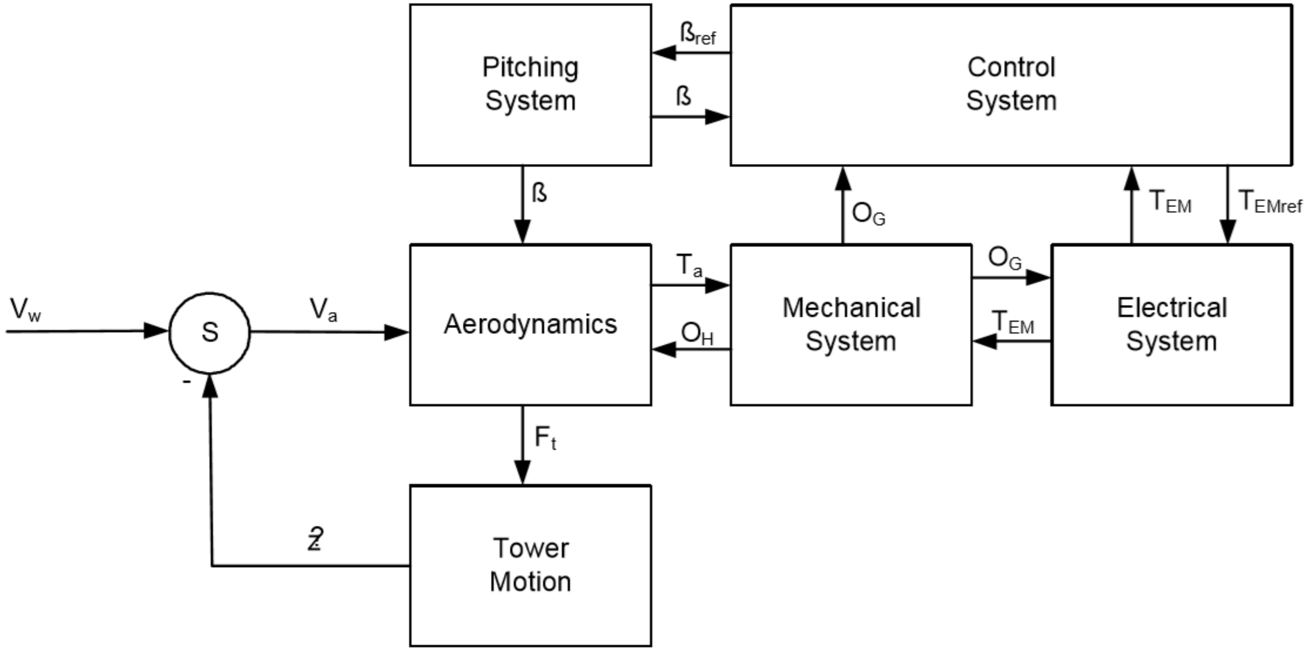
Co-funded by the Erasmus+ Programme of the European Union

www.weset-project.eu

The use of BG in WT modelling

The wind turbine generating system can be divided into several subsystems

$$P_a = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda,\beta).$$



The dimensionless tip-speed ratio (TSR) ʎ is defined as :

$$\lambda = \frac{v_b}{v}$$

$$T_a = \frac{1}{2}\rho\pi R^3 v^2 \frac{C_p(\lambda,\beta)}{\lambda}$$

$$F_t = \frac{1}{2}\rho\pi R^2 v^2 C_T(\lambda,\beta)$$

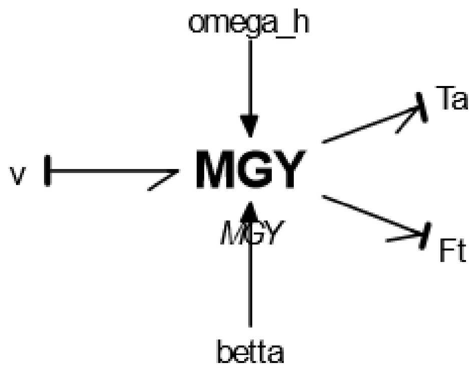
Co-funded by the
Erasmus+ Programme
of the European Union

www.weset-project.eu

Model description

Aerodynamics

In the aerodynamics part we need to find a way to convert the wind into torque and thrust force, i.e. transform a flow into efforts. This is done by means of a modulated gyrator. We use the torque and thrust equations.



Modulated gyrator transforming wind speed into aerodynamic torque and thrust force

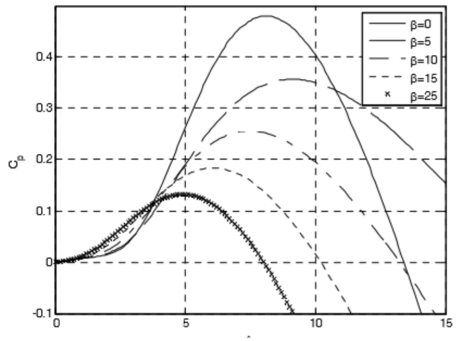
A generic equation is used to model Cp

$$\lambda = \frac{\omega_r R}{v}$$

$$\lambda_i = \frac{1}{\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^2 + 1}}$$

$$C_p = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)c^{\frac{c_5}{\lambda_i}} + c_6\lambda$$

where $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$ and $c_6 = 0.0068$.



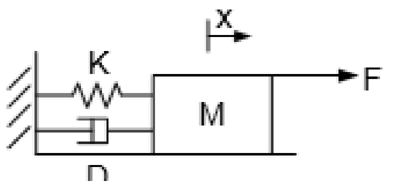
Cp curves

Pitching system

The pitching mechanism can be modeled as a second order system:

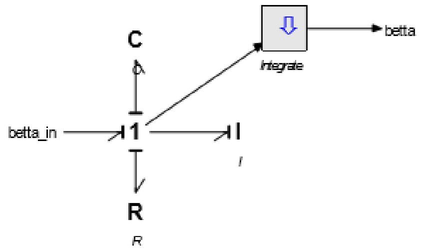
$$\omega_n^2\theta_{ref} = \ddot{\theta} + 2\zeta\dot{\theta} + \omega_n^2\theta$$

where θ ref is the reference pitch angle, ωn is the natural frequency and ζ is the damping ratio. By setting up the dynamic equation of the mass-spring-damper system : we can set up the bond graph with appropriate coefficients.



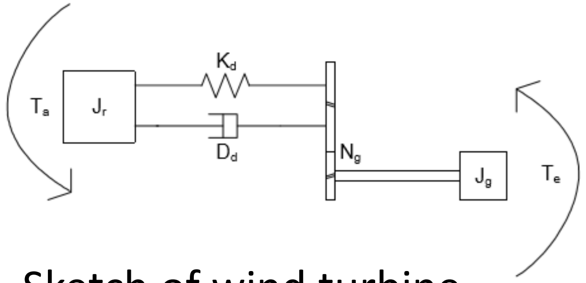
$$F = \theta_{ref} \qquad M = \frac{1}{\omega_n^2} \qquad D = \frac{2\zeta}{\omega_n^2} \qquad K = 1.$$

Mass spring damper



Bond graph of pitching system

Drive train



Sketch of wind turbine.

There are many types of drive train models, ranging from for example one- to six mass models. For simplicity we will assume a two-mass-model is enough.

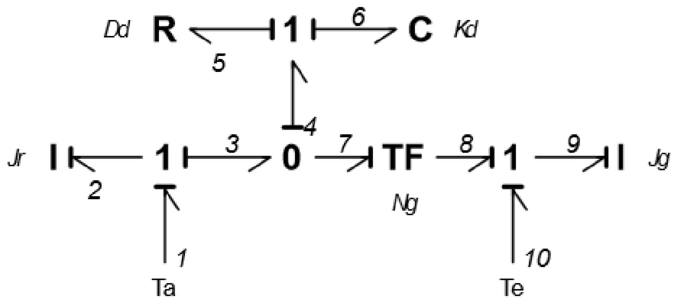
By utilizing Newton's second law on rotational form of the wind turbine sketch, we end up with the following differential equations:

$$T_r = I_r\dot{\omega}_r + \dot{\phi}_\Delta D_d + \phi_\Delta K_d$$

$$-T_g N_g = I_g N_g^2 \frac{\dot{\omega}_g}{N_g} - \dot{\phi}_\Delta D_d - \phi_\Delta K_d,$$

where

$$\phi_\Delta = \phi_r - \frac{\phi_g}{N_g}, \qquad \dot{\phi}_\Delta = \omega_r - \frac{\omega_g}{N_g}.$$



Bond graph of drive train

The bond graph model consists of three 1-junctions and one 0-junction. The 1-junction connected to the rotor inertia describes the rotor rotational speed. Since there are dynamics in between the rotor inertia and the generator inertia, they do not have the same speed. This is the reason for the 0-junction, because we know the transferred torque is the same (no loss included in the drive train). The 1-junction connected to the resistive- and the compliance element indicates the rotational speed difference between the two inertias. This connection also indicates that the compliance- and resistive element have the same rotational speed (flow), but different torque (effort). The last 1-junction is connected to the generator inertia and describes the generator rotational speed

Co-funded by the
Erasmus+ Programme
of the European Union

From the bond graph representation we see there are three dynamic elements, two inertias and one spring, i.e. three dynamic equations must exist. These first order differential equations are :

$$\dot{p}_2 = e_2 = e_1 - e_3$$
$$= T_a - \frac{q_5}{C_6} - R_5 f_5,$$
$$\dot{q}_5 = f_5 = f_3 - f_7$$
$$= \frac{p_2}{I_2} - N_g \frac{p_9}{I_9},$$
$$\dot{p}_9 = e_9 = e_8 + e_{10}$$
$$= -T_e + \frac{1}{N_g}\left(\frac{q_5}{C_6} + R_5 f_5\right).$$

Generator

There are many ways to model the generator dynamics. One of the recurring ways is with an equivalent circuit. In this system we assume that a first order transfer function will capture its dynamics. We do this in the same way as for the pitching system, but since it is first order we do not include the spring.

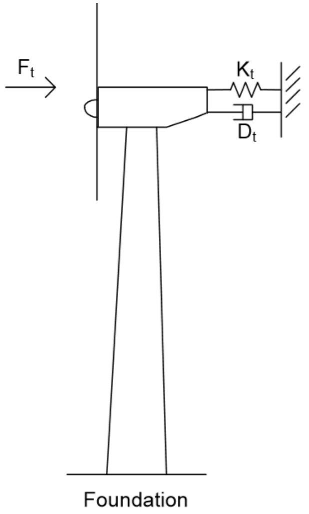
$$T_{ref} = \tau \dot{T}_e + T_e,$$

where T ref is the reference torque and τ is the time constant. In this way we can set up the bond graph with appropriate coefficients:

$$F = T_{ref}, \qquad M = \tau, \qquad D = 1.$$

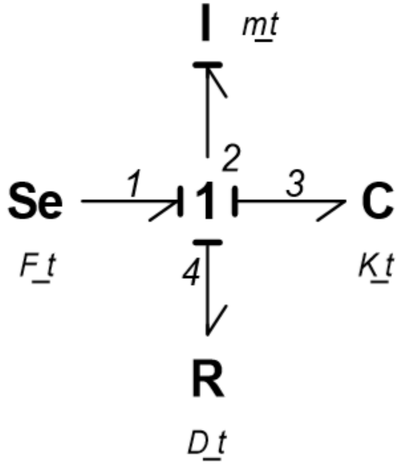
Co-funded by the Erasmus+ Programme of the European Union

Tower



Sketch of wind turbine structure

The thrust force is acting on the structure. It is assumed that the tower movement will not influence the mechanical system, it only affects its input, i.e. the wind speed. The bond graph model of the tower is :



$$\dot{p}_2 = S_e - \frac{p_2}{I} - \frac{q_3}{C}$$

$$\dot{q}_3 = \frac{p_2}{I}.$$

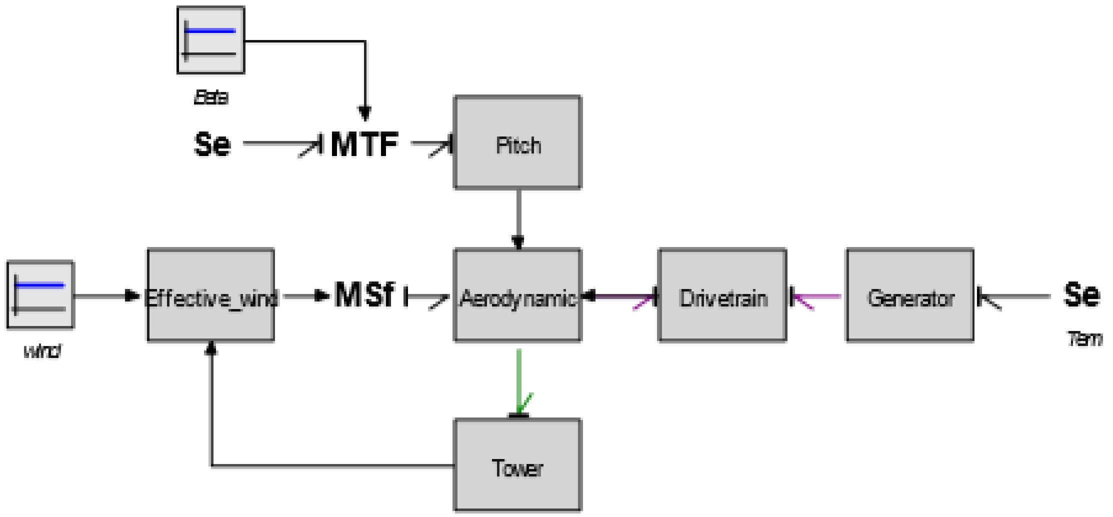
$$m_t \ddot{z} = F_t - D_t \dot{z} - K_t z,$$

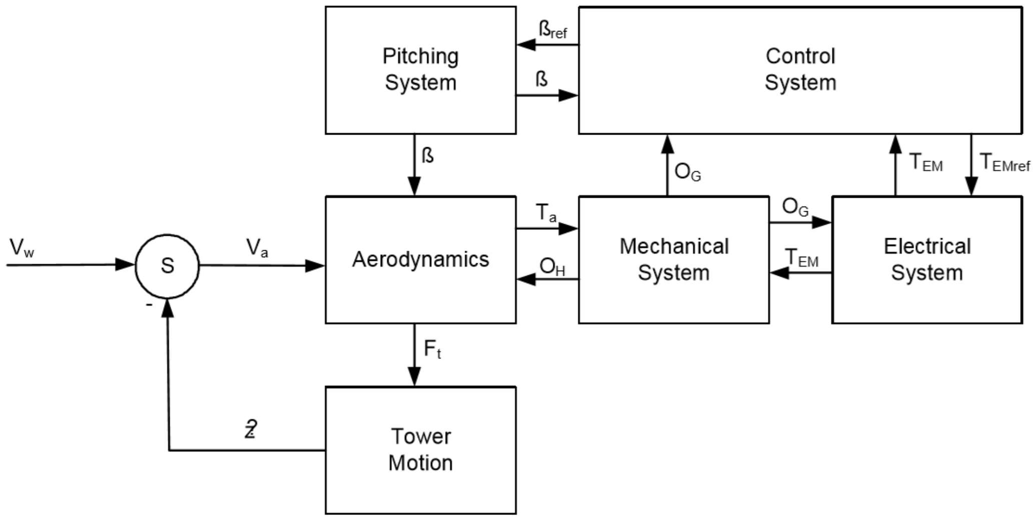
where m t is the tower mass, Ft is the thrust force acting on the tower, Dt is the tower damping and Kt is the tower stiffness.

Remark: Since the deflections of the tower are assumed to be small, we assume tower movement only in horizontal direction.

www.weset-project.eu

The bond graph representation of the system setup



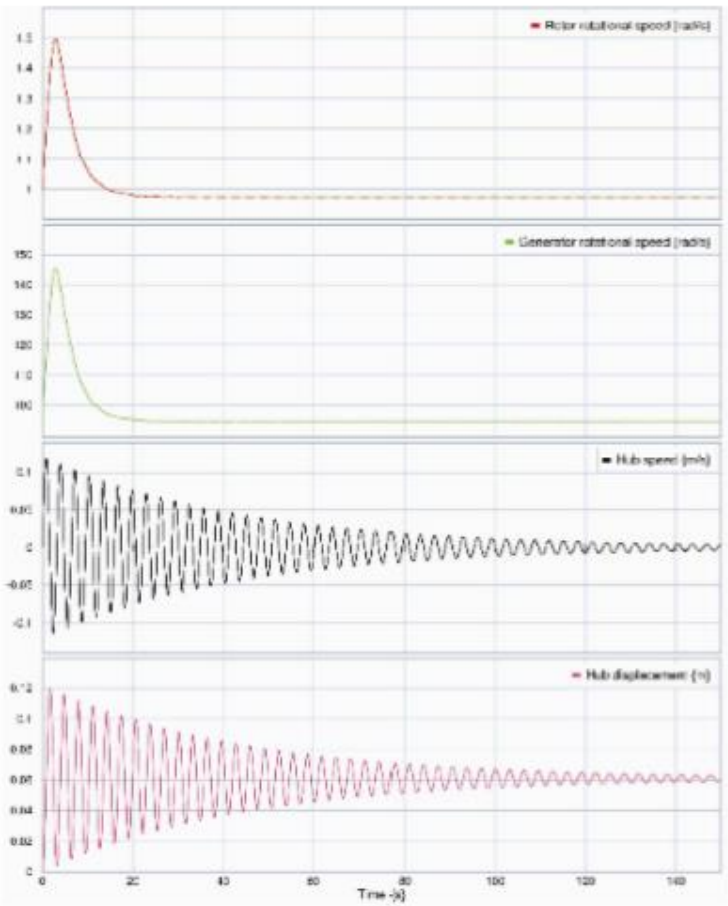


Co-funded by the Erasmus+ Programme of the European Union

www.weset-project.eu

Simulation Results with 20sim*

Pitch	
Natural frequency	$\omega_n = 0.88\left[\frac{rad}{s}\right]$
Damping ratio	$\zeta = 0.9[-]$
Maximum pitch angle	$\beta_{\max} = 25[°]$
Minimum pitch angle	$\beta_{\min} = -5[°]$
Drive train	
Nominal power	$P_{nom} = 5\times10^6[W]$
Rotor inertia	$I_r = 5.9154\times10^7[Kg\cdot m^2]$
Generator inertia	$I_g = 500[Kg\cdot m^2]$
Drive train stiffness	$K_d = 8.7354\times10^8\left[\frac{N}{rad}\right]$
Drive train damping	$D_d = 8.3478\times10^7\left[\frac{N}{rad\cdot s}\right]$
Gear ratio	$N_g = 97[-]$
Generator	
Time constant	$\tau = 0.1[s]$
Nominal generator speed	$\omega_{g\max} = 122.91\left[\frac{rad}{s}\right]$
Minimum generator speed	$\omega_{g\min} = 70.16\left[\frac{rad}{s}\right]$
Structure/Tower	
Rotor speed	$R = 63[m]$
Hub height	$h = 90[m]$
Tower mass	$m_t = 4.2278\times10^5[Kg]$
Tower stiffness	$K_t = 1.6547\times10^6\left[\frac{N}{m}\right]$
Tower damping	$D_t = 2.0213\times10^3\left[\frac{N}{m\cdot s}\right]$



Time behavior of the selected signals from 20-sim

** In order to use 20 sim Software , students are invited to see:https://www.20sim.com/downloads/files/20simGettingStarted47.pdf*

Co-funded by the
Erasmus+ Programme
of the European Union

Recommended literature

Books

[1] H. Paynter "Analysis and design of engineering systems", MIT Press, 1961

[2] D. Karnopp, R. Rosenberg "Systems dynamics : a unified approach", John Wiley & sons, 1975, 1991 (2nde édition)

[3] R. Rosenberg, D. Karnopp "Introduction to physical system dynamics", series in mechanical engineering, Mac Graw Hill, 1983

[4] P. Borne, G. Dauphin-Tanguy, J.P. Richard, F. Rotella, I. Zambettakis "Modélisation et identification des processus", Méthodes et pratiques de l'ingénieur, éditions Technip, volume 3, tome 2, 1992

[5] " Les bond graphs " ouvrage collectif, G. Dauphin-Tanguy coordonnateur, collection IC2, Hermès, septembre 2000

[6] M. Vergé, D. Jaume " Modélisation structurée des systèmes avec les bond graphs « , Méthodes et pratiques de l'ingénieur, Editions Technip, 2004

[7] Wolfgang Borutzky Editor Bond Graph Modelling of Engineering Systems Theory , Applications and Software Support: ISBN 978-1-4419-9367-0 e-ISBN 978-1-4419-9368-7 DOI 10.1007/978-1-4419-9368-7 Springer New York Dordrecht Heidelberg London Library of Congress Control Number: 2011927919

Co-funded by the Erasmus+ Programme of the European Union

Thank You for Your Attention!

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Contact: info@weset-project.eu *weset.erasmusplus@uva.es*

Co-funded by the
Erasmus+ Programme
of the European Union

Mechatronics in Wind conversion process

Module 3

Introduction to Modelling and Simulation for Wind Energy:

Multiphysical modeling

1

Co-funded by the
Erasmus+ Programme
of the European Union

Learning Outcomes

At the end of this lesson the students will be able to :

O1. Understand the importance of modelling and simulating using Multiphysics tools.

O2. To learn the basic ideas behind modelling wind turbines using Multiphysics tools.

Co-funded by the Erasmus+ Programme of the European Union

www.weset-project.eu

Objective

In this part of the course we will discuss the importance of modelling and simulating wind energy generators using multiphysics, and how thes tools can play a significant role in its analysis and design.

Co-funded by the Erasmus+ Programme of the European Union
Co-funded by the Erasmus+ Programme of the European Union

3

Technical Contents

1. **Introduction**

    Motivations for multiphysical modeling of wind generators

2. **Components of a Physical model**

    Power/Energy Notes
    Representation of the energy chain of a complex system

3. **Construction of a multiphysical model of wind generators using MODELICA**

    Modeling type
    Causal and acausal modeling
    Using MODELICA (tutorial)

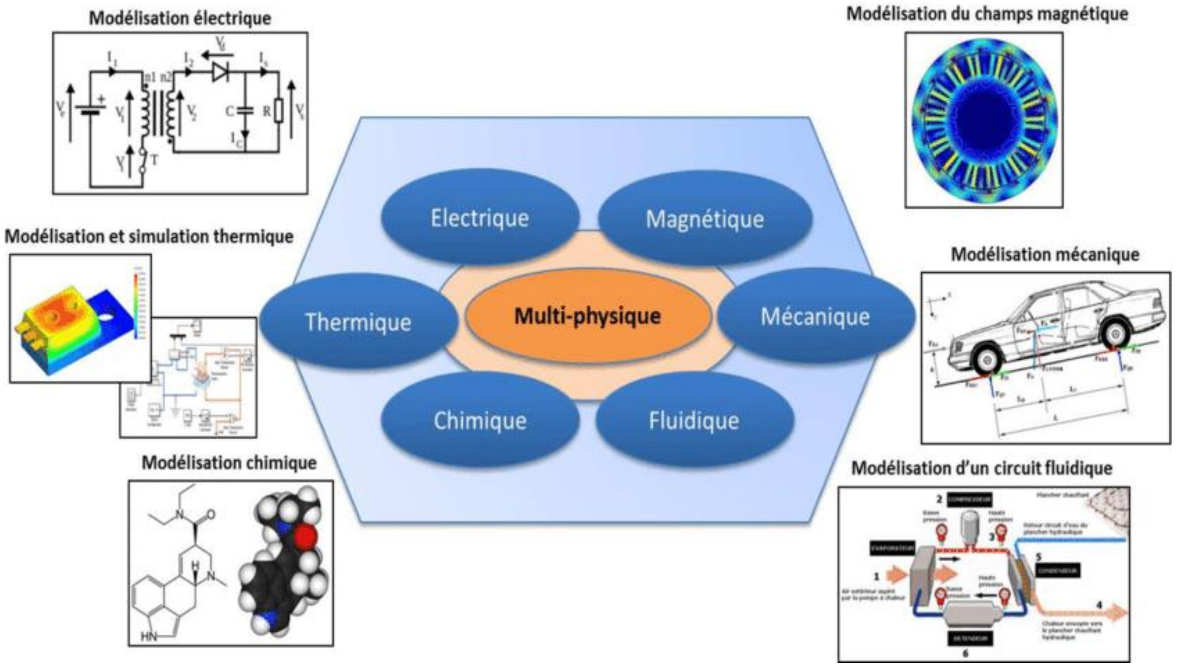
Co-funded by the
Erasmus+ Programme
of the European Union

Introduction

- The operation of most industrial products involves interactions between several physical phenomena of different natures

- In a simulation, it is often necessary to model these interactions to correctly predict the response of the product,

,



Co-funded by the
Erasmus+ Programme
of the European Union

Properties: Interests and motivation

The systems developed today are using more and more different technologies. This is why they can be called "multiphysical" or "pluritechnic".

To model the performance of a wind turbine it is necessary to determine the control of the different parts to obtain a given operation.

This problem is complex because it involves different physical domains: electric (engine control, energy management), mechanical (blades movements), aerodynamics, etc.

The goal is to build a model to make these different physical considerations interact is the principle of multiphysical modeling

Co-funded by the Erasmus+ Programme of the European Union

Definition: Multi-physical modeling

Multiphysical modelling is necessary to implement as long as a system is made up of sub-prime
groups mobilizing technologies that use different branches of physics:

Electrical;
mechanical;
hydraulics;
Etc..

- The writing of principles relating to these different disciplines (electric laws, principles of dynamics, energy conservations) results in the writing of differential equations that must be solved in order to predict the behavior of the system that one Models.
- The tools of multi-physical modeling allow to link the knowledge patterns and behavioral laws of the different subset of the system to build a very complete model. That is the purpose of this course.

Co-funded by the Erasmus+ Programme of the European Union

Reminders 1/2: Power/Energy Notes

Definition: Power/energy

- Energy: Energy measures a system's ability to modify a state or produce work.
- the unit of an energy is the Joule (J) which is homogeneous to the product of a force by a length.
- Power : is the amount of energy per unit of time.

Its unit is the Watt (W), which is homog'ene to the product of a force by a speed.
It is a scalar size that results from the product of two algal sizes: one is called flow and rated f (t); the other is called potential and is rated p(t). Generally it can be registered in the form:

$$P(t) = f(t) \times p(t) = \overrightarrow{f(t)} \times \overrightarrow{p(t)}.$$

Co-funded by the
Erasmus+ Programme
of the European Union

Reminders 2/2:

In addition to the block diagram to model continuous and invariant linear systems, the description of systems using SysML graphic language and multiphysical modeling are emerging. This is the time to clarify the concepts of causal and acausal modeling, and to emphasize the value of combining the use of SysML and That of Modelica in a model-guided system engineering approach, to which the languages "bond graph" and Modelica integrate fully, especially as SysML profiles.

We can also point out that a block scheme is not necessarily more telling than the differential equation system it represents. In addition, multi-physical models are easily reusable, thanks to the creation of libraries. The software used in multi-physical modeling allows to build abnormal models, unlike those that simulate block diagrams, which are causal models.

Co-funded by the
Erasmus+ Programme
of the European Union

Bond Graphs

- The description of the state of a multi-physical system requires the use of two sets of fundamental variables. Four of them are linked by mathematical relationships. They depend on the time t. Depending on the system studied, these variables may have more than one dimension: they are then expressed using vectors.

Two groupings are possible:

- Grouping 1 power variables, effort e and f flow energy variables, moment p and displacement q
- Grouping 2 kinematic variables, q displacement and kinetic f variable flows, moment p and f

Co-funded by the
Erasmus+ Programme
of the European Union

Tutorial: Modelica for Wind Energy

- **Motivations**
  - Why Modelica
  - Why use Modelica in wind turbine modeling
- **Model with with Modelica**
  - General principle
  - Language
- **Conclusions**
  - Potential inflows
  - Boundaries/lack

Co-funded by the
Erasmus+ Programme
of the European Union

Modelica

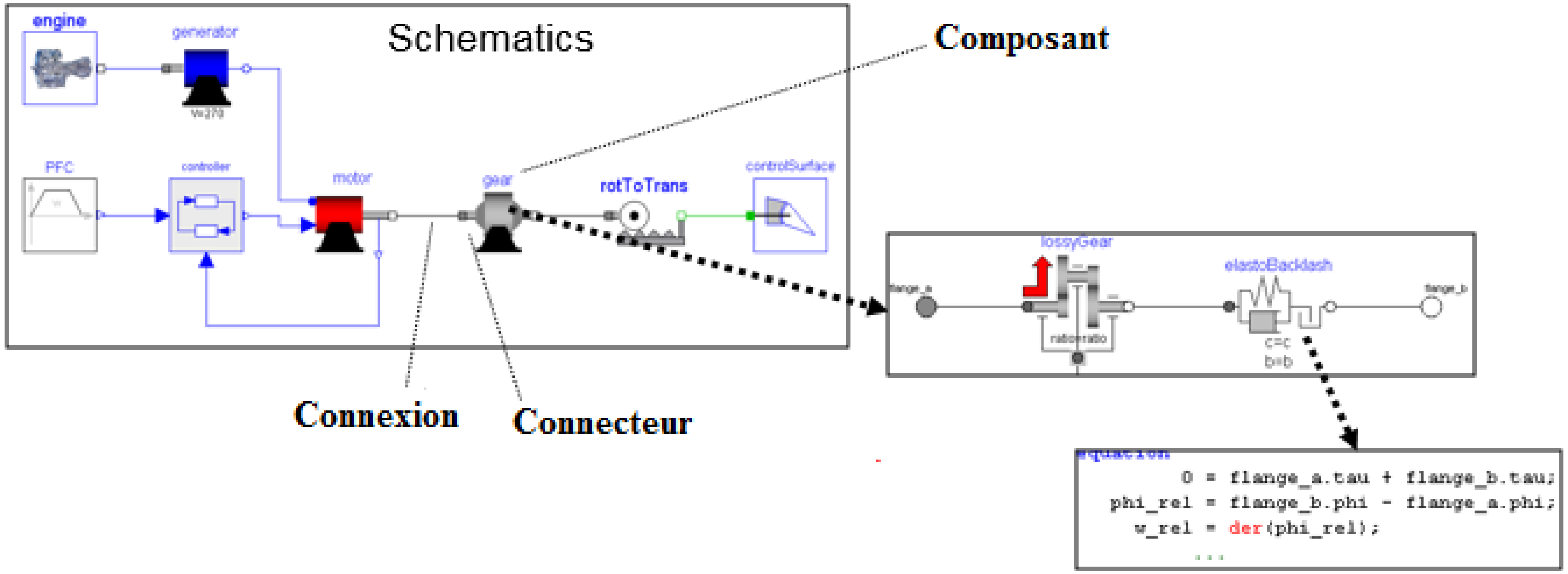
- Modelica is a multiphysical modeling language of complex systems
- It is based on the acausal approach to modeling
- A class can be considered as a description of a family of objects sharing common properties.
- The different Modelica classes are:
  - Records
  - Function
  - Connector
  - Block
  - Model

Co-funded by the Erasmus+ Programme of the European Union

Modelica

Structure of a modelica model

- Each icon represents a physical component. (electric resistance, mechanical device, pump, ...)
- A connection line represents the actual physical coupling (wire, fluid flow, heat flow, ...)



- A component is made up of connected sub-components (hierarchical structure) and/or is described by equations

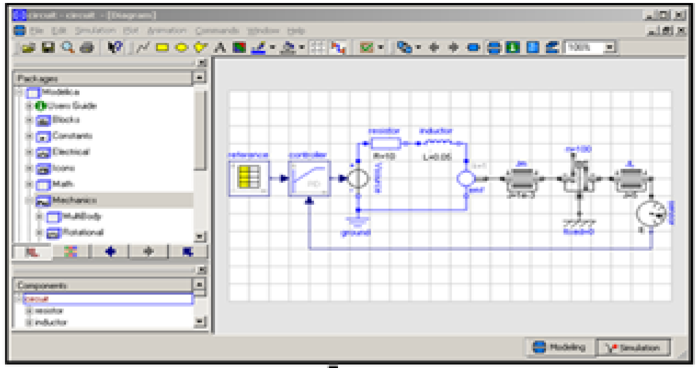
Co-funded by the Erasmus+ Programme of the European Union

WE SET
www.weset-project.eu

Modelica

Modelica Language and simulation environment

Graphic editor for Modelica models



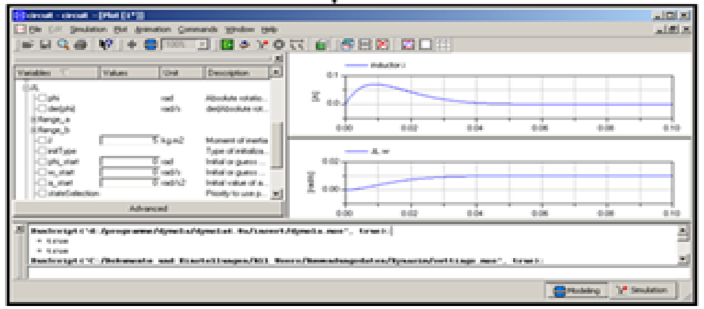
Text description

```
model circuit
  ;
  Modelica.Electrical.Analog.Basic.Resistor resistor(R=10) ;
  Modelica.Electrical.Analog.Basic.Inductor inductor(L=0.05) ;
  Modelica.Electrical.Analog.Basic.EMF emf(k=1) ;
  Modelica.Electrical.Analog.Sources.SignalVoltage Vsource ;
  Modelica.Electrical.Analog.Basic.Ground ground ;
  Modelica.Blocks.Continuous.LimPID controller ;
  Modelica.Mechanics.Rotational.Inertia Jm(J=1e-3) ;
  Modelica.Mechanics.Rotational.IdealGear n(ratio=100) ;
  Modelica.Mechanics.Rotational.Fixed fixed ;
  Modelica.Mechanics.Rotational.Inertia JL(J=5) ;
  Modelica.Mechanics.Rotational.Sensors.SpeedSensor sensor ;
  Modelica.Blocks.Sources.CombiTimeTable reference ;
```

Modelica language

MODELICA

Traduction C language for simulation



Co-funded by
Erasmus+ Program
of the European Union

Motivations : Why Modelica (1/2)

- A declarative, object-oriented language
- A language specially adapted to modeling systems
- Applying to all areas
- UML modela- for modellers?
- A language to describe hybrid models
- 'Hybrid' - discrete -continuous

Co-funded by the
Erasmus+ Programme
of the European Union

Motivations : Why Modelica (2/2)

- Towards a standardized modeling language

Specifications are standardized

The only obligation of computer tools (compilers) is to comply with these specifications

Applications to date

-Mechatronics, Electronics, Power Systems, Hydraulics, Aerodynamics..."

- Modelica comes from a community of modellers, familiar with the object approach (Scandinavian school)

Co-funded by the Erasmus+ Programme of the European Union

Motivations: why model wind turbines with Modelica

- Thanks to Modelica, the model of the wind turbine and its simulation can be expressed in a unified language at the same time

- Understandable by the modeller

- It's computable

- Characterizing all manipulated objects (semantics)

Co-funded by the Erasmus+ Programme of the European Union

Modelica: general process (1/2)

- Defining a system model
- 'component-oriented'
  Discrete and/or continuous state variables
- Dynamic (continuous time) described by
  Differential equation
  Program
- Inheritance between components
  Reusable components (component libraries)
  'model' - component assembly
- Graphic editors

Co-funded by the
Erasmus+ Programme
of the European Union

Model / Simulate with Modelica: general process (2/2)

- Setting the parameters of a simulation
- compilation of the set model
- Flattening the object model
  - Production of a hybrid EDA system
- Running the simulation program
- Exploitation of hybrid EDA solvers adapted to the problem

Co-funded by the Erasmus+ Programme of the European Union

Modelica: Language

- Key concepts
  A list of basic types of constructions
Real, Integer, String, Boolean
"Array, Enumeration"

- A general concept of class (class)
  Special class shapes
  model, record, block, connector, type,
package, function

- Dynamics: time is constantly changing. It is shared by all the components of a model

Co-funded by the
Erasmus+ Programme
of the European Union

Modelica: Classes

A class defines the properties common to the components attached to them

Takeover of existing class properties (multiple inheritance)

Such as what

Specialization (more specific types, parameter evaluation)

Co-funded by the Erasmus+ Programme of the European Union

State variables

- Variability
  Constant: value imposed in the model (immutable for any simulation)

- Parameter: free value to be specified at the beginning of the simulation (immutable for this simulation)

- Discreet: real value that can change during discrete events

- Causality
  'input': value to be derived from an output variable: value produced

- 'flow'
  Flow: variable of the flow genre (see connectors)

Co-funded by the Erasmus+ Programme of the European Union

Equations

List of equations linking state variables

Define the dynamics of continuous variables

Algorithm

Description of a program

Allows you to calculate discrete variable values

Co-funded by the Erasmus+ Programme of the European Union

www.weset-project.eu

Modelica: special classes

Type: defines a type, by extension of a predefined type for example

Example:

typeVoltage - Real (quantity" "Voltage"

Co-funded by the Erasmus+ Programme of the European Union

•connector: defines a connector

State variables are potentials

When two connectors are connected, the connection requires that the potential variables are equal

State variables are flows (flow)

When two connectors are connected, the connection requires that the flow variables have their sum equal to 0

No associated equations

Example:

```
Connector
Pin Voltage v;
flowCurrent i;
endPin;
```

Co-funded by the
Erasmus+ Programme
of the European Union

- model: class that cannot be operated as a connector

Examples:

An abstract model:

```
partial model TwoPins
        Pine p, n;
        Voltage u;
         Current i;

equation
        0 - p.i- n.i;
        u - p.v -n.v;
       i - p.i;

End TwoPins;
```

Concrete model:

```
Model Resistor
Extends TwoPins;
Parameter ResistanceR;
equation u = R*i;
 end Resistor;

Model Capacitor
Extends TwoPins;
Parameter Capacitance C;
equation C*der(u) = i;

End Capacitor;
```

Co-funded by the
Erasmus+ Programme
of the European Union

Examples :

Model Sinus Source :

Extends Two Pins;
Parameter Frequency F;
Parameter Voltage A;
Protected
 Constant Real PI - 3.14159265358979;
equation u - A - sin (time - 2-PI-F);

End SinusSource;

Co-funded by the
Erasmus+ Programme
of the European Union

Block: class to contain at least one causal variable (input or output), not usable as a connector

Function: class block that does not contain an equation and contains no more than one algorithm

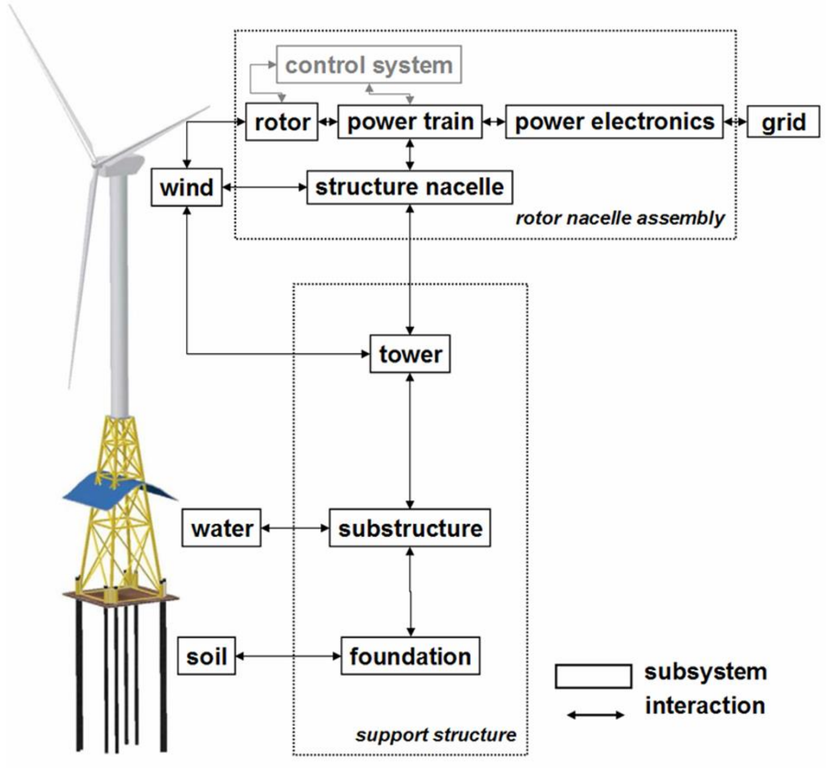
```
functionDistance
        parameterInteger N;
        inputReal[N] p1;
        inputReal[N] p2;
        outputRealresult;

algorithm result: 0;
For i loop result: end for;
result: sqrt(result);

End Distance;
```

Co-funded by the
Erasmus+ Programme
of the European Union

2.Example of a Wind turbine



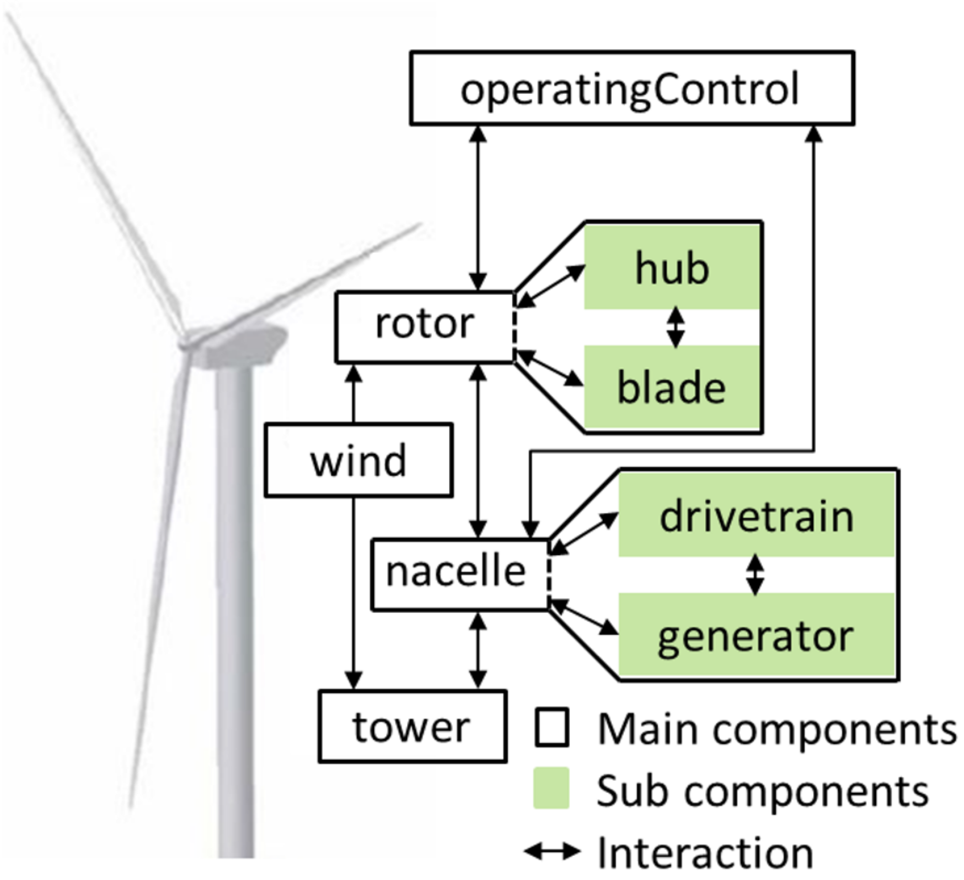
Key components of a wind turbine

Librairie OnWind

- OnWind
  - Connectors
  - WindTurbine
    - DriveTrain
    - Nacelle
    - OperationControl
    - Rotor
    - Tower
    - Water
    - Wind
    - package.mo
    - WindTurbine.mo
  - package.mo

Co-funded by the
Erasmus+ Programme
of the European Union

Wind turbine under MODELICA



Wind turbine with corresponding instances and interactions

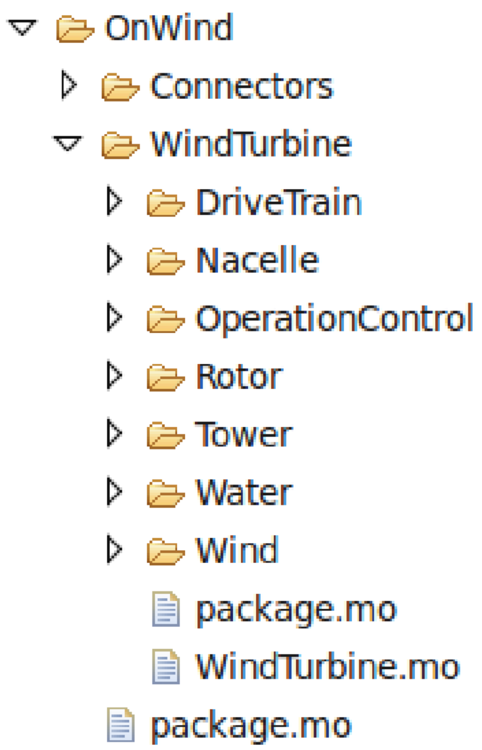
Co-funded by the
Erasmus+ Programme
of the European Union

Wind turbine under MODELICA

Wind Energy Library

The Wind Energy Library is a Modelica-based simulation library designed to help model components of wind power plants, including generators, power electronics and auxiliary components. It is intended to study the dynamic behavior of modern wind turbines with generator and grid components.

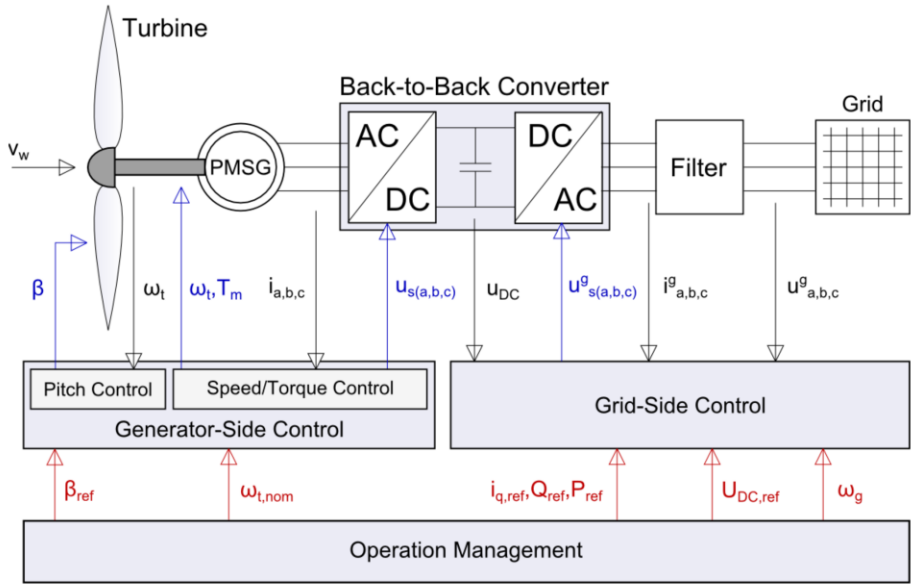
.



Co-funded by the
Erasmus+ Programme
of the European Union

www.weset-project.eu

Example of assembly to model with MODELICA



- Study the dynamical behaviour of the wind turbineÉtudier le comportement dynamique des éoliennes
- The control of the 'PMSG' is based on the 'Field Oriented Control' (FOC)
- Grid control is based on Voltage Oriented Control (VOC)

Co-funded by the
Erasmus+ Programme
of the European Union

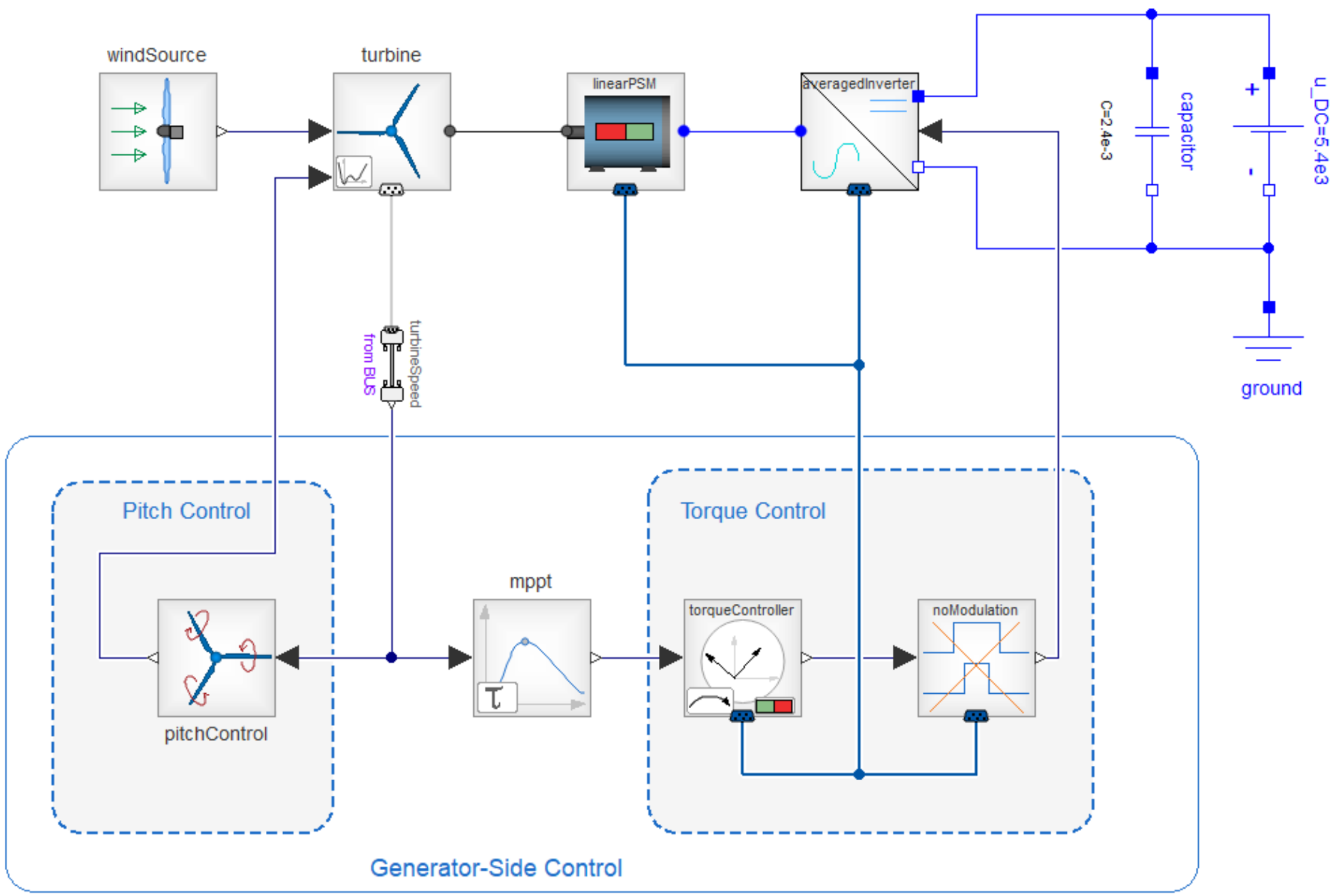
Implementation

- With the wind speed as input, the power that can be harvested from a wind turbine is calculated in the wind turbine model.
- The harvested wind energy is transferred to the permanent magnet synchronous generator (PMSG) and converted into electrical energy.
- The 'back-to-back' converter is required to decouple the variable frequency generator side from the side of the constant frequency grid (meaning the frequency is fixed by the network)
- a smooth filter the switch signals generated in the grid side converter.
- The bookstore includes various examples that demonstrate the control mechanism of modern wind turbines.
- Control -generator side
- MPPT via Optimal Torque
- MPPT via Tip-Speed Ratio
- 'pitch' pitch control
- Control - network side
- 'Voltage Oriented Control' voltage-oriented control

Co-funded by the Erasmus+ Programme of the European Union

www.weset-project.eu

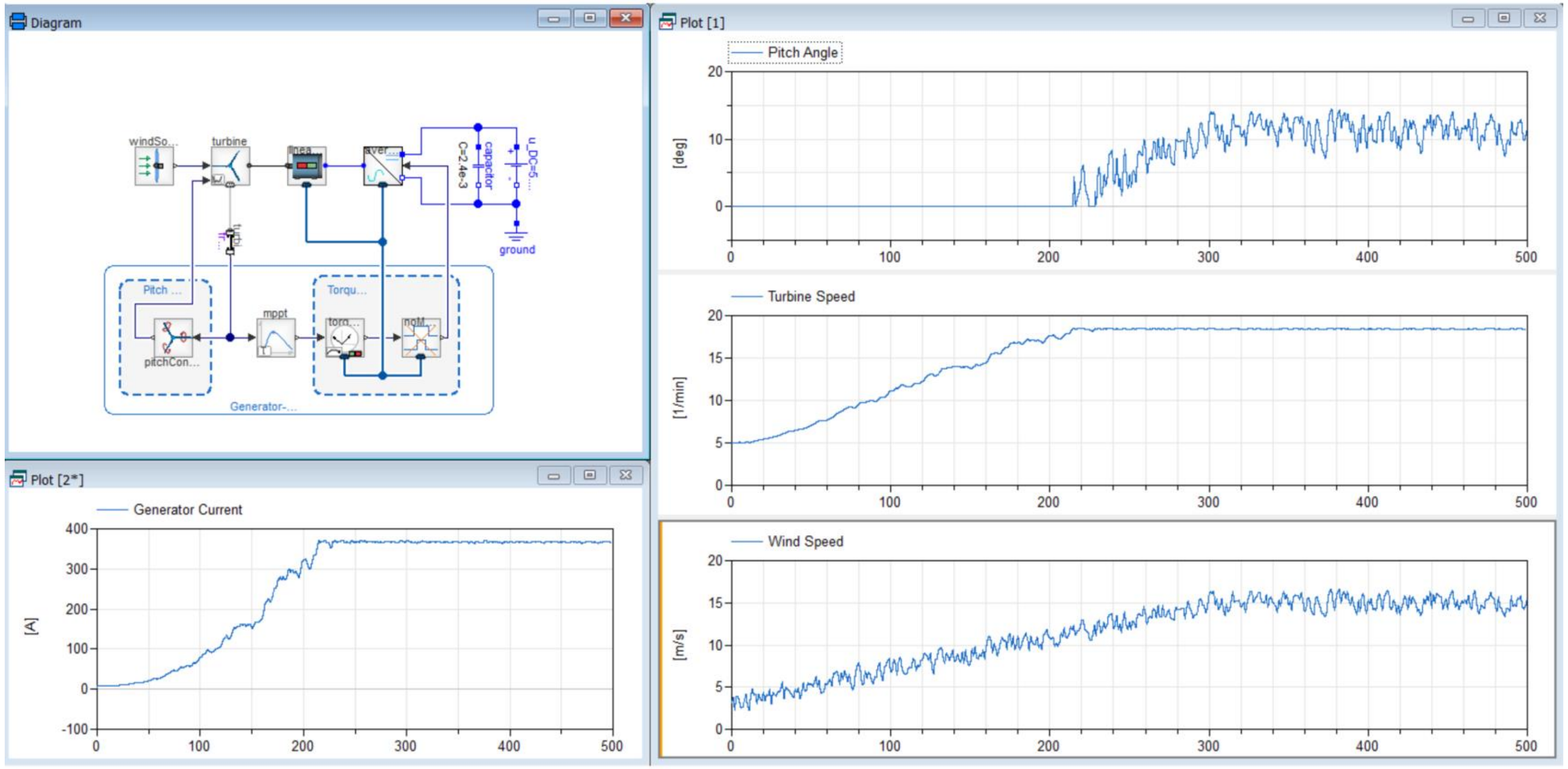
MODELICA Model



Co-funded by the
Erasmus+ Programme
of the European Union

www.weset-project.eu

Simulation Results



Co-funded by the
Erasmus+ Programme
of the European Union

Tutorials

Using the Matlab/Simulink MODELICA software, students are invited to

1. Taking control of software in the first stage

2. To process to fully understand the examples of modeling and simulation of systems wind turbines provided in 'examples' directories in Simulink and Modelical

3. Compare the results with the two software

Co-funded by the
Erasmus+ Programme
of the European Union

Recommended literature

Books :

1. Multiphysics Modeling
In Numerical Methods and Engineering Applications
A volume in Elsevier and Tsinghua University Press Computational Mechanics Series - 2015

2. Multi-Physics Modeling of Technological Systems
Author(s):Marc Budinger, Ion Hazyuk, Clément Coïc
Print ISBN:9781786303783 |Online ISBN:9781119644293 |DOI:10.1002/9781119644293

- Review articles:

- Application of Multiphysical Domain Modeling in Electrical System Simulation
Cao Zheng, Zhou Yuanjun, and Wang Na, in mathematical problems in engineering
Volume 2020 |Article ID 6245943 | https://doi.org/10.1155/2020/6245943

Web links:
[1] https://www.modelica.org/
[2] http://doc.modelica.org.
[3] http://mbe.modelica.university/.

Thank You for Your Attention!

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Contact: info@weset-project.eu weset.erasmusplus@uva.es

Co-funded by the
Erasmus+ Programme
of the European Union

Mechatronics in Wind conversion process

Module 2.3

Power Converters in Wind Energy

Co-funded by the
Erasmus+ Programme
of the European Union

Objective

In this part of the course we will see the advantages and disadvantages of different converters used in the conversion of wind energy

Co-funded by the Erasmus+ Programme of the European Union

Learning Outcomes

At the end of this lesson the students will be able to :

- *O1. Understand wind turbine technology i.e. generators, converters, connection of wind turbines to the network grid.*
- *O2. Appreciate the development of design needs and innovation in the international market.*
- *O3. Present, discuss and argue converter selection aspects of wind conversion process.*

Co-funded by the
Erasmus+ Programme
of the European Union

Technical Contents

1. Introduction : The connection of a wind turbine (WT) to the grid

2. WTS Power configurations

3. Grid Power Converter Topologies

Co-funded by the
Erasmus+ Programme
of the European Union

Power converters for Wind Energy

- Different topologies of converters are used for the power conditioning of wind turbine generator systems.
- Each converters provides certain advantages and disadvantages.
- Only unidirectional converters based on diode rectifiers and bidirectional topologies of back-to-back converter are commonly used in commercial wind generator systems.

Co-funded by the
Erasmus+ Programme
of the European Union

In this part of the course we will see the role of the following converters in the conversion of wind energy:

- Diode rectifier based converter '
- Back to back converter
- Matrix converter
- Z-source converter
- Improved Z-source converter
- Cycloconverter
- Multilevel converters

Co-funded by the Erasmus+ Programme of the European Union

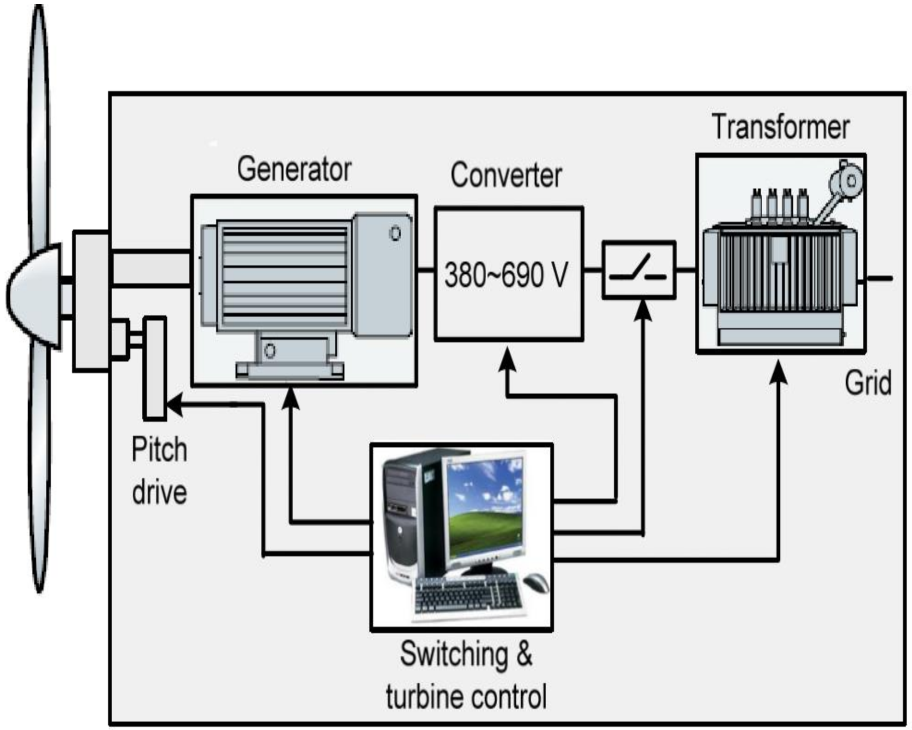
Introduction

The traditional converter voltage level is between **380 to 690 V**

To reduce electrical losses, a supply frequency (50/60 Hz) is commonly To increase the voltage at medium voltage (for example 11-33 kV) a transformer is required:.

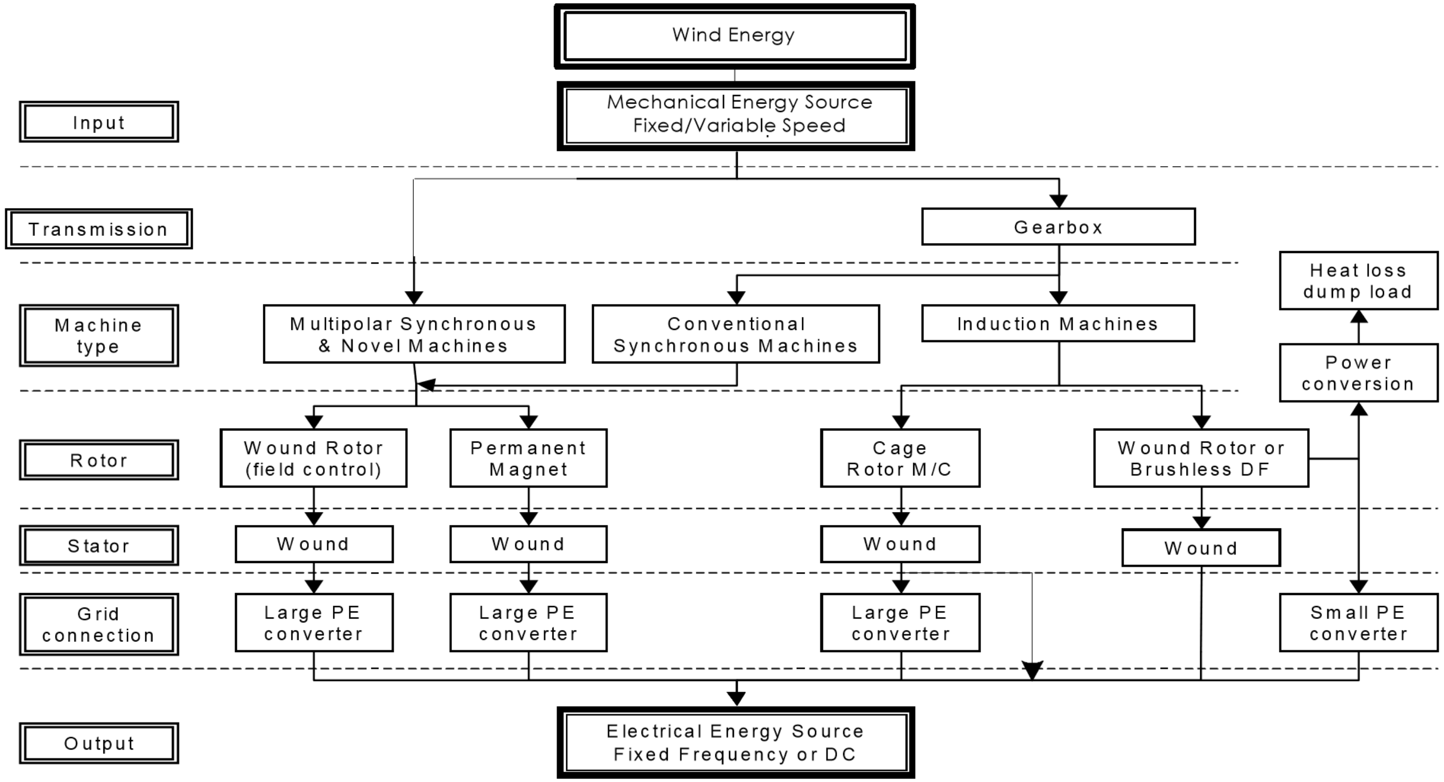
Nowadays, thanks to the power electronics, the components can accept higher currents and voltages, the power loss decreases and the devices become more reliable for power control on the megawatt scale.

Recent progress has led to the development of new medium voltage converters which eliminate the transformer.



wind energy conversion system

Co-funded by the
Erasmus+ Programme
of the European Union



Technological roadmap starting with wind energy / power by converting mechanical energy into electrical power

A technological roadmap starting with wind energy / power by converting mechanical energy into electrical power is presented. These are solutions with and without a multiplier as well as solutions with or without electronic power conversion. The electrical output can be either AC or DC. In the latter case, a power converter will be used as an interface to the network.

Co-funded by the
Erasmus+ Programme
of the European Union

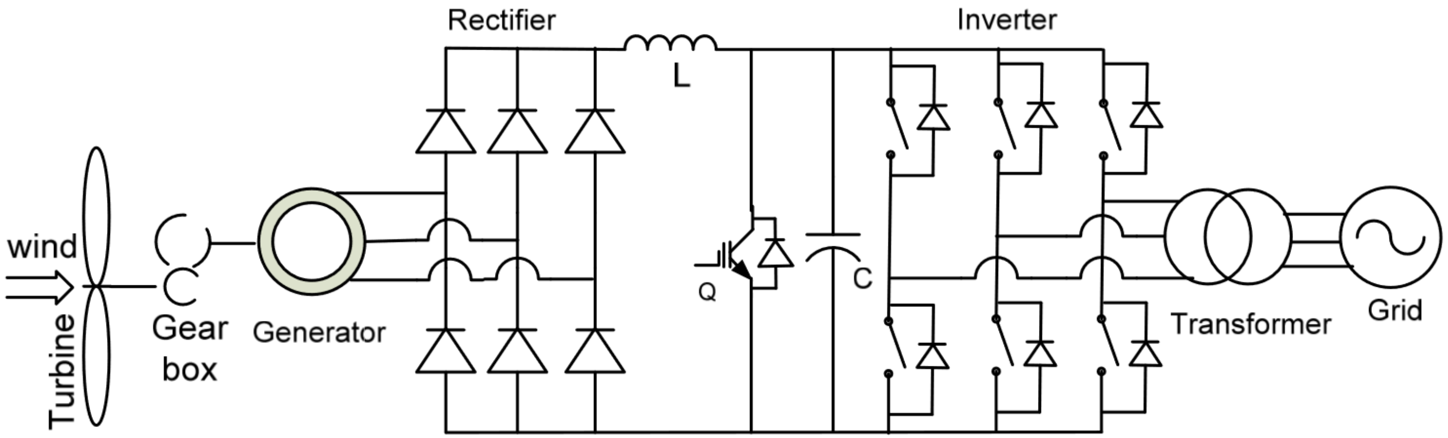
Converters in power generation

- Different topologies of converters have been studied for the power conditioning of wind turbine generator systems
- All the converters offered have certain advantages and disadvantages
- Only unidirectional diode rectifier converters and back to back bidirectional converter topologies are commonly used in commercial with turbine generator systems .

Co-funded by the
Erasmus+ Programme
of the European Union

Diode rectifier converter

In this converter system, AC power at variable frequency and at variable amplitude from the wind turbine generator is first converted to DC power by a diode rectifier circuit, then converted to AC power at a frequency and at a level of different voltage by a controlled inverter circuit.



Topology of the diode rectifier converter

Co-funded by the Erasmus+ Programme of the European Union

Benefits:

- Low production cost of the system and
- Simple to implement

Disadvantages:

- It produces a large amount of harmonics (input current), which affects the performance of the utility system
- Higher losses (output voltage) due to harmonics
- Unidirectional sense of power

www.weset-project.eu

Back to back converter

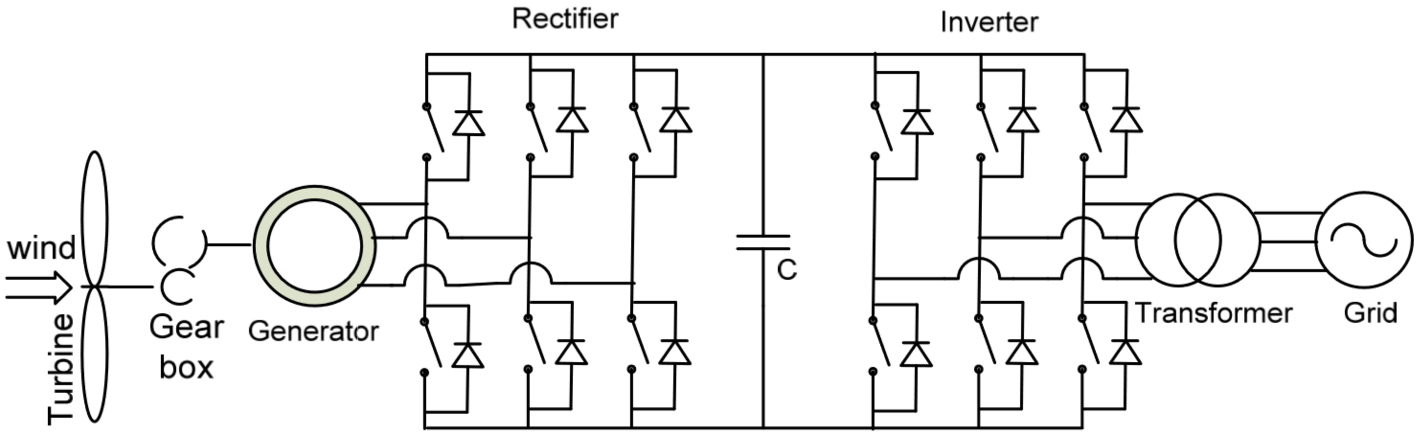
The converter based on a controlled diode rectifier and a controlled inverter is called a ‘back-to-back‘ converter, which is made up of two converters with conventional pulse-width modulated voltage source (PWM).

It differs from the conventional converter as shown in the figure.

The controlled rectifier allows a bidirectional power flow. In addition, the controlled rectifier greatly reduces the input current harmonics and harmonic losses.

The line-side converter controls active and reactive power flow to the network and keeps the DC voltage constant, improving the quality of output power by reducing total harmonic distortion (THD).

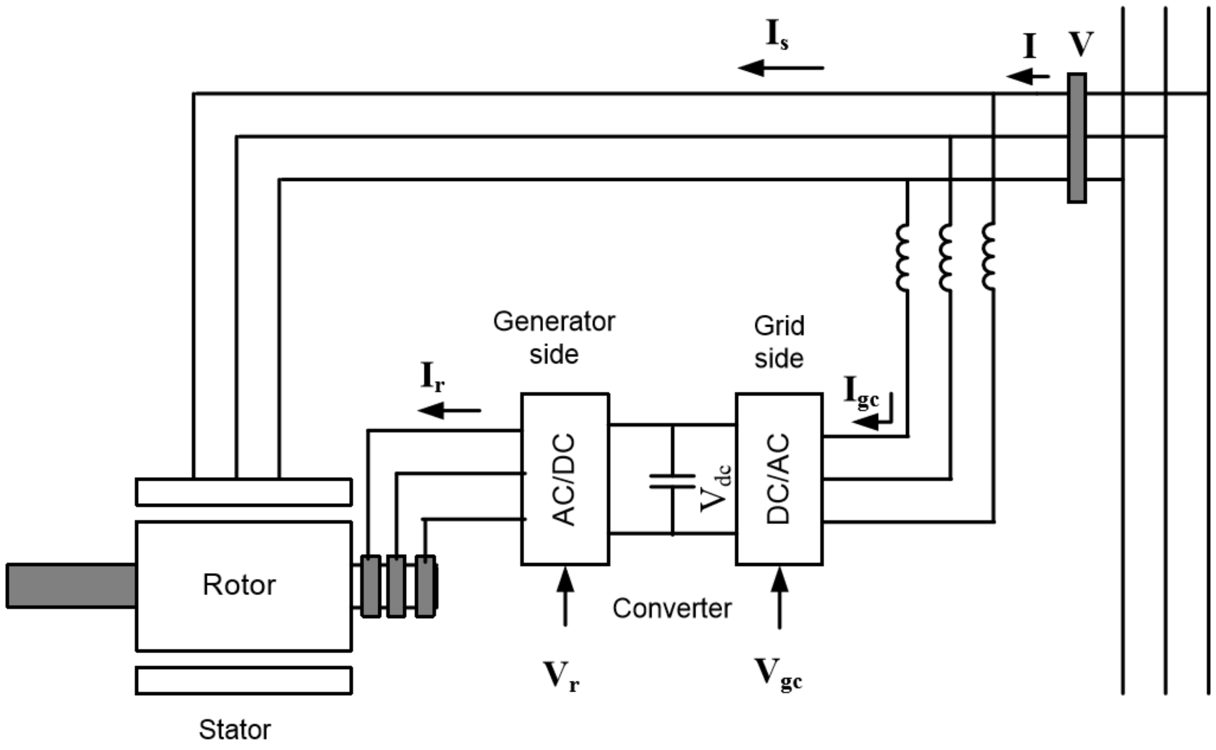
The generator's side converter operates as a conductor, controlling the magnetization demand and the desired generator rotor speed. The decoupling capacitor between the line side converter and the generator side converter provides independent control capability of the two converters.



‘Back to back’ converter generator system

Co-funded by the Erasmus+ Programme of the European Union

The back-to-back converter is of significant interest for the wind turbine system using the dual power induction generator (DFIG).



DFIG with back-to-back converter

Recall on the dual power generator

- A dual power generator (DFIG) composed of a wound rotor, an induction generator and an AC / DC / AC converter based on IGBTs.
- The stator winding is connected directly to the network while the rotor is supplied at variable frequency by the AC / DC / AC converter.
- Vr is the rotor voltage and Vgc is the lateral network voltage.
- The AC / DC / AC converter is essentially a PWM converter which allows the reduction of the harmonics present in the DFIG system controlled by the wind turbine.
- Crotor is the lateral rotor converter and Cgrid is the lateral network converter
- To control the speed of the wind turbine, multipliers or an electronic control can be used

Co-funded by the Erasmus+ Programme of the European Union

Benefits:

- The back-to-back power converter is a bidirectional power converter
- The DC link voltage can be increased to a level higher than the amplitude of the trunk line voltage in order to achieve full control of the grid current
- The capacitor between the inverter and the rectifier makes it possible to decouple the control of the two converters, allowing compensation for the asymmetry on the generator side and on the grid side.
- Component costs are low (commercially available as a module).

Disadvantages:

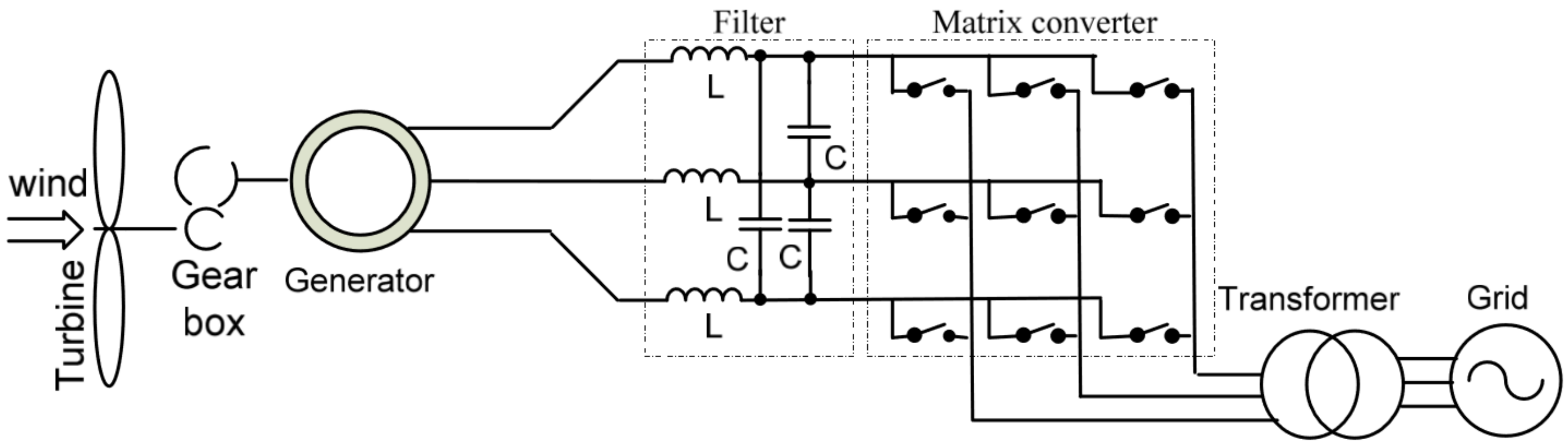
- Heavy, bulky DC link capacitor increases costs and reduces overall system life
- Switching losses: Each switch in the grid-side inverter and the generator-side converter between the upper and lower branch causes losses.
- The high switching speed to the grid may also require additional EMI filters.
- The combined control of the rectifier and the controlled inverter is quite complicated.

Co-funded by the Erasmus+ Programme of the European Union

Matrix converter

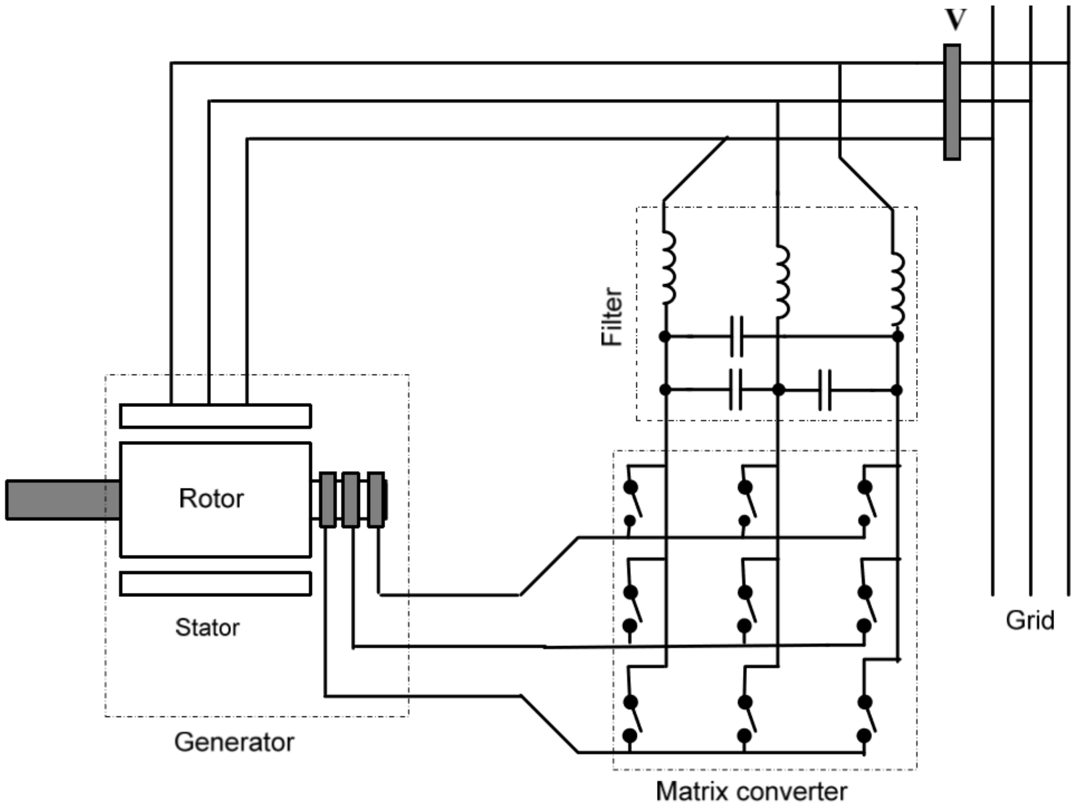
The matrix converter (MC) is a unique topology of the AC to AC power converter that eliminates the need for DC intermediate conversion and the passive reactive filter components associated with this DC link. This is a direct topology or with a single AC to AC conversion step. The converter consists of bidirectional switches positioned at the points of intersection of the input and output phases. The output is synthesized by selective closings and switch openings. A filter on the input side facilitates switching and prevents the harmonics generated by switching from propagating to the power input. MCs offer the possibility of considerably reducing the size and weight of power converters due to the absence of new energy storage elements, such as DC link capacitors. Compared to a conventional back-to-back converter, the MC is much smaller in size.

The THD coefficient of MC is much better than that of 'back to back' and diode rectifier based converters.



Wind Generator with Matrix converter

Due to its advantages over the back-to-back converter, the MC is currently replacing the back-to-back converter in DFIG wind turbine generator systems.



DFIG Wind Energy generator with Matrix converter

Co-funded by the
Erasmus+ Programme
of the European Union

Benefits:

- Matrix converters offer the potential for significant size and weight reductions in power converter applications due to the absence of large energy storage elements, such as DC-link capacitors.
- Although the matrix converter includes six additional power switches when compared to the back-to-back converter, the absence of the capacitor can increase the efficiency and service life of the converter.
- Depending on the design of the bi-directional switches, the switching losses of the matrix inverter can be lower than that of the back-to-back converter, because half of the switching becomes natural switching.
- They provide practically sinusoidal waveforms of input and output currents with low level of harmonics.
- The thermal stresses of the semiconductors in a matrix converter are lower than those of a conventional converter.
- The matrix converter is suitable for DC to AC energy conversion, which is an attractive solution for the adjustable speed wind generator, especially for the DFIGs.

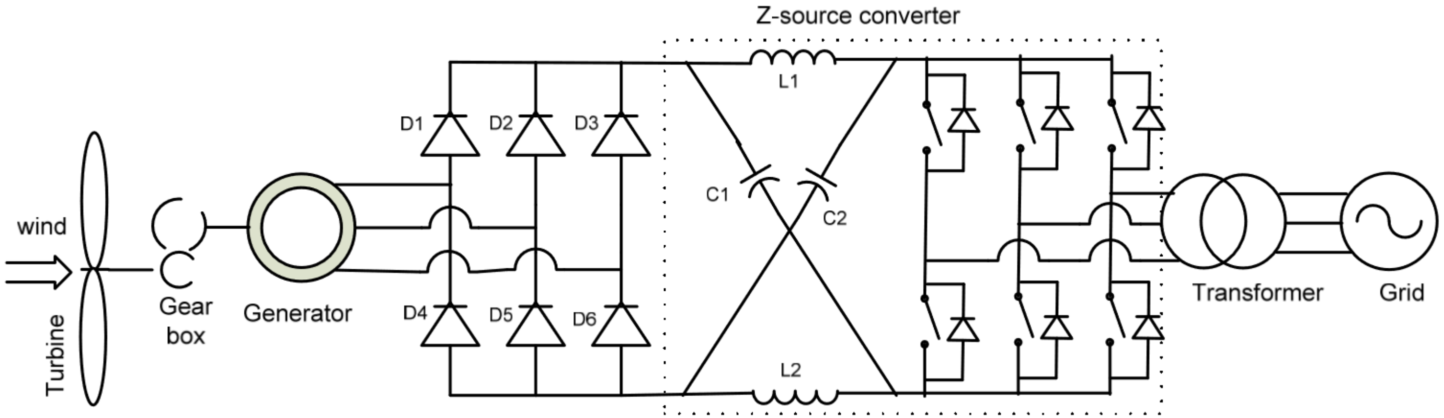
Disadvantages:

- The ad-link DC voltage cannot be increased like that of the back-to-back converter. Without entering the overmodulation range, the maximum output voltage of the matrix converter is 0.866 times the input voltage.
- To obtain the same output power as the back-to-back converter, the output current of the matrix converter must be 1.15 times higher, which results in higher line losses in the converter.
- Due to the absence of the DC link, there is no decoupling between the input and the output of the converter. In ideal terms, this is not a problem, but in the case of unbalanced or distorted input voltages, or unbalanced load, the input current and the output voltage also become distorted.
- The modulation technique and switching control are more complicated than those of the conventional PWM inverter.
- The protection of the matrix converter in a fault situation is not as good as that of the back-to-back converter.

Z-source converter

The impedance source or the energy converter powered by the impedance is abbreviated as Z-source converter. It can be used for implementing DC to DC, AC to DC, AC to AC and DC to AC energy conversions.

In this converter, a two-port network that consists of fractional inductors L1 and L2 and capacitors C1 and C2 connected in X form is used to provide an impedance source coupling the converter to the DC source, the load, or a other converter. The DC source or load can be either a voltage, or a source or current load. Therefore, the DC source can be a battery, a diode rectifier, a thyristor converter, a generator, an inductor, a capacitor, or a combination of the two.



Z-source converter for Wind Energy

Benefits:

- The output voltage can be any value between zero and infinite (buck and boost) regardless of the input voltage.
- It uses fewer components than conventional converters.
- Because of its ability to manipulate shooting states through its application is more reliable.
- It is cheaper and smaller the conventional converter (inductors and capacitors can be optimally designed).
- More effective than the others.

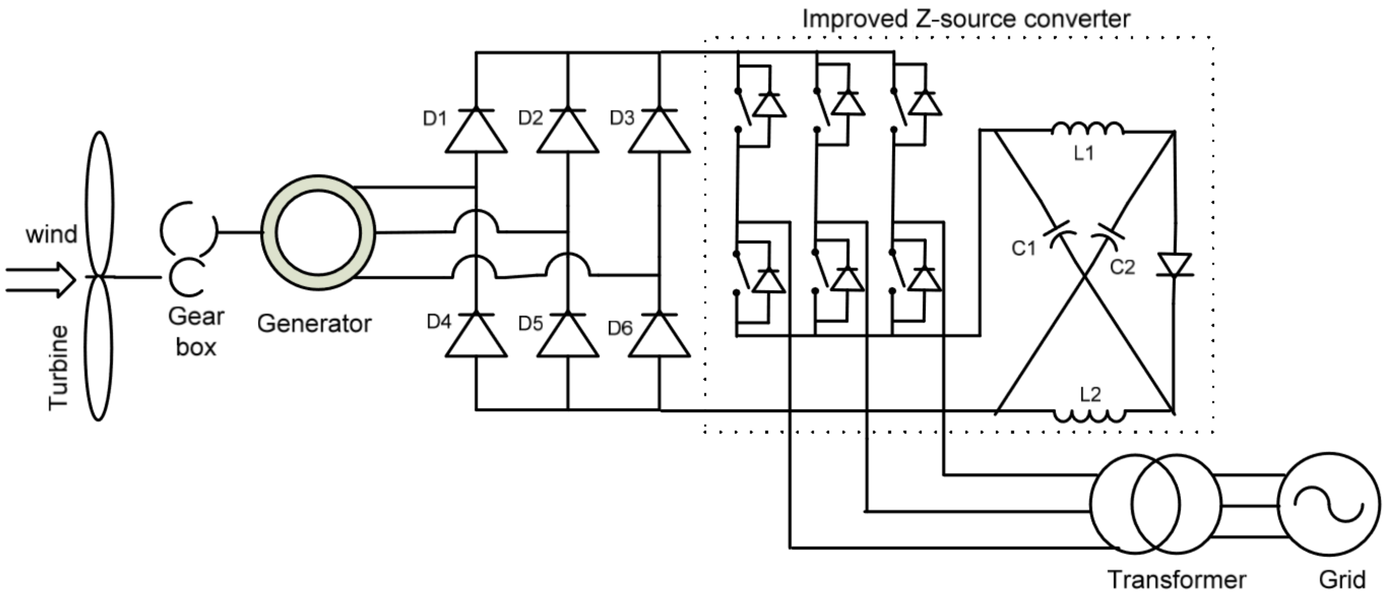
Disadvantages:

- To perform the voltage boost function for the source Z stage, the voltage of capacitor Z is greater than the input voltage. Thus, high voltage Z capacitors should be used, which can increase the volume and cost.
- The Z-source converter cannot suppress the precipitation current and the resonance between the Z capacitors and the Z inductors at start-up. This causes overvoltages and current surges and can destroy the device.
- It is intrinsically a unidirectional converter.

Co-funded by the Erasmus+ Programme of the European Union

Improved Z-source converter

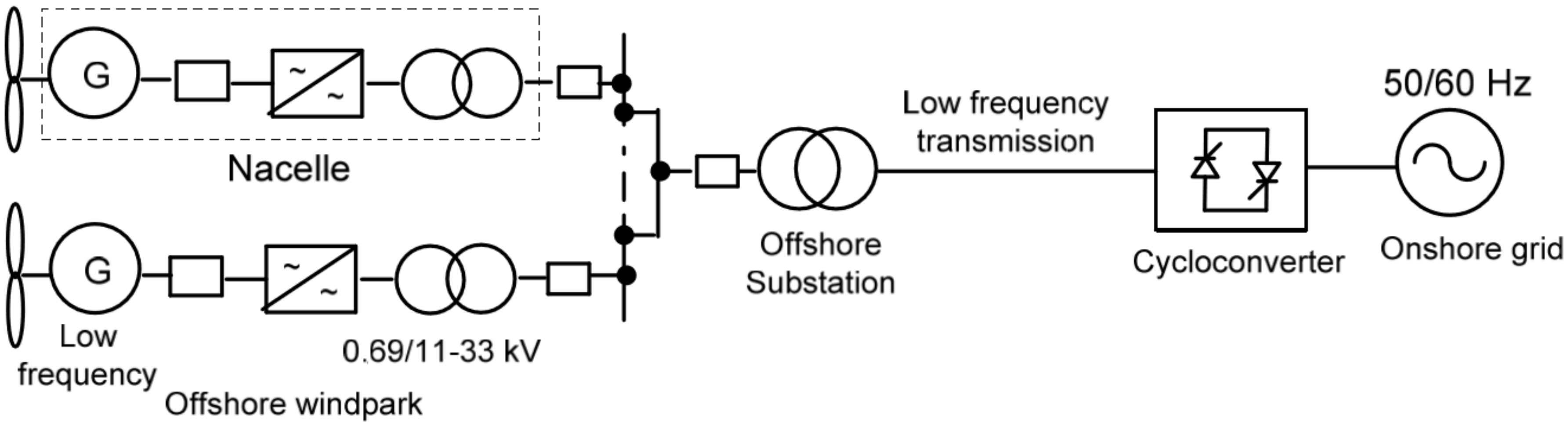
This improved z-source converter has all the features, but also overcomes the disadvantages of the Z-source converter. Exactly the same elements are used as in the Z-source converter, but the positions of the bridge and the diode of the converter are exchanged and their connection direction is reversed. Due to the voltage polarity of Z Zacators keeping the same as the input voltage polarity, the voltage stress of Z-capacitor can be greatly reduced and get the same push voltage across the converter bridge. In this system, there is no current path at startup, so it has inherent inrush current limiting ability.



Improved Z-source converter for power generation

Cycloconverter

Like the MC converter, the cycloconverter also converts AC to AC directly without using any DC-link intermediate capacitors. It is also called a frequency converter.
Cycloconverters are used for offshore wind farms because the investment cost of the low frequency transmission network for the offshore wind farm is less expensive than the HVDC system and the maintenance costs are also greatly reduced.
When generators are operated at lower frequencies, the system requires only an increasingly rapid cycloconverter at the end of the transmission line. If the generators operateat 50 Hz or 60 Hz, both ends require frequency converters.



Wind Energy Converter using cycloconverter

Benefits:

- Reduction of switching and conduction losses
- Bidirectional power flow capacity and
- The design of the power circuit is compact

Disadvantages:

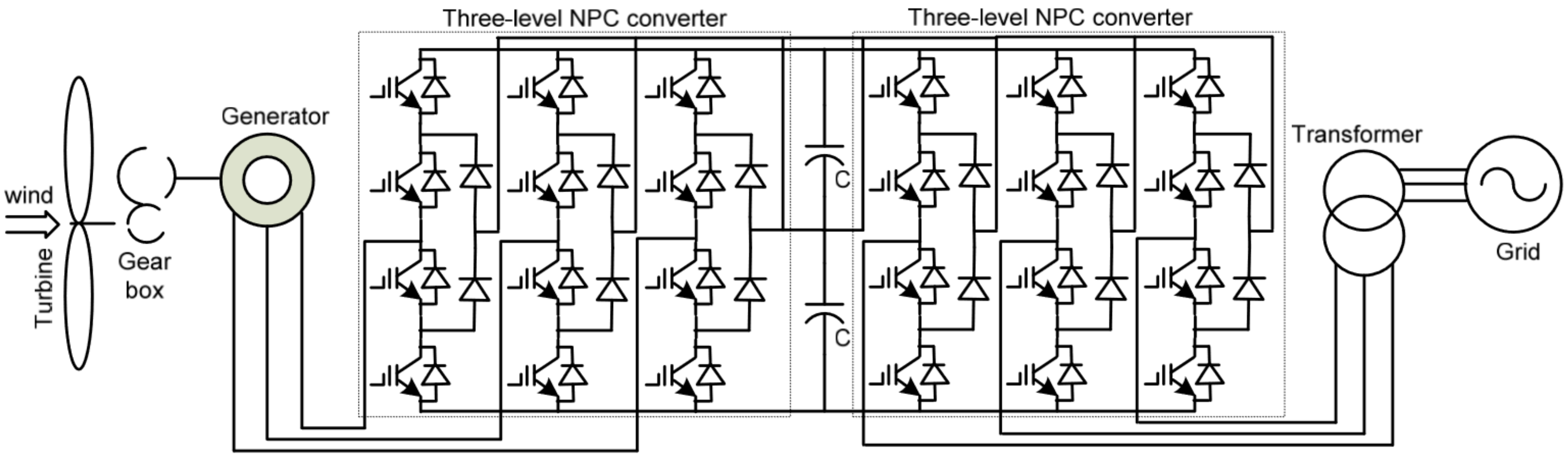
- There is an upper output frequency limit
- Poor input power factor
- Lower voltage transfer rate
- It requires complex control circuits

Multilevel converters

Co-funded by the Erasmus+ Programme of the European Union

The multi-level converter is an electronic power circuit which can be operated in inverter or rectifier mode.

In order to achieve high voltage using low voltage switching devices, the topology of the multilevel converter uses a series of switching devices with low voltage DC sources. Renewable energy sources: wind turbine generators, photovoltaic solar panels and fuel cells can be used as multiple voltage sources. Appropriate control of switching devices consists of superimposing these multiple DC sources in the form of a staircase in order to reach the high voltage at the output. Currently, there is a growing interest in multi-level power converters, especially for medium voltage applications. The topologies of neutral point converters (NPC), flying capacitor (FC) and H-bridge conversion converters (SCHB) connected in series are the three types of multilevel converters commonly practiced in high power and medium applications / high voltage



Neutral point clamped multilevel converter for wind energy

Co-funded by the Erasmus+ Programme of the European Union

Benefits:

- The main advantage of the multi-level converter is the ability to handle at high voltage.

- Lower switching losses and higher overall efficiency than others.

- Allows a reduction in the size of the filter elements, which affects the dynamic response of the converter.

Disadvantages:

- Requires a number of semiconductor devices, which increases the complexity of the control circuit.

- The voltage imbalance between the upper capacitor and the lower DC bus capacitor.

- Uneven stress on semiconductors.

Co-funded by the
Erasmus+ Programme
of the European Union

Conclusions

- The applications of electronic energy for wind turbine technology have been briefly explained.
- The applications of power electronics in various types of wind turbines show that the behavior of the wind turbine / performance is greatly improved.
- Power components are capable of facilitating frequency and voltage control through active and reactive power control.

Co-funded by the
Erasmus+ Programme
of the European Union

Recommended literature

Books

[1]. Lubosny, Z., Wind Turbine Operation in Electric Power Systems Advance Modeling, Berlin–Heidelberg: Springer, 2003, Hardcover, 259 pages. ISBN 3-540-40340-X.

[2]. Ackermann, T., Wind Power in Power Systems, John Wiley & Sons, Ltd., 2005. ISBN 0-470-85508-8.

[3]. Heier, S., Grid Integration of Wind Energy Conversion Systems, John Wiley & Sons, Ltd, 1998

Review articles:

[1]. ‘Working with Wind, Integrating Wind into the Power System’. IEEE Power and Energy Magazine, 3(6), November/December 2005.

[2]. Pepermans, G., Driesen, J., Haeseldonckx, D., Belmans, R. and D’haeseleer, W., ‘Distributed Generation: Definition, Benefits and Issues’. Energy Policy, 33(6), April 2005, 787–798. ISSN 0301-4215, DOI: 10.1016/j.enpol.2003.10.004.

[3]. Hansen, L.H., Madsen, P.H., Blaabjerg, F., Christensen, H.C., Lindhard, U. and Eskildsen, K., ‘Generators and Power Electronics Technology for Wind Turbines’. In Proceedings of IECON ‘01, Vol.3, 2001, pp. 2000–2005.

[4]. Petru,T.andThiringer,T.,‘Modellingofwindturbinesforpowersystemstudies’.IEEE TransactionsonPower Systems, 17 (4), November 2002, 1132–1139.

[5]. Hansen, L.H., Helle, L., Blaabjerg, F., Ritchie, E., Munk-Nielsen, S., Bindner, H., Sørensen, P. and Bak-Jensen, B., ‘Conceptual Survey of Generators and Power Electronics for Wind Turbines’, 2001, Risø-R-1205 (EN). ISBN 87-550-2745-8.

Co-funded by the Erasmus+ Programme of the European Union

Thank You for Your Attention!

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Contact: info@weset-project.eu weset.erasmusplus@uva.es

Co-funded by the
Erasmus+ Programme
of the European Union

Mechatronics in Wind conversion process

Module 2.3

Integration of Wind Energy into the power grid

Co-funded by the
Erasmus+ Programme
of the European Union

Objective

In this part of the course we will discuss the issues arising when integrating wind energy into the power grid, and the solutions.

Co-funded by the
Erasmus+ Programme
of the European Union

www.weset-project.eu

Learning Outcomes

At the end of this lesson the students will be able to :

O1• Understand the issues arising in the connection of wind turbines to the network grid.

02.Appreciate the development of design needs and innovation in the international market.

03. Present, discuss and argue grid connection technologies.

Co-funded by the Erasmus+ Programme of the European Union

Technical Contents

- Introduction : The connection of a wind turbine (WT) to the grid
- WTS Power configurations
- Grid Power Converter Topologies

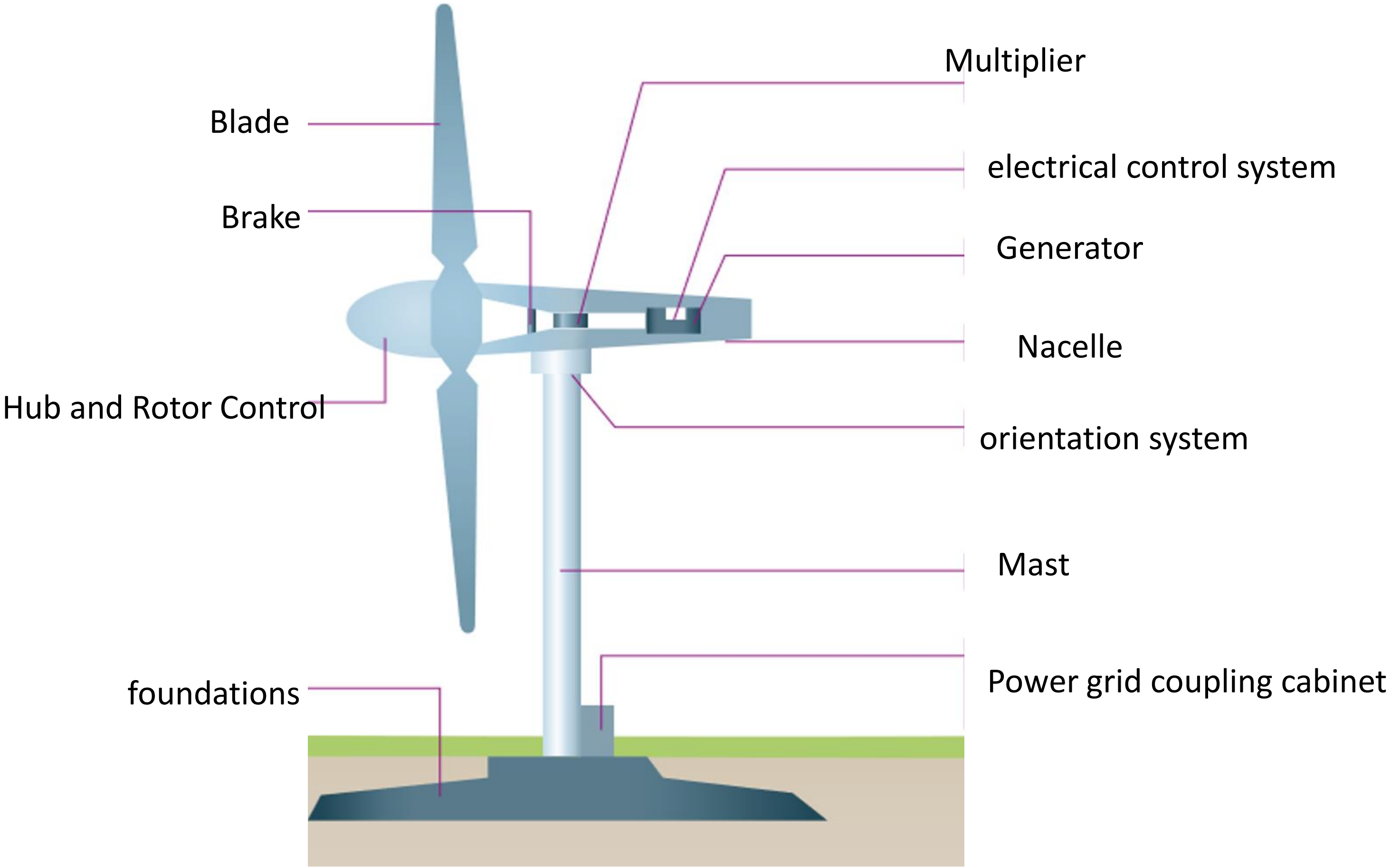
Co-funded by the
Erasmus+ Programme
of the European Union

Integration of wind energy into the electricity grid

Introduction

- The Electric System = matching production supply with consumption demand across a network.
- The demand is variable, even if it is foreseeable, there remains a stochastic aspect.
- To cope with the uncertainty of demand, the means of production must be controllable: control of the energy injected, supply of production program, rapid upward or downward modulation, ...
- Wind production is variable, inflexible (stop / start) and provides uncertain production programs.
- Wind production is not programmable and represents an additional hazard in the system

Co-funded by the
Erasmus+ Programme
of the European Union



Wind Generator

What are the problems to solve?

- Connection to the network (reception capacity, voltage quality, ...)

- _ The functioning of the electrical electrical system (resistance to faults,
participation in system services, reserve, ...)

- Electricity markets (planning of insertion of renewable energy, D-1 market, adjustment, ...)

What are the solutions for large-scale integration?

The solutions depend on the wind technology

Co-funded by the Erasmus+ Programme of the European Union

Wind Energy Technology

Growing Power

Fixed speed wind turbines

Variable speed wind turbines

- Asynchronous cage machine
- Synchronous machine with wound rotor
- Synchronous permanent magnet machine
- Double feed machine

Co-funded by the Erasmus+ Programme of the European Union

FIXED-SPEED WIND TURBINES

FIXED SPEED WIND TURBINES

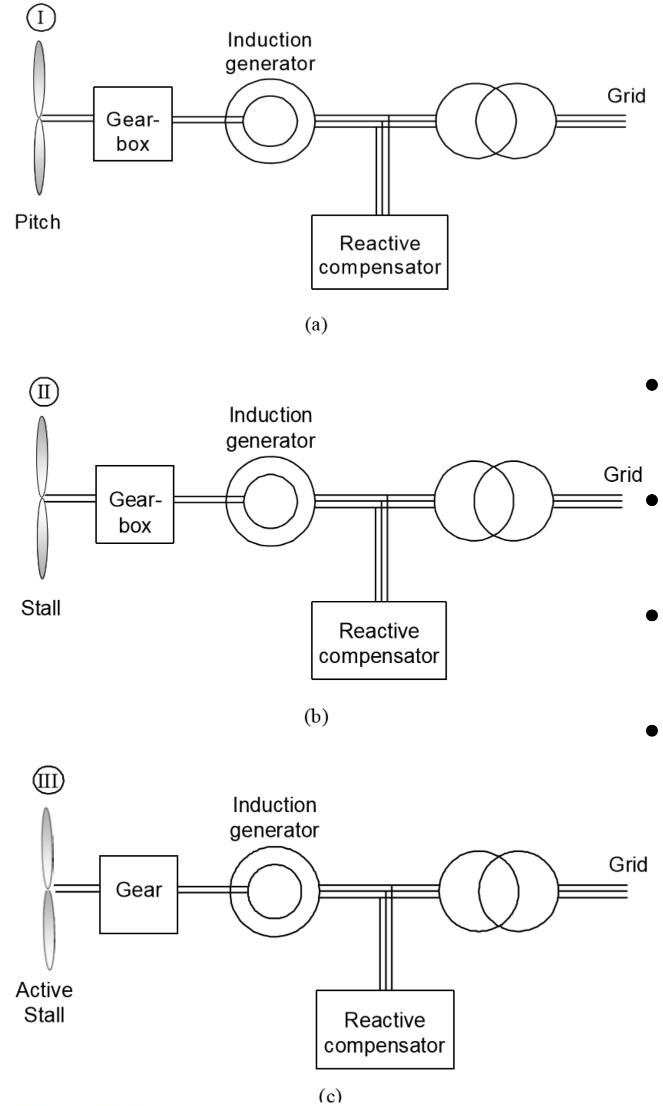
- The conversion of wind energy into mechanical power is done aerodynamically.
- It is important to be able to control and limit the mechanical power converted to a higher wind speed, because the power in the wind is a cube of the wind speed.
- The power limitation can be carried out either by the stall control (the position of the blade is fixed, but the wind stall appears along the blade at a higher wind speed), active stall (the angle of the blade is adjusted to create stall along the blades) or height control (the blades are oriented out of the wind at a higher wind speed).

Wind turbine technology can basically be divided into three categories:

1. systems without power electronics,
2. wind turbines with partially rated power electronics (small PE converter)
3. large-scale electronic power of interface wind systems (large PE converter).

Co-funded by the
Erasmus+ Programme
of the European Union

Wind turbine systems without power converter but with aerodynamic power control.

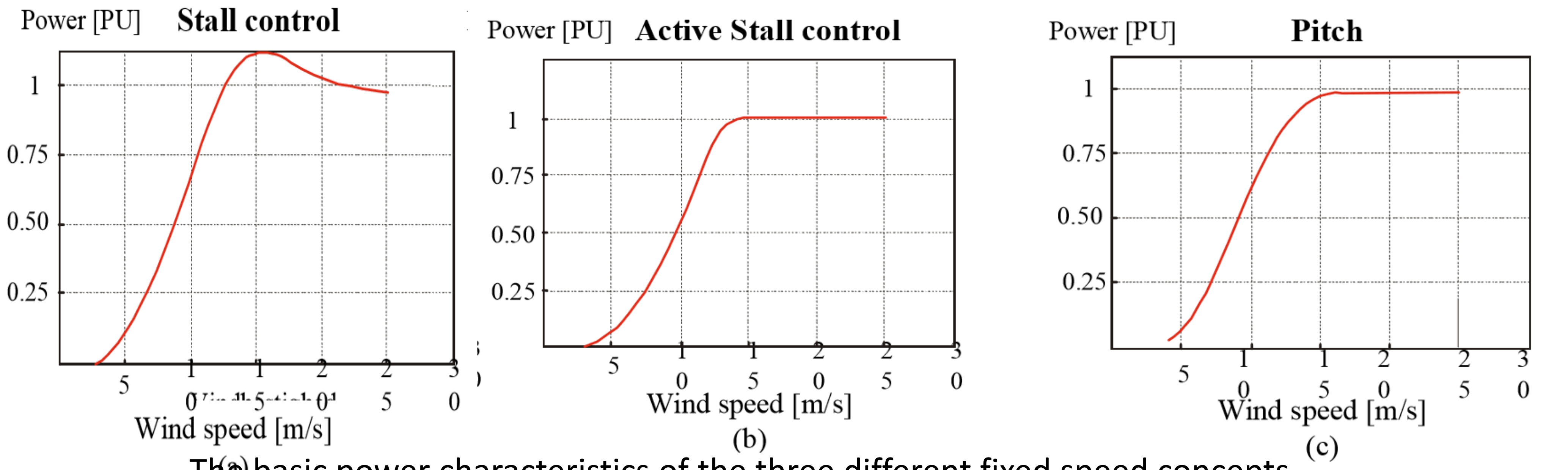


[BLA 06],

a) Controlled pitch (System I)
b) Controlled stall (System II)
c) Active controlled stall (System III)

- Wind turbine systems use induction generators, which operate almost independently of the variation of the torque at a fixed speed.
- The power is aerodynamically limited either by stall, active stall or by pitch control.
- All three systems use a soft starter to reduce the current of inrush and thus limit flicker problems on the grid.
- They also need a reactive energy compensator to reduce (almost eliminate) the demand for reactive energy from turbine generators to the grid. It is generally done by continuously changing the capacitor banks according to the production variation (5-25 steps)..

Co-funded by the Erasmus+ Programme of the European Union



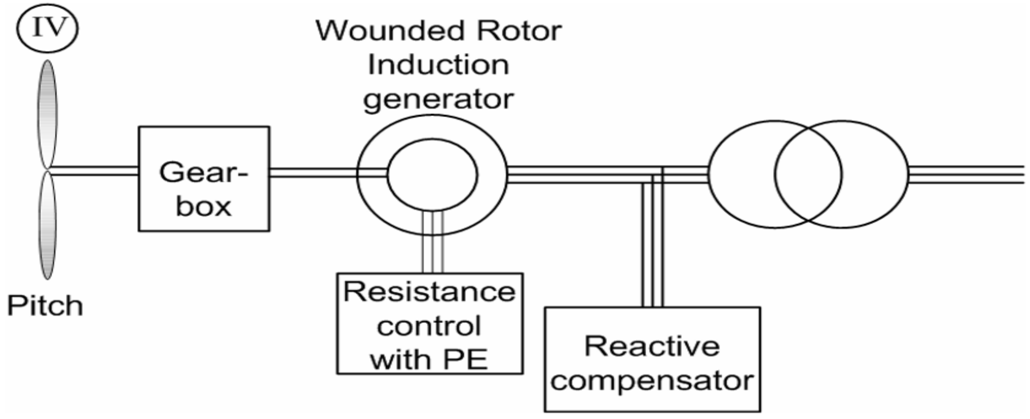
The basic power characteristics of the three different fixed speed concepts
a) Stall control b) Active stall control c) Pitch control

By turning the blades either by pitching or active stall control, it is possible to limit the power precisely while the power measured for the turbine controlled by stall shows a small go-around. It depends a lot on the final aerodynamic design.

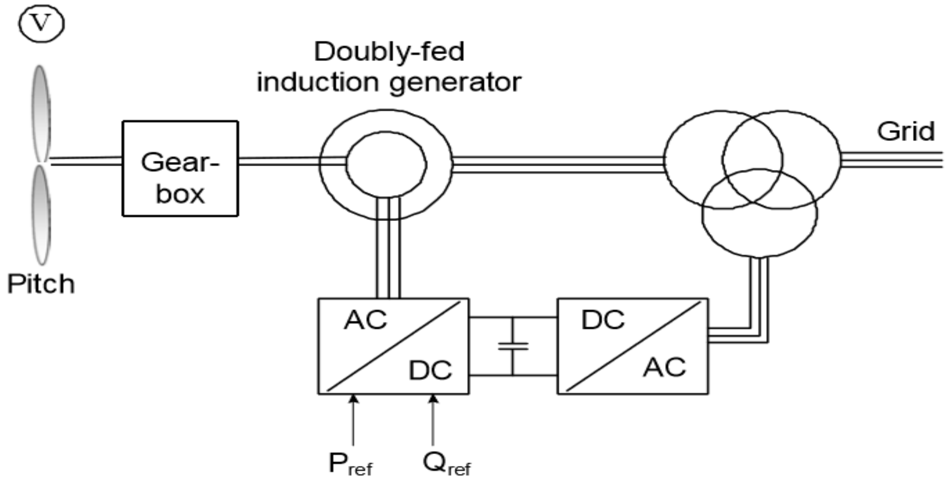
Co-funded by the Erasmus+ Programme of the European Union

VARIABLE SPEED WIND TURBINES

The next category is wind turbines with partially evaluated energy converters and thereby improved control performance can be obtained:



(a)



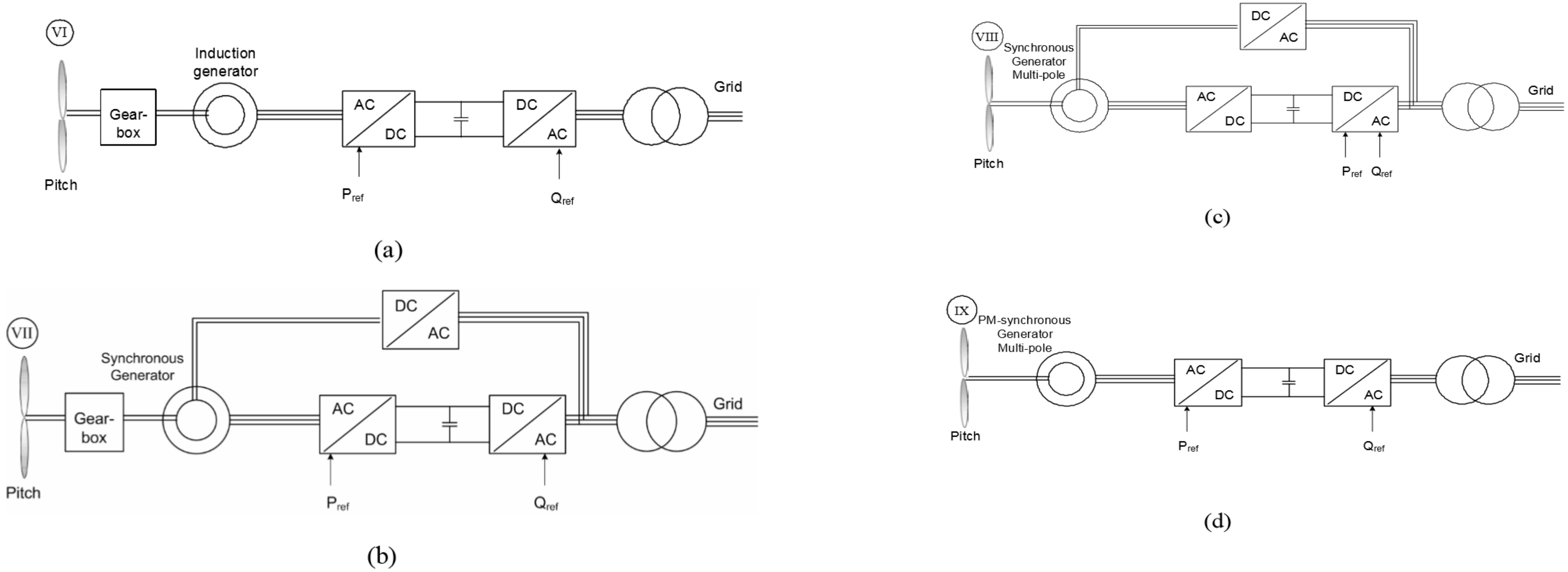
[BLA 06],

(b)

Wind turbine topologies with partially rated power electronics and limited speed range. a) Rotor resistance converter (system IV) b) Double-powered induction generator (system V)

Co-funded by the Erasmus+ Programme of the European Union

The third category is wind turbines with a large-scale energy converter between the generator and the grid, which are the ultimate solutions technically. It gives additional losses in power conversion, but it can be gained by additional technical performance. Four possible, but not exhaustive, solutions with full-size power converters:



[BLA 06],

Wind turbine systems with full-scale power converters. a) Induction generator with gear (System VI) b) Synchronous generator with gear (System VII) c) Multi-pole synchronous generator (System VIII) d) Multi-pole permanent magnet synchronous generator (System IX)

The solutions indicated in a) and b) are characterized by a gear. A synchronous generator solution shown in b needs a small power converter for field excitation.

Multi-pole systems with the synchronous generator without gears are indicated in c) and d).

The last solution is to use permanent magnets, which are still less and less expensive and therefore more attractive. The four solutions have the same controllable characteristics since the generator is decoupled from the network by a DC link.

The grid power converter allows the system to control active and reactive power very quickly. However, the negative side is a more complex system with more sensitive electronic parts

Co-funded by the Erasmus+ Programme of the European Union

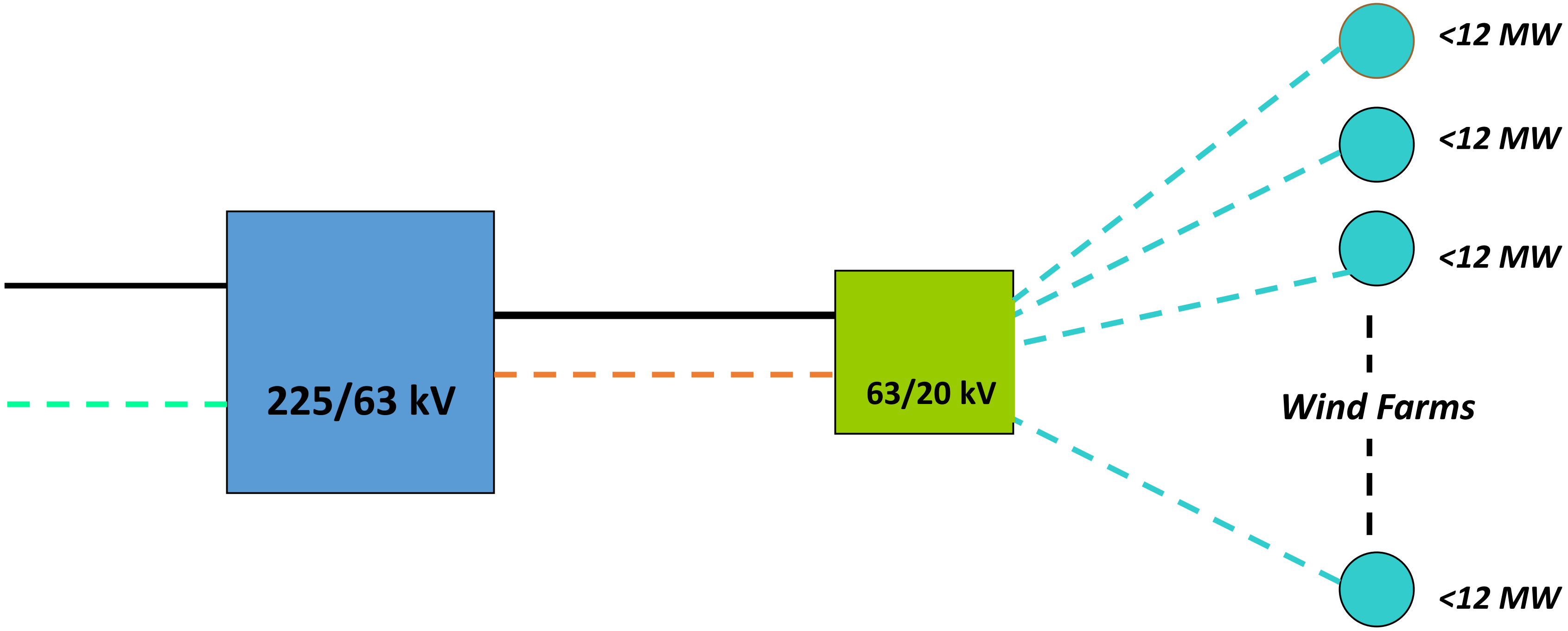
System comparison of wind turbines									
System	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**
Variable speed	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Control active power	Limite d	No	Limite d	Limite d	Yes	Yes	Yes	Yes	Yes
Control reactive power	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Short circuit (fault-active)	No	No	No	No	No/Ye s	Yes	Yes	Yes	Yes
Short circuit power	contribute	contribute	contribute	contribute	contribute	limit	limit	limit	limit
Control bandwidth	1-10 s	1-10 s	1-10 s	100 ms	1 ms	0.5-1 ms	0.5-1 ms	0.5-1 ms	0.5-1 ms
Standby function	No	No	No	No	Yes +	Yes ++	Yes ++	Yes ++	Yes ++
Flicker (sensitive)	Yes	Yes	Yes	Yes	No	No	No	No	No
Softstarter needed	Yes	Yes	Yes	Yes	No	No	No	No	No
Rolling capacity on grid	Yes, partly	No	Yes, partly	Yes, partly	Yes	Yes	Yes	Yes	Yes
Reactive compensator (C)	Yes	Yes	Yes	Yes	No	No	No	No	No
Island operation	No	No	No	No	Yes/N o	Yes/No	Yes/No	Yes/No	Yes
Investment	++	++	++	++	+	0	0	0	0
Maintenance	++	++	++	++	0	+	+	+	+

[BLA 06],

N.B Over 75% of all wind turbines sold are controlled by power electronics.

Co-funded by the Erasmus+ Programme of the European Union

Schematic of integration into power grid



Co-funded by the
Erasmus+ Programme
of the European Union

Grid operation

The network operator must ensure:

- production / consumption balance

- respect for transit in lines: dispatching;

- the quality of the electric wave.

Co-funded by the
Erasmus+ Programme
of the European Union

Connection of wind turbines and overall effects

<u>Global effects:</u>

- frequency adjustment problem
- network planning problem

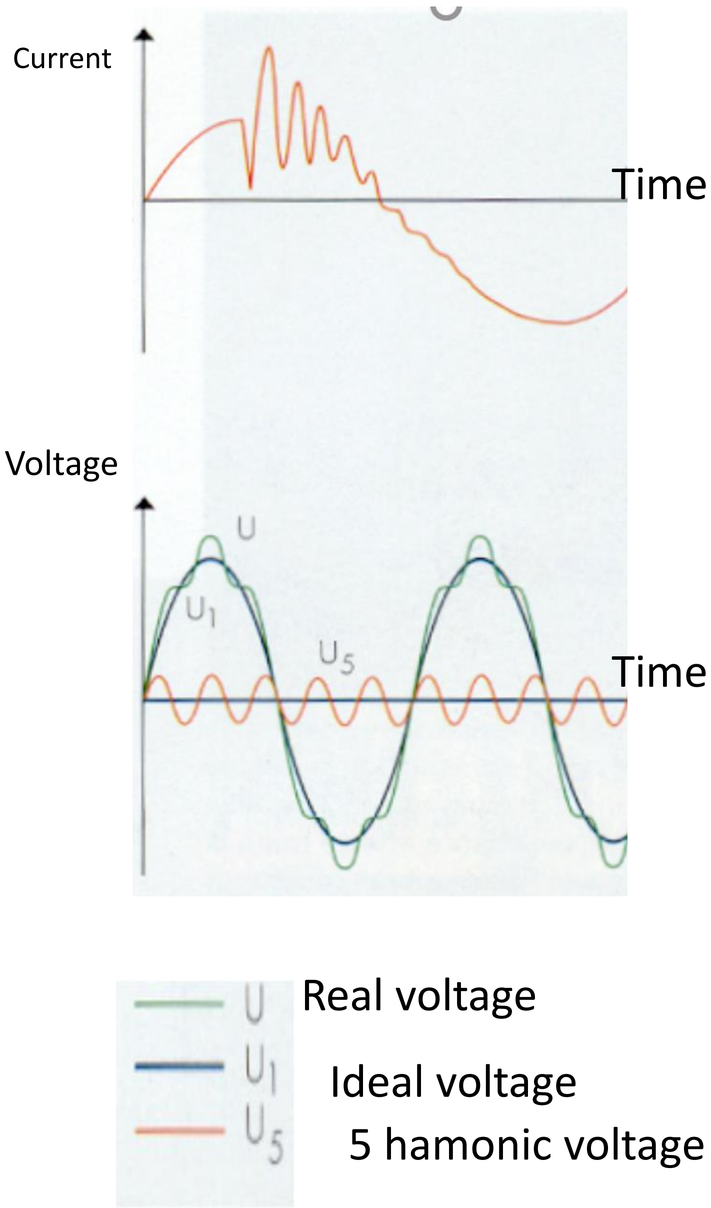
<u>Local effects:</u>

- voltage adjustment
- Use of technologies capable of regulating the voltage

Co-funded by the
Erasmus+ Programme
of the European Union

www.weset-project.eu

Connection of wind turbines



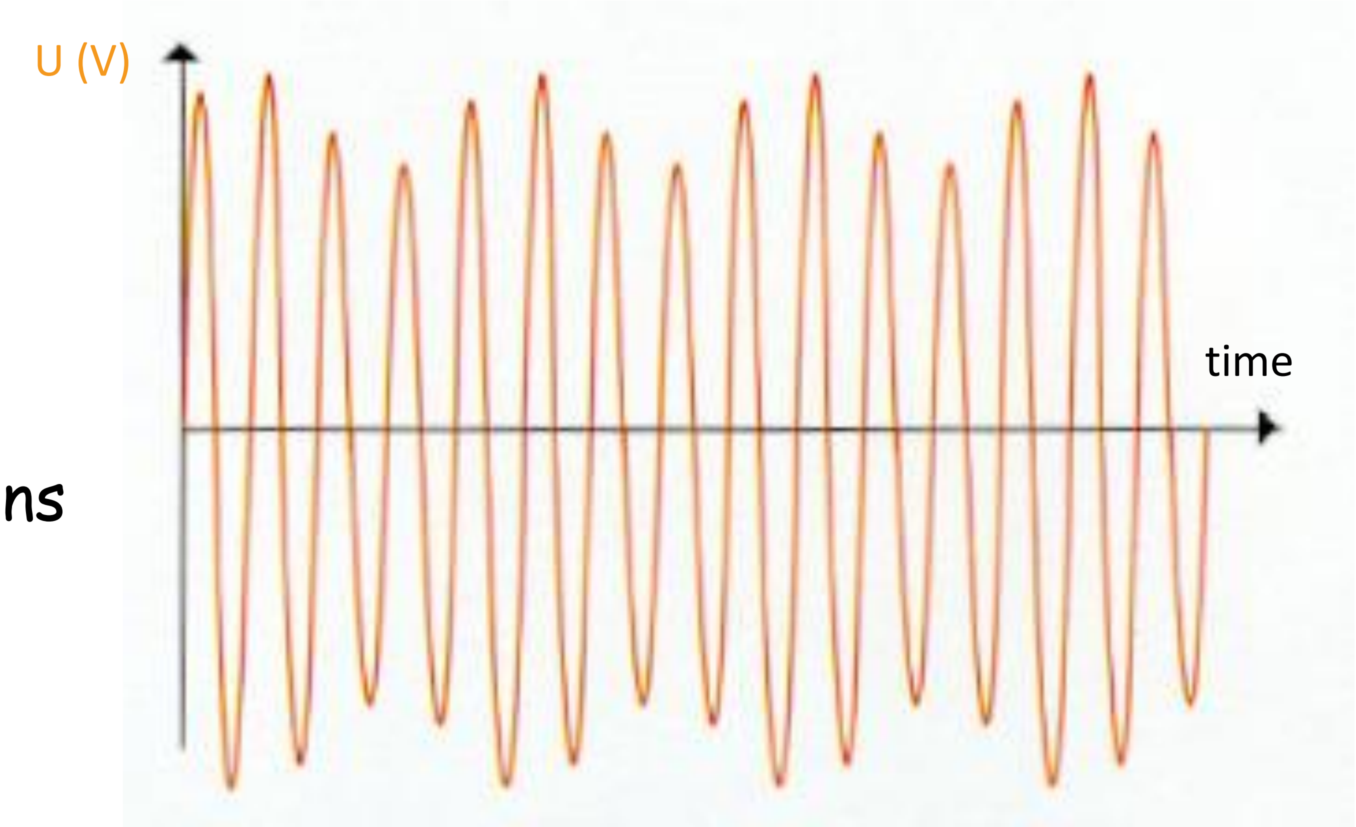
Voltage quality

- Resistance to short cuts: disconnection of the machine

- Harmonics: distort the wave

Co-funded by the Erasmus+ Programme of the European Union

Connection of wind turbines



Voltage quality

- Flicker: caused by periodic variations in the wind

Co-funded by the Erasmus+ Programme of the European Union

Which connection type?

All these problems mentioned have solutions, but they are costly

➯ Adopt a pragmatic approach: network reception capacity (without reinforcement): 5000MW

Solutions may appear in the short term:

- planning of the connection of wind turbines;
- power electronics.

5000MW threshold may increase

Co-funded by the
Erasmus+ Programme
of the European Union

Which connection type?

When short-term leads are exhausted, development of the wind industry conditioned by the emergence of certain solutions:

- forecasting tools;

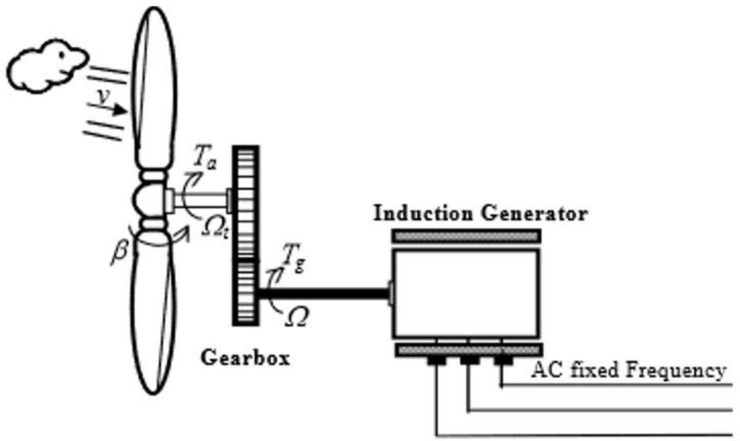
- energy storage

Co-funded by the
Erasmus+ Programme
of the European Union

Connection : Flicker

- Rapid change in voltage
- Depends on wind turbine technology

Wind turbine at fixed speed



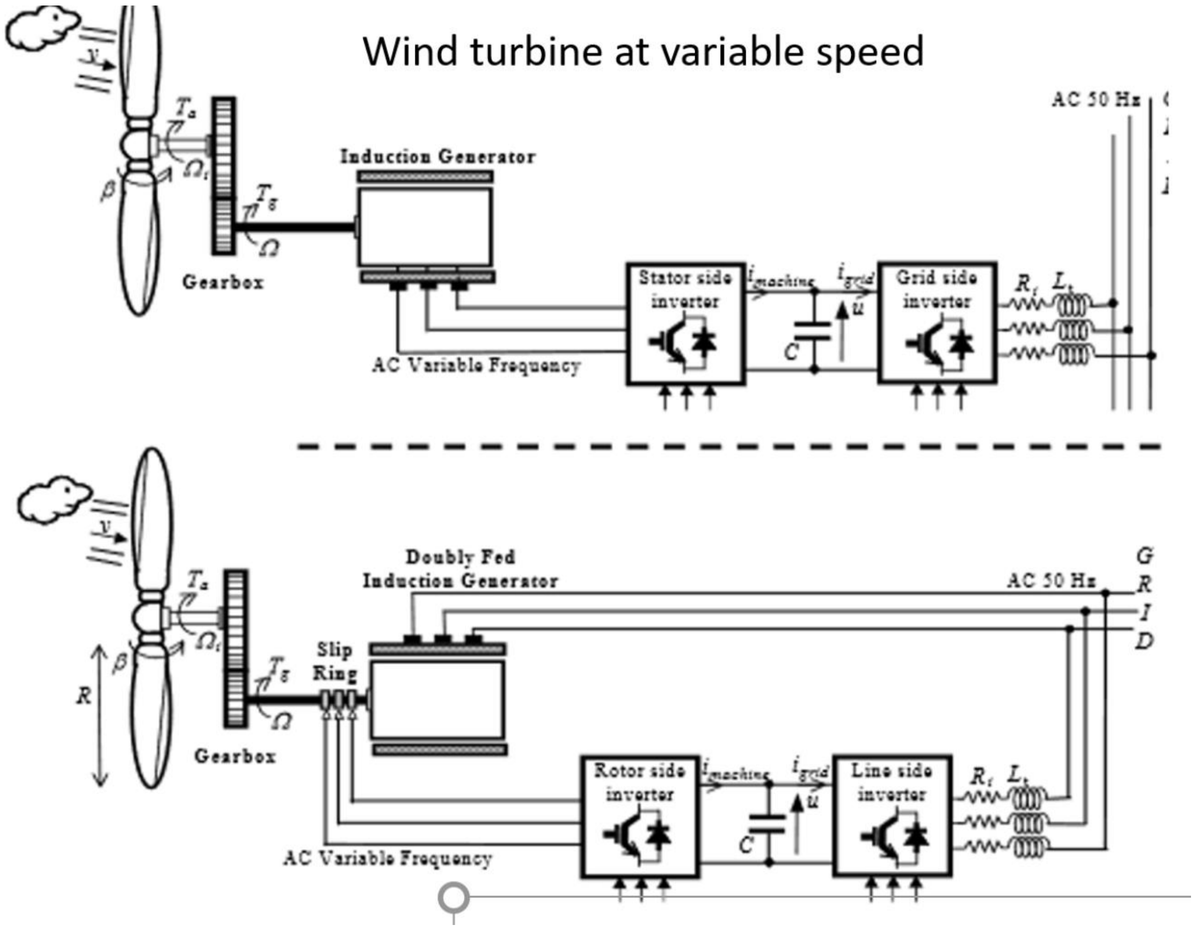
$$J\frac{d\Omega}{dt} = C_{electromecanique} - C_{pertes}$$

Direct transfer of changes in aerodynamic power on the grid

Co-funded by the
Erasmus+ Programme
of the European Union

Connection : Flicker example

Wind turbine at variable speed



No transfer if

-Continuous bus change

- control of average power (MPPT), blade orientation and machine control

No transfer if

-Voltage regulation

-Functioning of the network grid converter in D statcom

[B.ROB06],

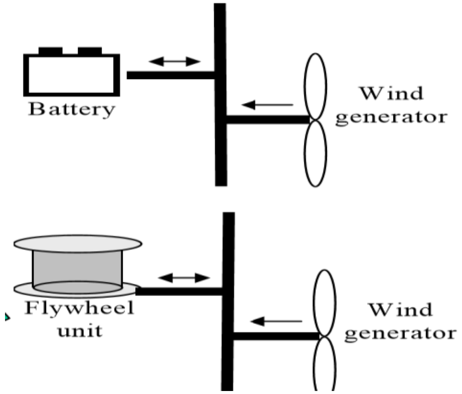
The control system has a great influence on rapid voltage variations

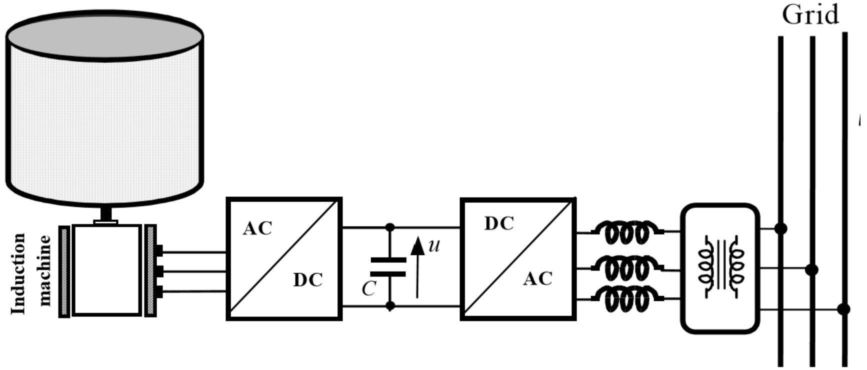
Co-funded by the Erasmus+ Programme of the European Union

Connection : Flicker

Solutions

Storage to compensate for power spikes:
-Batteries (aging)
-Flywheel unit





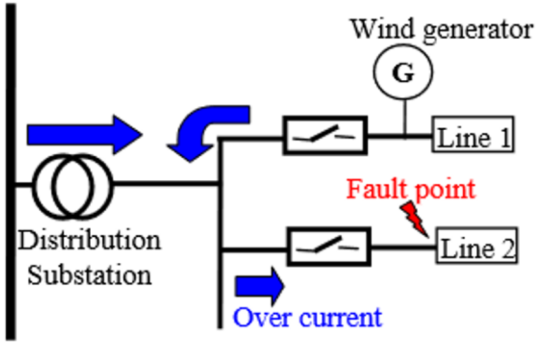
[B.ROB06],

Two advantages:
- Quick tension control
- Regulation of static law: Frequency/Power

Co-funded by the Erasmus+ Programme of the European Union

Connection: Protection plan

- The distribution networks are designed for a transfer of the electrical power of the transmission grid to the charges
- Influence in terms of quality of protection and safety
- A significant impact : Increased short-circuit current
- Example: The current during a defect is supplied by both the transmission grid and the wind turbine.
- If the current coming from the transmission grid decreases, the protection will not trigger and the defect will not be detected will persist because always powered by the wind turbine!

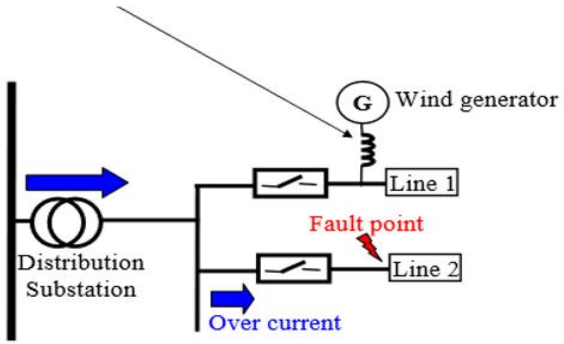


Co-funded by the
Erasmus+ Programme
of the European Union

Protection plan

- Special protection systems: Negative phase relay, Ground over-voltage relay

- External solutions :inductances that saturate to reduce the fault current



- Notes

-With variable speed wind turbines and therefore electronic power converters, the impact is reduced because the Command controls the currents generated and therefore limit them to the maximum value

How the system works

- **Wind penetration rate** seems limited to 20%
  Passive Generator

  - **To cope with variability**, 2 objectives :

    - Use wind turbines to increase power grid management opportunities

    - involve them in system services

  - **Technically**:

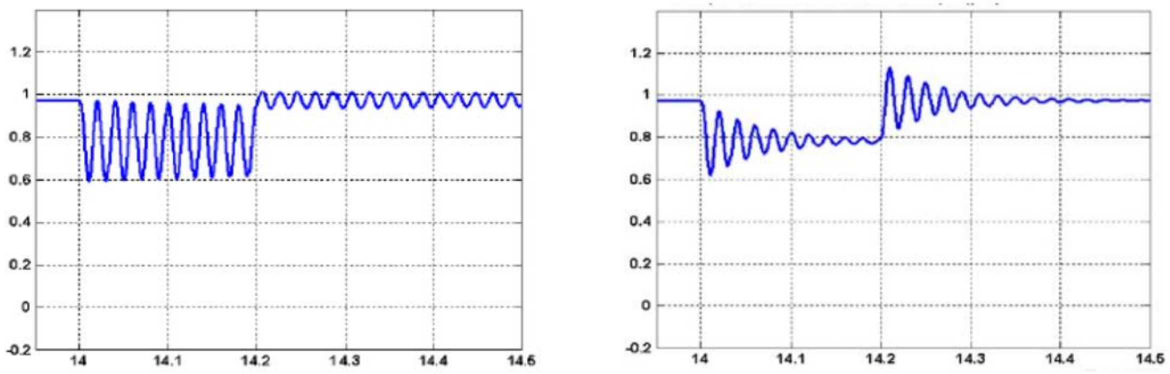
    - Defect Behavior
    - Additional Needs in Reserve
    - Participation in System Services
      - Voltage Adjustment
      - Frequency Adjustment

Co-funded by the Erasmus+ Programme of the European Union

Behaviour on voltage defects

- Thanks to power electronics and the control of active and reactive powers during the defect, wind technologies can hold these defects

- Example: Improved current stability generated by a GADA-based wind turbine by controlling the stator flux



(a) Synchronous approach (b) Asynchronous approach

Timing evolution of the stator flux [ELA 05]

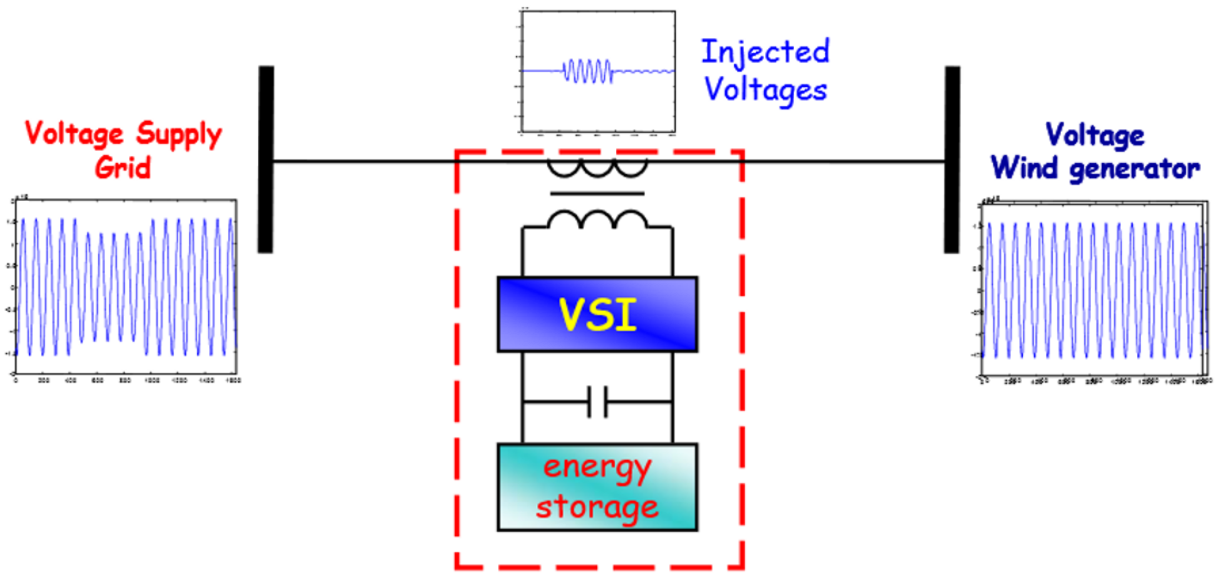
Co-funded by the Erasmus+ Programme of the European Union

www.weset-project.eu

Behaviour on voltage defects

- **External solutions**

Dynamic Voltage Restorer



[B.ROB06],

Co-funded by the
Erasmus+ Programme
of the European Union

Conclusions

Solutions for integrating wind into the system

Forecasting and driving system
A few hours, error of 3 to 5% of the installed power
• D-1, error of 5% of the installed power
•> 4D, error> 7.5% of the installed power
Interest, recalculate reserve margins

New sources of flexibility
1. 1.Coupling with other means of production look for complementarities in across markets (economic)
2. 2.Storage

New dedicated network architectures
1. Cluster micro grid
2. Continuous urban grid (eco-district)
3. Offshore high voltage continuous grid

Co-funded by the Erasmus+ Programme of the European Union

Recommended literature

Books

•1. S. Heier. Grid integration of wind energy conversion systems. 2nd Ed. John Wiley & Sons: W. Sussex, England, 2006. ISBN:0470868996.

• 2. Wind power in power systems. (Ed.) T. Ackermann. John Wiley & Sons: W. Sussex, England, 2006. ISBN: 9780470855089.

•3. J. D. Glover, M. S. Sarma, T. J. Overbye. Power system analysis and design. 5th Ed., CL Engineering, 2012. (ISBN: 1111425779)

Reviewed articles

[1]. [BLA 06],F. Blaabjerg, Z. Chen, R. Teodorescu, F. Iov « Power Electronics in Wind Turbine Systems » in IPEMC 2006

[2]. [ELA05],S. El Aimani, B. François, B. Robyns, F. Minne, « Modeling and Simulation of Doubly Fed Induction Generators for Variable Speed Wind Turbines integrated in a Distribution Network », Proceedings of the 10h European Conference on Power Electronics and Applications : EPE'2003, September 2 - 4, 2003, Toulouse (France), CD, ISBN 90- 75815-07-7.

[3]. [B.ROB06],B.Robyns, Arnaud Davigny &al. « Impact de l'éolien sur le réseau de transport et la qualité de l'énergie», June 2006,J3eA Vol. 5 – Hors Série 1-DOI: 10.1051/j3ea:20060028

Thank You for Your Attention!

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Contact: info@weset-project.eu weset.erasmusplus@uva.es

Co-funded by the
Erasmus+ Programme
of the European Union

www.weset-project.eu

Mechatronics in Wind conversion process

Module 3

Booklet about

Generators in wind turbines

Co-funded by the
Erasmus+ Programme
of the European Union

Objectives

This course presents Recalls on important concepts in wind energy conversion. This part is a prambule to the other lectures about power converters and Integration of Wind Energy into the power grid

Co-funded by the Erasmus+ Programme of the European Union

Contents

The wind turbine generator

1kw-Wind-Turbine-Generator-GL-PMG-15K

Generator converts mechanical energy into electrical energy

Wind turbine generators differ somewhat from other types of generators connecteded to the power grid. One of the reasons for this difference is that the generator of a wind turbine must be able to operating with a power source (i.e. the rotor of the wind turbine) that provides a mechanical power (a torque) very fluctuating

.

The voltage of the electric generation

On large wind turbines (above 100 to 150 kW), the voltage generated by the wind turbine is most often
a three-phase alternating current of 690 V (CA). The current is then driven through a transformer located right next to the wind turbine (or inside) to increase the voltage to approximately 10,000 to 30,000 V, depending on the standard of the local power grid. Major manufacturers supply both 50 Hz wind turbine models (for almost all of the world's power grids) and 60 Hz models (for the U.S. power grid).

The cooling system

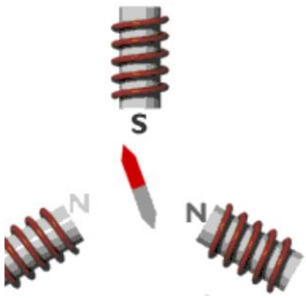
Generators need to be cooled when they are working. On most wind turbines, this cooling is ensured by coating the generator in a duct and installing a large fan in it that cools the air. However, there are a small number of wind turbine manufacturers who instead use water-cooled generators. These generators can be built more compactly, which has some electrical efficiency advantages, but at the same time require the installation of a radiator in the nacelle to get rid of heat from the liquid cooling system.

What design of the generator and which connection to the grid to choose?

A wind turbine can be built with a synchronous or asynchronous generator connected to the grid in several forms, directly or indirectly.
Direct connection to the network means that the generator is connected directly to the alternative current network (triphase in general).
Indirect connection to the grid means that the current produced by the wind turbine passes through a series of electrical devices adjusting the current to match that of the grid. With an asynchronous generator, such an adjustment takes place automatically.

The synchronous generator

Principles of three-phase generators



All three-phase generators use a rotating magnetic field.

Each electromagnet is connected to its own phase in a three-phase electrical grid, and alternately produces a south pole and a north pole towards the center. The fluctuation of magnetism corresponds exactly to that of the tension of each phase. When one of the three phases reaches its maximum, the current flows in the other two in the opposite direction and at half-voltage. As the current passing through each of the three magnets is always one-third of a period behind the previous one, the magnetic field will circle a whole cycle.

How a synchronous engine works ?

The magnetized needle (with the north pole marked in red) will follow the magnetic field very precisely, doing exactly one turn per cycle. In a 50 Hz grid, the needle will do 50 turns per second, i.e. 50 times 60 - 3,000 turns per minute.

We are in the presence of a bipolar synchronous engine with permanent magnet. If the engine is said to be synchronous, it is because the magnet in the center rotates at a constant speed that is synchronized with the rotation of the magnetic field.

It is said that the engine is permanent magnet because the compass needle in the center is a permanent magnet and not an electromagnet. You can build a real engine by replacing the compass needle with a strong permanent magnet, or by an electromagnet that maintains its magnetism through a coil (rolled around an iron core and fed direct current).

The construction with the three electromagnets is called the engine stator since part of the engine remains static, i.e. in the same place. If the compass needle is called the rotor, it is obviously because it rotates.

How a synchronous generator works ?

If the magnet is forced to turn (instead of letting the current from the electrical grid move it), we will see that it works like a generator, returning the electricity to the grid. (However, you need a stronger magnet to be able to generate a lot of electricity.) The greater the force (torque) used, the greater the power generation will be, although the generator continues to operate at exactly the same speed, determined by the frequency of the grid.

You can unplug it completely from the grid and create your own three-phase electrical grid by coupling light bulbs with three coils rolled around the electromagnets. However, if you disconnect the generator from the main network, it will have to rotate at a constant rotational speed to produce alternating current at a constant frequency. Therefore, with this type of generator, an indirect connection to the network will normally be used.

In practice, synchronous generators with permanent magnets are used very little. There are several reasons for this: first, permanent magnets tend to demagnetize when working in the powerful magnetic fields inside the generator. In addition, strong magnets (made from rare metals such as neodyms) are quite expensive, despite the recent price drop.

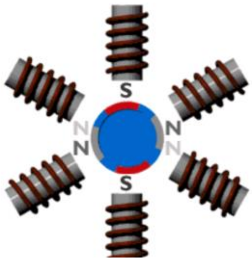
.

Wind turbines with synchronous generators

In the rotor of a wind turbine with a synchronous generator, electromagnets powered by direct current of the electrical grid are normally installed. Because the electrical grid provides alternating current, it must be converted into direct current before it is sent to the coils rolled around the rotor electromagnets.

The rotor electromagnets are connected to the current with brushes and collector rings attached to the generator shaft.

Change in generator rotation speed



The tetrapolar generator

The speed of a generator (or engine) connected directly to a three-phase grid is constant and determined by the frequency of the network.

However, by doubling the number of magnets placed in the stator, you can make the magnetic field spin at half speed.

This generator (or engine) has four poles at any given time, two south poles and two north poles. Since a tetrapolar generator runs only one U-turn per cycle, it will do 25 turns per second (or 1,500 laps per minute) if connected to a 50 Hz grid.

By doubling the number of stator poles of a synchronous generator, we also need to double the number of rotor magnets. Otherwise the poles will not go well together. (In this case, we could use two horseshoe-shaped magnets).

Other pole numbers

It is obviously possible to redo what we have just done and introduce another pair of poles by installing three more electromagnets in the rotor. With 9 magnets, we will have a 6-pole machine that will run at 1,000 rpm in a grid at 50 Hz. The overall results will be:

Different speeds of a synchronous generator (rpm)

Number of poles	**50Hz**	**60Hz**
2	**3000**	**3600**
4	**1500**	**1800**
6	**750**	**900**
8	**600**	**720**
12	**500**	**600**

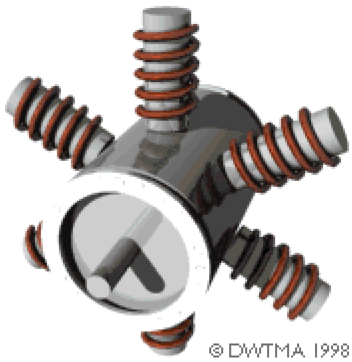
The term "synchronous generator speed" refers to the speed of the generator when it rotates in sync with the frequency of the network. The table is therefore valid for virtually all types of generators. However, in the case of asynchronous (induction) generators, the table figures correspond to the speed when the generator is running empty).

Low- and high-speed generators

The majority of wind turbines are equipped with generators of 4 to 6 poles. The advantages of relatively high-speed generators are the savings they provide, both in size and cost.

The maximum torque a generator can handle depends on the volume of its rotor. For a given output power, you have to choose between a large and fairly expensive generator at low speed, and a smaller (and cheaper) generator at high speeds.

The asynchronous generator (induction generator)

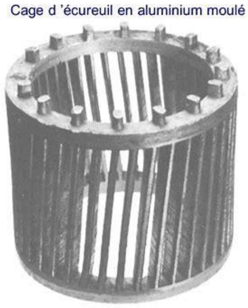


Most wind turbines in the world use a three-phase (squirrel) asynchronous (squirrel) generator, also known as an induction generator, to produce alternating current. In fact, this type of generator is very rarely used, except in the wind industry and in small hydropower plants. Notwithstanding, we have a pretty good knowledge of this technique.

The curious fact of this type of generator is that it was originally designed as an electric motor. In fact, one-third of the world's electricity consumption is used to operate induction engines that operate machines, pumps, fans, compressors, elevators and other types of equipment requiring the conversion of electrical energy into mechanical energy.

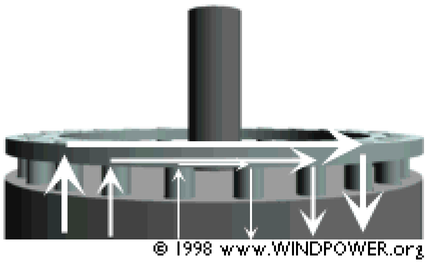
One advantage of this generator is that it is very reliable and relatively inexpensive compared to other types of generators. It also has some mechanical characteristics that makes it very suitable for the conversion of wind energy (sliding the generater) as well as some overload capacity).

Squirrel cage rotor



It is actually the rotor that distinguishes the asynchronous generator from the synchronous generator. The rotor has a number of copper and aluminum bars electrically connected by two aluminum circles at both ends.

In the image at the top of the page, you see the rotor with an iron core that has several thin steel blades insulated with holes for the aluminum conductor bars. The rotor is placed in the center of the stator which, also in this case, is a four-pole stator connected directly to the three phases of the electrical grid.



How the motor works ?

When the current is connected, the machine begins to rotate like an engine, at a speed slightly below the synchronous speed of the rotating magnetic field produced by the stator. How is it done?

If we look at the rotor bars shown above, we have a rotating magnetic field that moves in relation to the rotor. This magnetic field induces a strong current in the rotor bars, which, being short-circuited by the two circles at their ends, offer very little resistance to the current.

The rotor thus creates its own magnetic poles which are in turn driven by the electromagnetic force from the rotating magnetic field of the stator.

How the generator works ?

What happens if you manually turn the rotor at exactly the synchronous speed of the generator, at, say, 1,500 laps per minute, as was the case with the tetrapolar synchronous generator on the previous page? The answer is simple: nothing! As the magnetic field rotates at exactly the same speed as the rotor, there will be no induction in the rotor, so there will be no interaction between the rotor and the stator.

On the other hand, if we exceed the speed of 1,500 rpm, the rotor will rotate at a speed greater than that of the rotating magnetic field, which means that the stator begins to induce a strong current in the rotor. The faster we rotate the rotor, the greater the power transferred as an electromagnetic force to the stator and then converted into electricity.

Generator slip

The speed of an asynchronous generator varies depending on the torque of rotation applied to it. In practice, the difference between the rotation speed at maximum and empty power is very small, about 1%. This difference expressed as a percentage of synchronous speed is also called generator sliding. Thus, a tetrapolar generator will make 1,500 rpm empty if it is connected to an electrical grid at 50 Hz. If the generator is running at its maximum power, it will run at 1,515 rpm.
The fact that the generator increases or decreases its speed slightly depending on the variations in torque, is a very useful mechanical feature, mainly because it reduces the wear of the multiplier (due to a reduction in maximum torque). This is one of the most important assets related to the choice of an asynchronous generator instead of a synchronous generator for a wind turbine connected directly to the electrical grid.

Automatic adjustment of the rotor poles

Did you observe that we did not indicate the number of poles in the stator when we described the rotor? What gives the cage rotor its finesse is that it automatically adapts to the number of poles of the stator. The same rotor can therefore be used with a wide variety of number of poles.

Need for a grid connection

The permanent magnet synchronous generater can operate without being connected to the electrical grid.

The same is not true for the asynchronous generator, as its stator needs to be powered by current to create the magnetic field needed for the generator to run.

However, it is possible to operate an asynchronous generator in a stand-alone system, if it has been equipped with capacitors providing the current needed for magnetization. This solution also requires some remanence in the rotor iron, i.e. some remaining magnetism, used for the start of the wind turbine. Otherwise you will need a battery and power electronics - or a small diesel generator - to start the system.

Changing the number of generator poles

It seems logical to believe that a stator containing twice as many magnets costs twice as much. However, this is not the case. In any case, as you can see from the picture, generators (and motors) are normally designed with a large number of magnets in the stator.

The stator is designed to minimize the air breach between the rotor and the stator. At the same time, it is necessary to ensure the cooling of the magnets. In reality, the iron of the stator consists of a large number of thin insulated steel blades (0.5 mm thick) that are assembled to form the stator. This provision prevents the reduction of the efficiency of the generator as a result of the Currents of Foucault caused in the iron of the stator.

The problem of increasing the number of poles of a squirrel cage asynchronous generator is actually limited to the connection of the nearby magnets, a connection that can be achieved in two different ways: either we take one group of magnets at a time, connecting them to the same phase as we move into the stator , or we change to the next phase, every time we arrive at a new magnet.

Generator with variable poles that can operate at two speeds

Some builders equip their wind turbines with two generators, one small for periods of low winds and one large for those of strong winds.

However, it is more common to equip modern wind turbines with a generator with a variable number of poles, i.e. a generator that (depending on the connection form of the stator magnets) can operate with different numbers of poles, and therefore at a variable rotation speed.

Generators are sometimes built on a "two-in-one" basis, allowing them to operate alternately as e.g. a 400 kW generator or a 2000 kW generator, and at two different speeds. This design is increasingly being used by wind turbine manufacturers.

Whether or not it is worth using a dual generator or more poles for low winds depends on the distribution of winds at the site in question, and the additional price of variable pole generator compared to the price the owner of the wind turbine can get for the electricity produced (you have to take into account that the energy content of the low winds is not very high).

However, a good reason for choosing the dual generator system is that it allows the wind turbine to rotate at a low rotational speed during periods of low wind. This improves efficiency from an aerodynamic point of view, while reducing the nuisance caused by rotor blades (which is usually only a problem at low wind speeds).

It is not impossible that - unknowingly - you have already seen several engines with variable numbers of poles at home: in general, washing machines able to centrifuge clothes are equipped with motors with variable poles allowing them to wash laundry at a low speed and centrifuge it at a high speed. Similarly, kitchen hoods are often designed to work two or three different speeds (in the case of a multi-speed kitchen hood, you can use the knowledge you have gained about wind energy: if you want to get twice as much air out of your kitchen per minute, it will cost you eight times more electricity).

The variable-slip generator

For many years, electric motor manufacturers have had to deal with the problem that their engines are only fit to operate at a certain number of fixed speeds determined by the number of engine poles.

As we saw on the previous page, the sliding of the engine (or generator) into an asynchronous (induction) machine is normally very small for efficiency reasons, which means that the change in the speed of rotation between the empty and full load is around 1%.

Sliding, however, is a function of the resistance (measured in ohms) in the coils of the generator rotor: the greater the resistance, the greater the slippage. Therefore, the slippage can be varied by varying the strength of the rotor. In this way, it is possible to increase the sliding of the generator to e.g. 10 %.

On engines, this is normally achieved by the use of a coiled rotor, i.e. a rotor wrapped in copper wires coupled with stars and connected to external variable rheostats, in addition to an electronic control system designed to operate rheostats. The coupling is normally done with brushes and drive rings, which is a clear drawback compared to the simple and elegant design of the squirrel cage rotors. This technique also involves the use of components that wear out in the generator - so it needs more maintenance than normal.

Opti Slip

An interesting variant of the variable-slip asynchronous generator avoids the use of drive rings and brushes - and thus the additional maintenance problem.

By placing the external rheostats - as well as the control system - on the rotor itself, there is always the question of how to communicate to the rotor the necessary amount of slippage. This communication can be performed in a very elegant way by using optical fibers to emit a signal through the rotor electronics, each time it passes in front of a fixed optical fiber.

How a wind turbine works at variable speeds and steps

There are several advantages associated with the use of a variable-speed wind turbine.

A good reason to be able to operate a wind turbine at varying speeds is the mechanical process of the blade variable-stall control system the blade-based control system (torque control to avoid overloading the multiplier and generator by rotating the turbine's blades). This means that the reaction time of the stalling mechanism becomes a critical factor in the design of the wind turbine.

However, if you have a variable-slip generator, you can start increasing the slide as soon as it approaches its rated power. The control strategy applied by one of the major Danish manufacturers is to operate the generator at half its maximum slide when it is close to reaching its rated power. In the event of a gust, the device control indicates that the rotor slide must be increased to allow for a slight increase in rotor speed until the timing mechanism has rotated the blades slightly out of the wind. As soon as the stalling mechanism has completed its work, the slip can be reduced again. In the event of a sudden decrease in wind speed, the same process is applied in reverse.

While these concepts may seem fairly simple at first glance, ensuring that the two power control mechanisms cooperate effectively is a real technical challenge.

Improved power quality

It can be argued that a generator operating with a high slip will have increased heat production, making it less efficient than a generator with less slippage. This is not a problem in itself, however, as the only alternative is to lose the extra energy of the wind by rotating the blades out of the wind.

One of the real advantages of the control strategy we have just described is that you will get a better quality of power, since fluctuations in output power are absorbed or compensated by the variation in the sliding of the generator and by the storage or release of some of the energy in the form of rotating energy in the rotor of the wind turbine.

Indirect connection to the power grid

Variable frequency alternating current (AC) production

Most wind turbines operate at near-constant speeds with direct connection to the grid. However, if it is indirectly connected to the grid, the wind turbine operates in its own small separate network at AC, as you can see in the image above. This network is controlled electronically (by the use of an inverter) to allow the variation of the frequency of the alternating current in the generator stator. Thus, it is possible to operate a wind turbine at a variable rotation speed, which means that the wind turbine produces alternating current at exactly the same variable frequency as that applicable to the stator.

The generator can be either synchronous or asynchronous. Similarly, the wind turbine is often equipped with a multiplier, just as is the case in the image above. Although its generator has many poles as explained on the next page, it can still work without a multiplier.

Direct current conversion (CC)

The variable-frequency alternating current is not usable in the public power grid. Therefore, it must first be converted into a dc. Variable-frequency CA conversion to CC is achieved by the use of thyristors and large power transistors.

Conversion to fixed-frequency alternating current

We then convert the direct current (fluctuating) into an alternating current at exactly the same frequency as that of the electrical grid (through the use of a transformer). The same conversion can also be achieved using thyristors or transistors.

Thyristors or transistors are large semiconductor switches that operate without mechanical parts. The alternating current obtained by a transformer looks quite deformed at first glance, not resembling at all the soft sinusoidal curve on the page on the alternating current. Instead, we get a whole series of sudden fluctuations in both voltage and current.

Alternate current filtering

However, rectangular-shaped waves can be mitigated by using appropriate inductions and capacitors forming a so-called alternating current filtering mechanism. As explained below, however, filtering does not completely erase the chipped appearance of the voltage curve.

Benefits of indirect grid connection: variable speed

The main advantage of an indirect connection to the grid is that it allows the wind turbine to operate at a variable speed. Thus, it is possible to increase the rotational speed of the rotor during gusts, while storing the additional energy in the form of rotating energy until the end of the gust. This obviously requires a very intelligent control system that is able to distinguish between a real gust and simply high wind speeds. In this way, the maximum torque (reducing the wear of the multiplier and generator) and the fatigue loads of the tower and rotor blades can be reduced.

Another advantage is the ability to control reactive power (i.e. shifting the current from voltage in the alternating current network), thus improving the power quality of the power grid. This can be very useful, especially in the case of a wind turbine connected to a weak power grid.

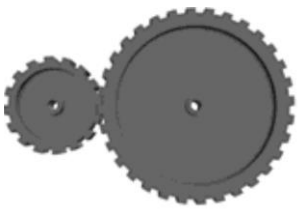
In theory, variable speed can also have a slight advantage in terms of annual production, as it allows a wind turbine to operate at the optimum speed of rotation depending on wind speed. However, from an economic point of view, the benefit thus obtained is so negligible that it does not even deserve to be mentioned.

Cons of indirect connection to the grid

The main drawback of indirect connection to the network is its cost. As we have just learned, the wind turbine will need a grinder and two inverters, one to control the current of the stator, and another to produce the output current. Currently, it appears that the price of power electronics exceeds the gains associated with the construction of lighter wind turbines, but it is possible that this trend will change as the price of power electronics decreases. Statistics on the operation of wind turbines using power electronics (published by the German institute ISET) also indicate that the availability of these machines is somewhat lower than that of conventional machines, due to power electronics failures.

Other drawbacks are the loss of energy during the CA-CC-CA conversion process as well as the harmonic distortion of the alternating current that power electronics can introduce into the electrical grid. A harmonic distortion occurs when the filtering process mentioned above is imperfect, leaving some harmonic sounds (multiple of network frequency) in the output current.

The wind turbine multiplier



Why use a multiplier?

The power produced by the rotor rotation of a wind turbine is transmitted to the generator through a whole dynamic chain, i.e. by the slow shaft, the multiplier and the fast shaft, just as we saw on the page citing the main components of a wind turbine.

But why, in fact, use a multiplier? Is it not possible to drive the generator directly by the power produced by the slow tree?

If we used a regular generator, connected directly to a CA network (alternative current) at 50 Hz and three phases with two, four or six poles, we would need a turbine at an extreme speed ranging from 1,000 to 3,000 laps per minute (see possibly the page on the change of the speed of rotation of the generator). With a rotor diameter of 43 meters, this will imply a tangential velocity of the rotor blades at their end more than twice the speed of sound - so it's best to drop this idea right away.

Another option is to build a slow-moving CA generator with a multitude of poles. But if you want to connect your generator directly to the grid, you'll need a 200-pole generator (i.e. 300 magnets) to get a reasonable rotation speed of 30 turns per minute.

Another problem is that the rotor mass of the generator must be more or less proportional to the torque (moment or torque of twisting) that the rotor must be able to support. In any case, a generator driven directly will be very heavy - and will be very expensive.

Less torque, more speed

The practical solution also used in many other industrial machines as well as in car engines, is to install a multiplier. By using it, it is possible to transform the power at slow speed and high torque, produced by the rotor of the wind turbine, into a high-speed power and low torque used by the generator.

The multiplier of a wind turbine does not change gears in the same way as a car's gearbox. There is normally a constant relationship between the rotor's rotational speed and that of the generator. For a 600 or 750 kW wind turbine, this ratio is typically approximately 1 to 50 rpm.

The wind turbine's control system

The wind turbine control system consists of a number of computers that constantly monitor the condition of the wind turbine, while collecting statistics on its operation. As the name suggests, this unit also controls several switches, hydraulic pumps and valves located inside the wind turbine..

Image from https://sine.ni.com/cms/images

As the size of wind turbines increases, it becomes even more important that their availability rate is very high, so that their operation is reliable at all times.

Communication with the outside world

The control-control system communicates with the owner or operator of the wind turbine through a communication link, e.g. transmitting alarms or maintenance requests over the phone or radio. It also makes it possible to call the wind turbine in order to collect statistics and control its current condition. In a wind farm, it is normal for one of the wind turbines to have a computer to monitor and collect data from other wind turbines in the park. You can call this computer by phone or radio.

Internal communications

In general, a control-control system is installed at the bottom of the tower, and inside the gondola. On recent models, communication between the two systems is normally provided by optical fibers. The image on the right shows a fiber optic communication unit.

On some of the new models, a third control system was placed in the rotor hub. This unit communicates with the control system located in the gondola through serial communications through cables coupled with rings and brushes on the slow tree.

Resilient mechanisms and redundancy

On new large wind turbines, computers and sensors are generally duplicated (redundant) in all locations requiring a high level of safety and stability in operation. The controller constantly compares the results of measurements taken throughout the wind turbine to ensure that both sensors and computers function properly. The photo at the top of the page shows the control-control system of a megawatt-class wind turbine with two main computers (we removed the cache from one of the two computers to show you the electronics contained in it).

Control Strategies

Many of the manufacturing secrets of wind turbine manufacturers concern the interaction between the control-control system and the other components of the wind turbine. In fact, much of the increase in wind turbine efficiency that has occurred in recent years is due to improved control strategies.

An interesting strategy pursued by some of the manufacturers is to adapt the operational strategy to the local wind regime. In this way, for example, it is possible to minimize the unprofitable wear of the machine during (rare) periods of heavy weather.

Power quality control

Most people think of the control-control system as the unit that operates the wind turbine, starting it, steering it in the direction facing the wind,

checking the way security systems work, etc.

The controller does all these things, but he also monitors the quality of the current generated by the wind turbine.

Connection to the grid and power quality

Power companies require that wind turbines be connected flexibly to the grid and that the alternating current and voltage move in sync.

Pictured is the high-voltage section of a control-control system designed for a megawatt-class wind turbine. This part of the system operates, among other things, the thyristors, which provide a flexible coupling to the electrical grid.

Reactive power control

Image from www.Boddingtons Power Controls

Current voltage and intensity is typically measured 128 times per cycle of the alternating current (i.e. 50 x 128 times per second or 60 x 128 times per second, depending on the frequency of the network). Based on these measurements, a processor called DSP calculates the stability of the network frequency as well as the active and reactive power of the wind turbine (reactive power is primarily the question of whether the voltage and current are in phase or not).

To ensure good power quality, the control-control system can connect or disconnect a large number of electrical capacitors that adjust reactive power (i.e. the phase angle between voltage and current). As you can see from the photo on the left, the switchable capacitor battery is itself a fairly large control unit in a megawatt-class wind turbine.

Electromagnetic compatibility

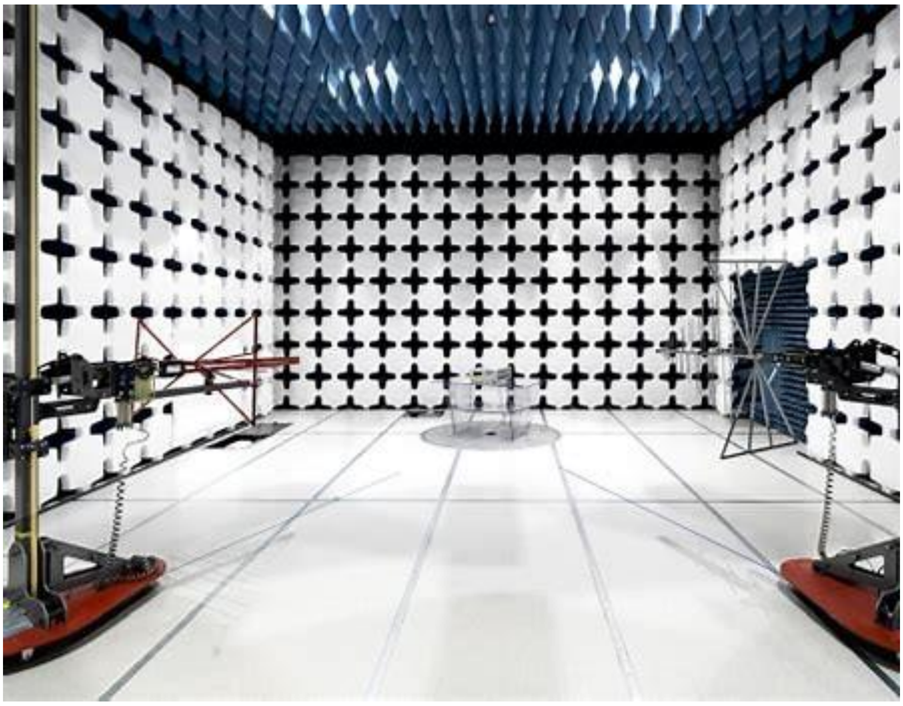


Image from www.agilent.com

In a wind turbine, there are very powerful electromagnetic fields around the cables and generator. This means seeking to insensitize the electronics of the control system to electromagnetic fields.

Conversely, electronics should not emit electromagnetic radiation that could interfere with the operation of other parts of the electronic equipment. The photo shows you a room completely free of radiation and surrounded by metal walls, located in the laboratory of one of the largest manufacturers of wind turbines. The room equipment is used to measure electromagnetic emissions from the control-control system components.

Recommended literature

Books :

1.. BURTON, T. « Wind energy handbook »2011 - Wiley - Chichester, West Sussex AENews. 2016.

Weblinks

1.Wind Turbines. [online] Available at: <http://www.alternativeenergynews.info/technology/wind-power/wind-turbines/>

2. Meyers, C., 2015. *How Generators Work*. [online] Centurionenergy.net. Available at: <http://centurionenergy.net/how-generators-work>

www.weset-project.eu

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein

Contact:

info@weset-project.eu

weset.erasmusplus@uva.es

.

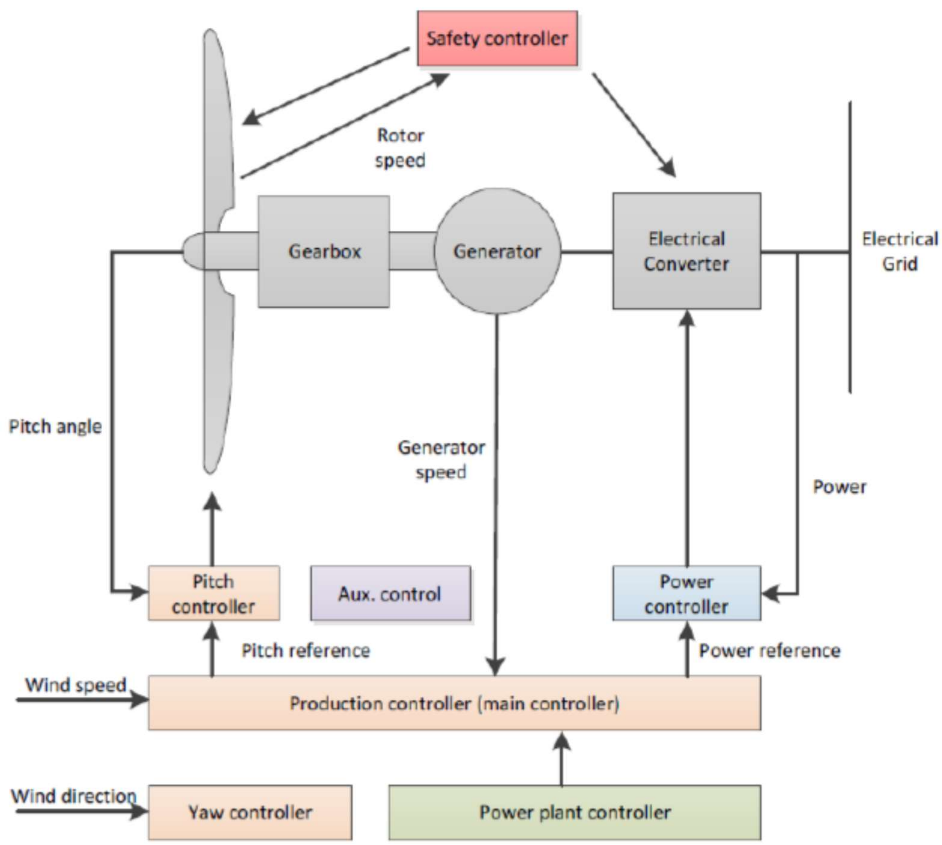
Co-funded by the
Erasmus+ Programme
of the European Union

Module 2.3 Assignment

(Q4) 10 marks [3.a]

4-a) The Wind turbine control system has different control function, the following figure illustrate the control autonomy of wind turbine, it is required to:

i) illustrate the function of each control function in automation control level.
ii) Select one function that can be implemented using neural network and Fuzzy control system and explain it in details.



This project has been funded with support from the European Commission. This communication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein

www.weset-project.eu

Experiment 1

Wind Turbine Generating power

Objective

Illustrate the effect of wind speed on the injected power into the grid from aerogenerator without load.

Equipment

1- Wind turbine as in Fig.1

Fig,1 Wind turbine 400W

2- Servo Motor to simulate the wind speed as in Fig. 2

Fig.2 Servo Motor 400W

3- Power meters, isolating switch, wind turbine grid connected inverter, connecting cable

Procedure

1- Remove the wind blades of the wind turbine
2- Connect the servo motor to the aerogenerator shaft as shown in Fig. 3

Fig. 3 Aerogenerator coupled with servo motor to simulate wind speed

3- Connect the wire of aerogenerator, motor, wind inverter, meter disconnector, and power socket as shown in Fig. 4

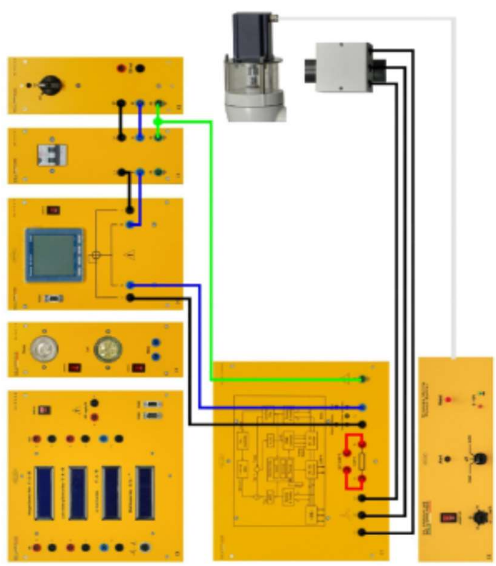


Fig. 4 Circuit connection

4- Turn ON the devices.
5- Set the inverter (DL 2555ALWS) to operate in manual mode.
6- Adjust the number of motor revolutions through the knob 0-100 %, the speed of motor simulates the wind speed that would do spin the blades of aerogenerator.
7. Set the speed of motor to 50%.
8. The green LEDs on the DL 9013G3D module indicate that you are feeding energy into the grid as shown in Fig. 5.

Fig.5 generated power integrator

9. Check on DL 9030 (power meter) display that the system produces in grid about 30 W , 230 V AC as shown in Fig. 6.

Fig. 6 Generated power output

10. Adjust the motor revolutions to fill the table below

Speed motor [%]	Power P_{gen} [W]
0	
10	
25	
40	
50	
65	
75	
90	
100	

Discussion

1- Based on the circuit connection identify the main control loop of the inverter
2- Discuss the aerogenerator output characteristic with respect to shaft speed

This project has been funded with support from the European Commission. This communication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein