EMR'12
Madrid
June 2012

Universidad Carlos III de Madrid

Joint Summer School EMR'12
"Energetic Macroscopic Representation"

Université Lille1 Sciences et Technologies

« Energetic Macroscopic Representation (EMR) »

Prof. Daniel HISSEL

FEMTO-ST Energy Department, FCLAB, University of Franche-Comte,

daniel.hissel@univ-fcomte.fr

Dr. Walter LHOMME, Prof. Alain BOUSCAYROL

L2EP, University of Lille 1,

walter.lhomme@univ-lille1.fr, alain.bouscayrol@univ-lille1.fr

femto-st SCIENCES & TECHNOLOGIES

FC LAB Research

UFC UNIVERSITÉ DE FRANCHE-COMTÉ

Université Lille1 Sciences et Technologies

L2EP LILLE

- Outline -

1. EMR basic elements

- General principles
- Source, accumulation and conversion elements
- Coupling elements

2. EMR of a whole system

- Action and tuning path
- Association rules
- Example

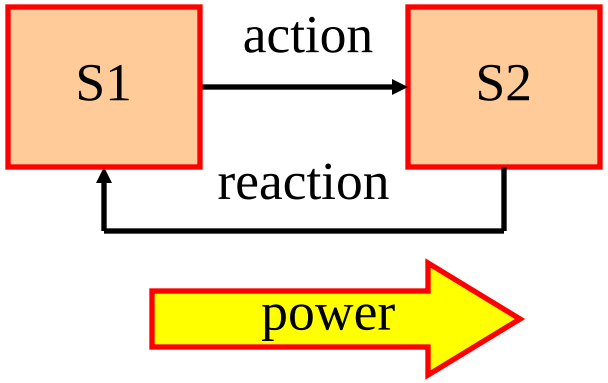
3. Conclusion

Universidad Carlos III de Madrid

Université Lille1 Sciences et Technologies

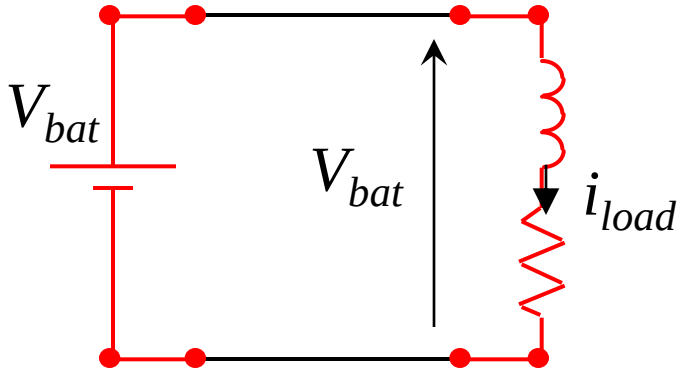
« EMR basic elements »

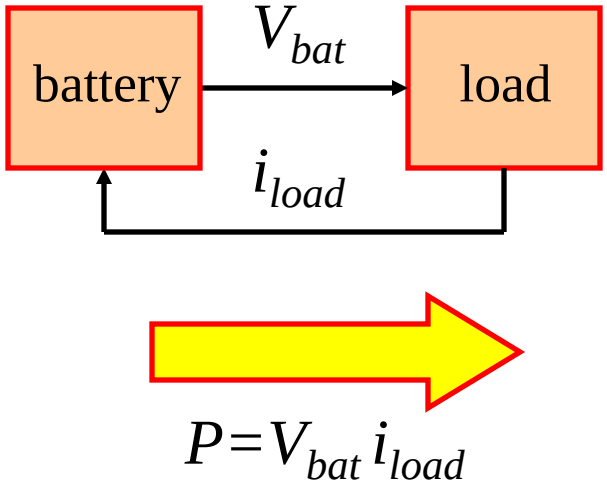
Interaction principle
Each action induces a reaction



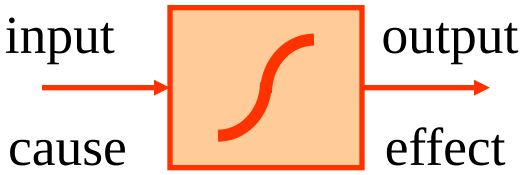
Power exchanged between S1and S2 = action x reaction

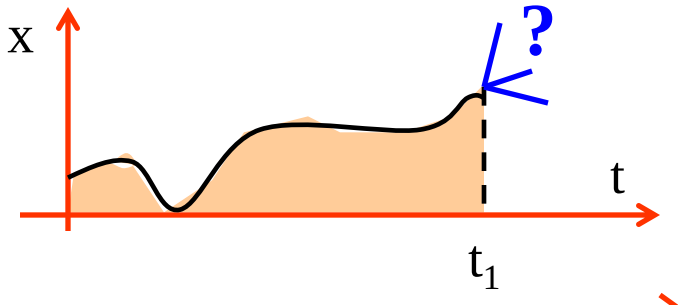
Example





Principle of causality
physical causality is integral





$\int xdt$ ⇨ area

⇩

knowledge of past evolution

OK in real-time

slope ⇦ $\frac{dx}{dt}$

⇩

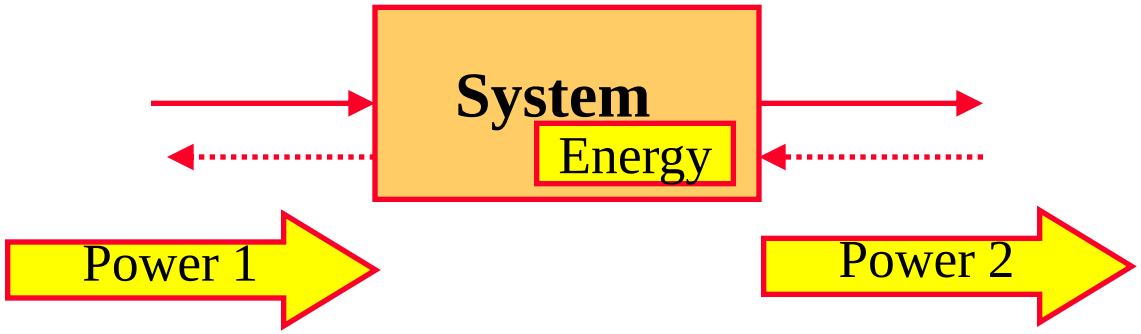
knowledge of future evolution

impossible in real-time

Energy is the integrative of power

$$Energie(t) = \int_0^t Power(\tau).d\tau$$

A system can store energy : in this case power1(t) ≠ power2(t)



Energy cannot vary instantaneously !

In fact, as : $Power(t) = \frac{d}{dt} Energy(t)$ we would obtain $Power(t) \rightarrow \infty$

➔ Physically impossible

Energy varies thus « slowly », according to the charge and the discharge of the energy storage devices

Examples :

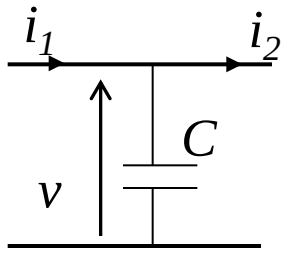
- *filling the tank of a car*
- *energy storage in the capacitors*
- *energy storage in flywheels*
- *thermal energy storage in a heater*
- *compressed air storage*
- ...

Variable linked to the stored energy

Example :

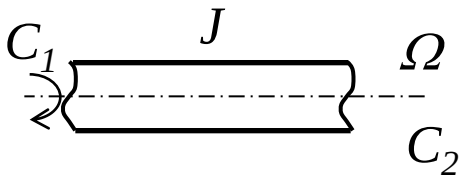
- *energy stored in a capacitor (value C) :*

$$E = \frac{1}{2} C.V^2$$



➔ *variable linked to energy = voltage V*

➔ *the voltage V of a capacitor cannot vary instantaneously*



Variable representing the stored energy

Example :

- energy stored in a flywheel (moment of inertia J) : $E = \frac{1}{2} J.\Omega^2$

➔ *variable linked to the energy = angular speed Ω*

➔ *angular speed Ω of a flywheel cannot vary instantaneously*

➔ *angular speed directly represents the energetic **state** of the flywheel system*

State variable = Energy linked variable

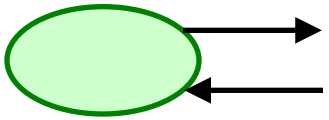
An energetic system:

- Energy sources
- Energy storage elements
- Energy conversion elements
- Energy distribution elements

Energy storage element versus energy conversion element:

- Different in view of control – state variable control
- The state of a energy storage element can not change instantaneously

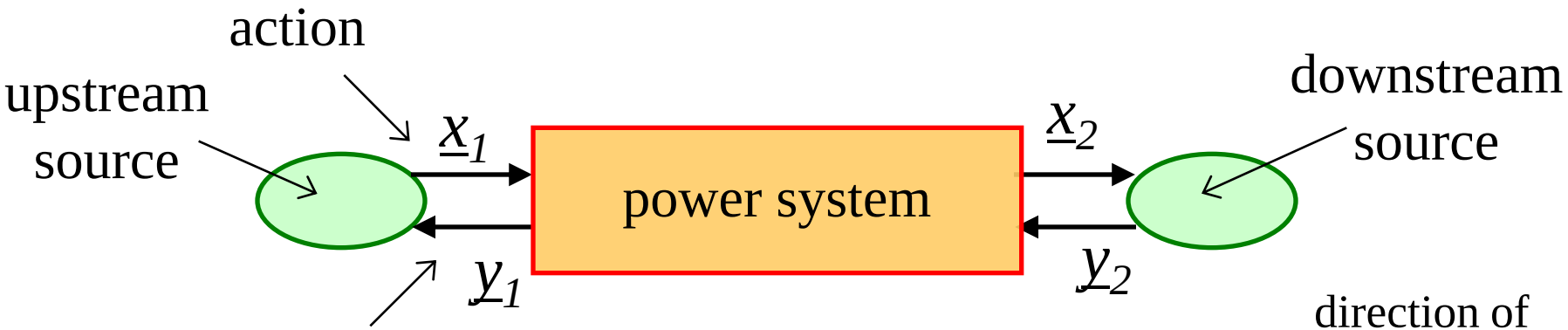
Source



oval pictogram
background: light green
contour: dark green
1 output vector (dim n)
1 input vector (dim n)

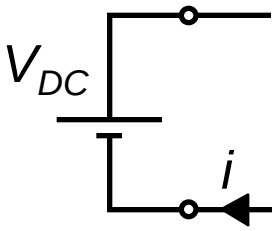
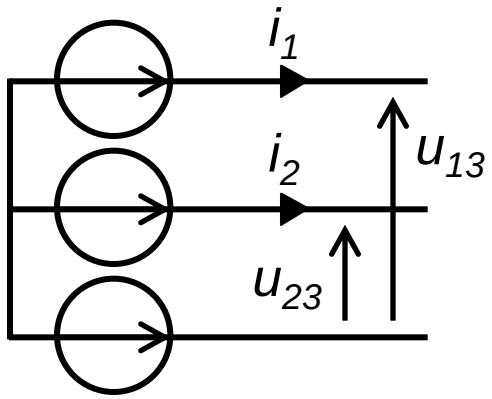
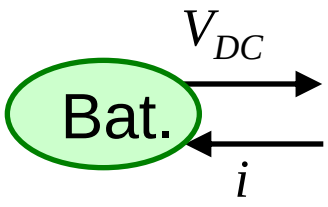
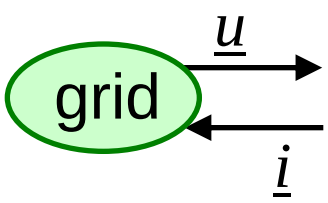
terminal elements which represent the environment of the studied system

generator and/or receptor of energy



$$p_1 = \underline{x}_1 \cdot \underline{y}_1 = \sum_{i=1}^{n} x_{1i} y_{1i} \qquad p_2 = \underline{x}_2 \cdot \underline{y}_2$$

- Energetic sources: examples (1) -

	Battery	**Electrical grid**
structural description		
EMR (functional description)		
	$p = V_{DC}\, i$	$p = \underline{u}\,\underline{i}$

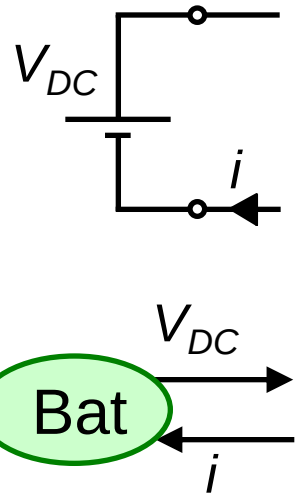
$$\underline{u} = \begin{bmatrix} u_{13} \\ u_{23} \end{bmatrix} \quad \underline{i} = \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}$$

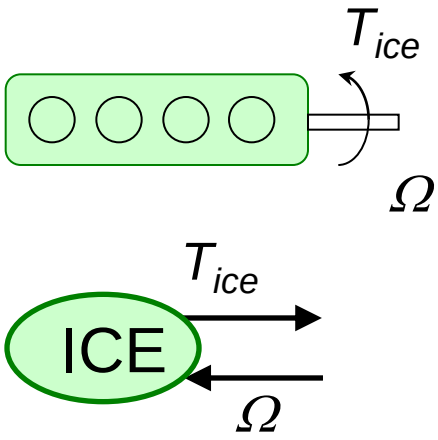
2 independent currents

2 independent voltages

- Energetic sources: examples (2) -

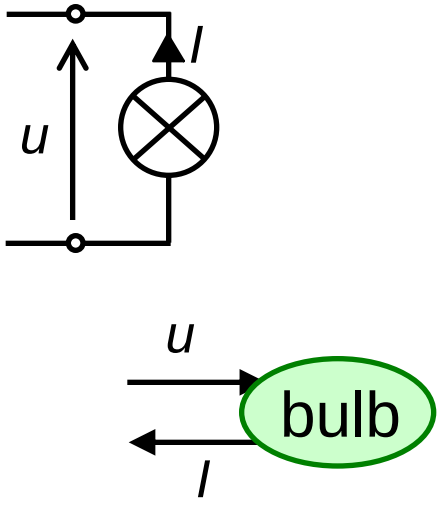
Battery
(voltage source)
generator and
receptor of energy

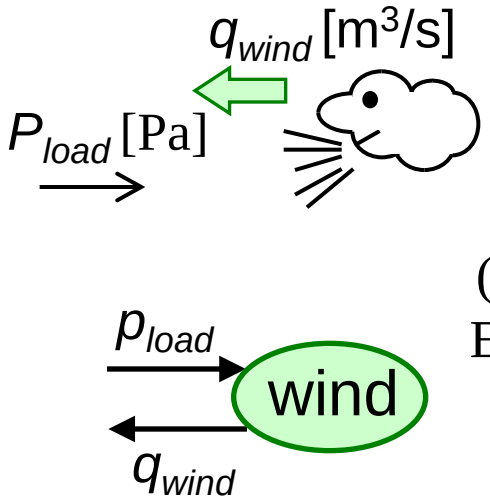




IC engine
(torque source)
Energy generator

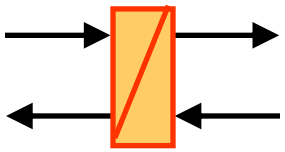
Ligthing bulb
Energy receptor





Wind
(air flow source)
Energy generator

Accumulator



rectangle with an oblique bar
background: orange
contour: red
upstream I/O vectors (dim n)
downstream I/O vectors (dim n)

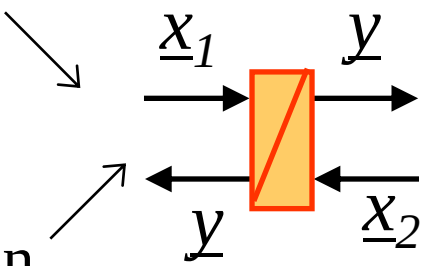
internal accumulation of energy (with or without losses)

causality principle

$$\text{output(s)} = \int \text{input(s)}$$

action

reaction



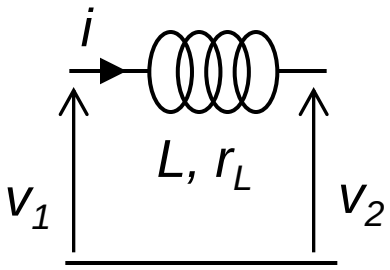
$$p_1 = \underline{x}_1 . \underline{y} \qquad p_2 = \underline{x}_2 . \underline{y}$$

$$\underline{y} \propto \int f(\underline{x}_1, \underline{x}_2) dt$$

$\underline{y}$ = output, delayed from input changes

inductor

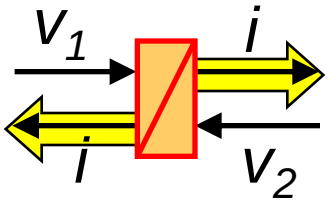
structural description



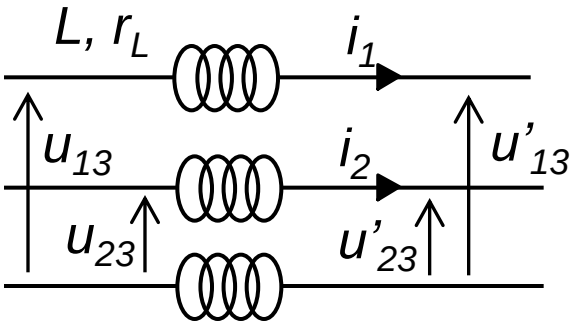
mathematical Model

$$L\frac{d}{dt}\,i + r_L\,i = v_1 - v_2$$

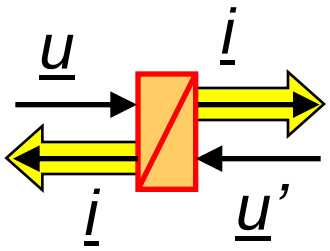
EMR (causal representation)



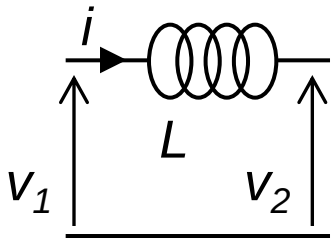
3-phase line



$$[L]\frac{d}{dt}\underline{i} + r_L\,\underline{i} = \frac{1}{3}\begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}(\underline{u} - \underline{u}')$$

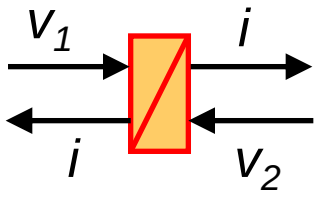


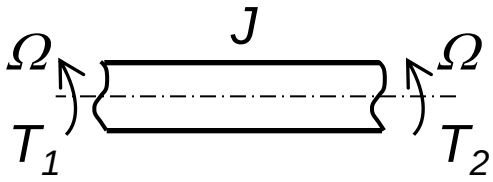
- Accumulation elements: examples (2) -



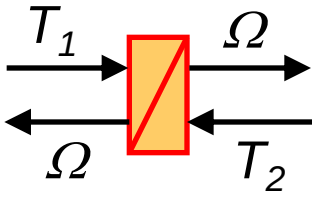
inductor

$$E = \frac{1}{2} L\, i^2$$

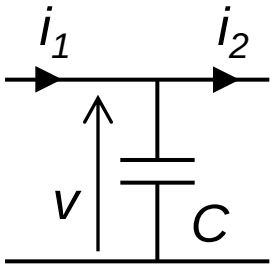




inertia

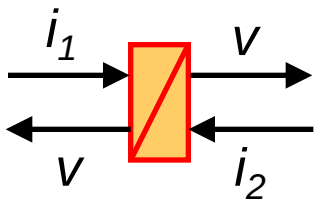


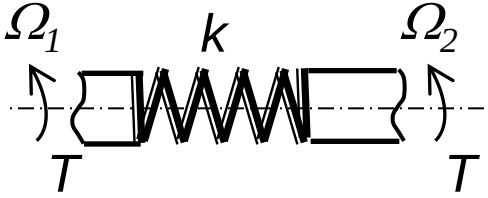
$$E = \frac{1}{2} J\, \Omega^2$$



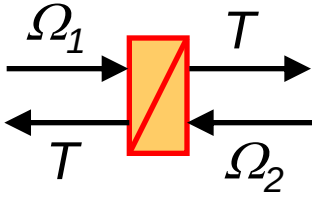
capacitor

$$E = \frac{1}{2} C\, v^2$$



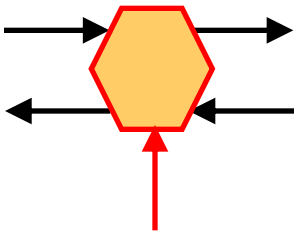


stiffness



$$E = \frac{1}{2} \frac{1}{k} T^2$$

conversion element



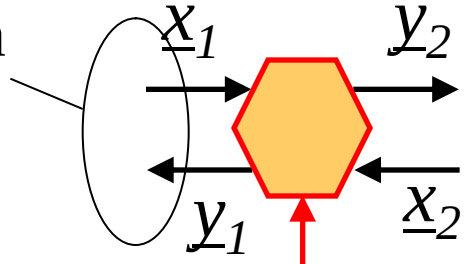
two pictograms
background: orange
contour: red
upstream I/O vectors (dim n)
downstream I/O vectors (dim p)
Possible tuning input vector (dim q)

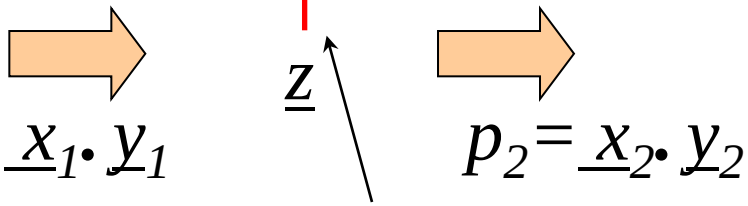
conversion of energy without energy accumulation (with or without losses)

$$\begin{cases} \underline{y}_2 = f(\underline{x}_1, \underline{z}) \\ \underline{y}_1 = f(\underline{x}_2, \underline{z}) \end{cases}$$

no delay!

action / reaction

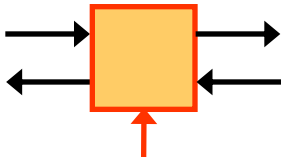




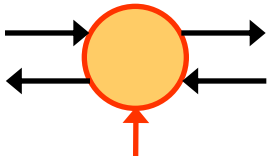
tuning vector

upstream and downstream I/O can be permuted (floating I/O)

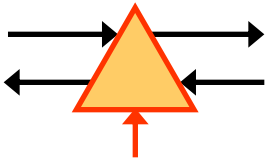
- Conversion element pictograms -



Square = electrical conversion



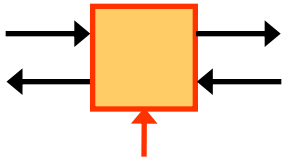
Circle = electromechanical conversion



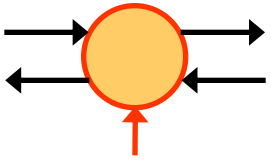
Triangle = mechanical conversion

More general pictograms

For multiphysical systems

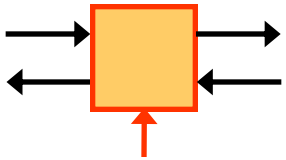


Square = monophysical conversion

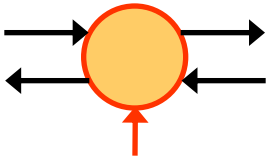


Circle = multiphysical conversion

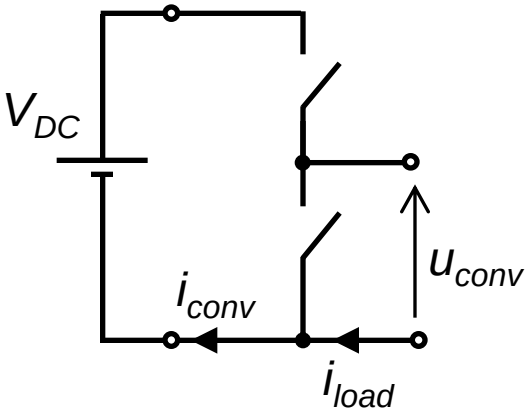
- Conversion element pictograms -

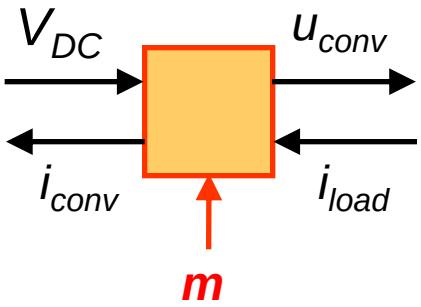


Square = monophysical conversion



Circle = multiphysical conversion



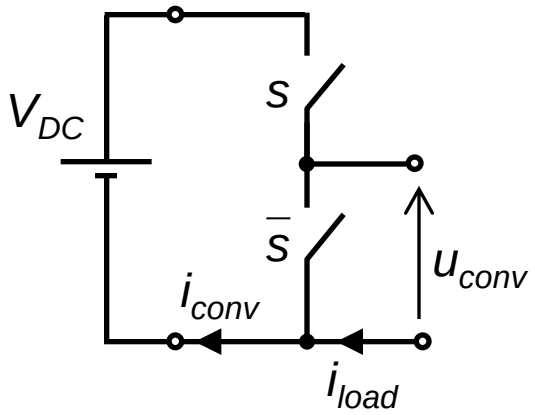


$$\begin{cases} u_{conv} = m \quad V_{DC} \\ i_{conv} = m \quad i_{load} \end{cases}$$

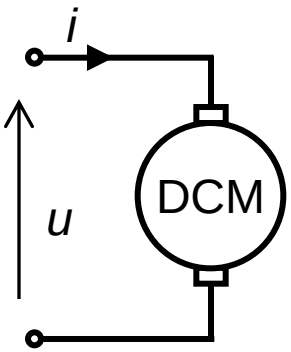
m: modulation function of the converter

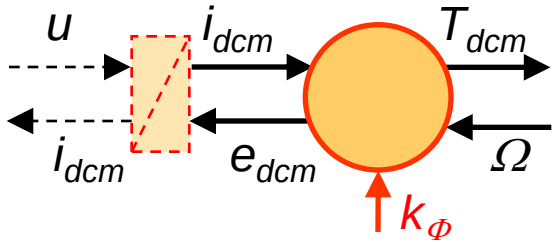
$$\langle m \rangle = D = \text{duty cycle}$$

- Conversion elements: examples -



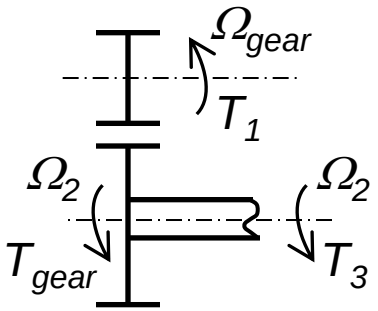
$$\begin{cases} u_{conv} = m \;\; V_{DC} \\ i_{conv} = m \;\; i_{load} \end{cases}$$

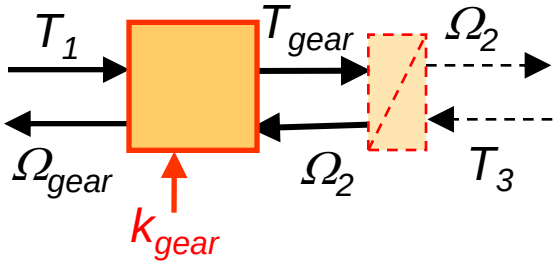




$$L \frac{d}{dt} i_{dcm} + r \; i_{dcm} = u - e_{dcm}$$

$$\begin{cases} T_{dcm} = k_\Phi \; i_{dcm} \\ e_{dcm} = k_\Phi \; \Omega \end{cases}$$

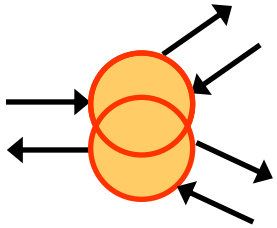




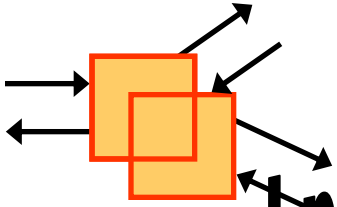
$$\begin{cases} T_{gear} = k_{gear} \;\; T_1 \\ \Omega_{gear} = k_{gear} \;\; \Omega_2 \end{cases}$$

$$J \frac{d}{dt} \Omega_2 = T_{gear} - T_3$$

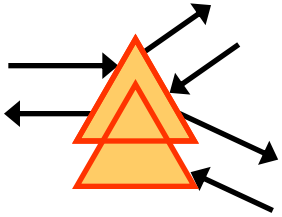
coupling elements { overlapped pictograms background: orange contour: red



electro mechanical coupling



electrical coupling

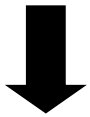


mechanical coupling

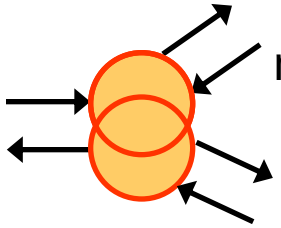
distribution of energy

no tuning vector

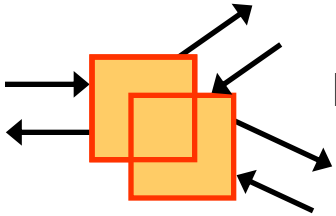
More general pictograms



coupling elements { overlapped pictograms background: orange contour: red

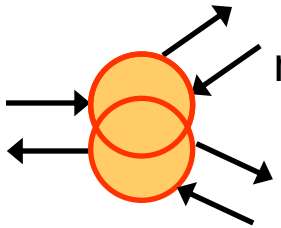


multiphysical coupling

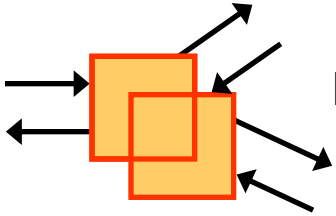


Monophysical coupling

coupling elements { overlapped pictograms
background: orange
contour: red



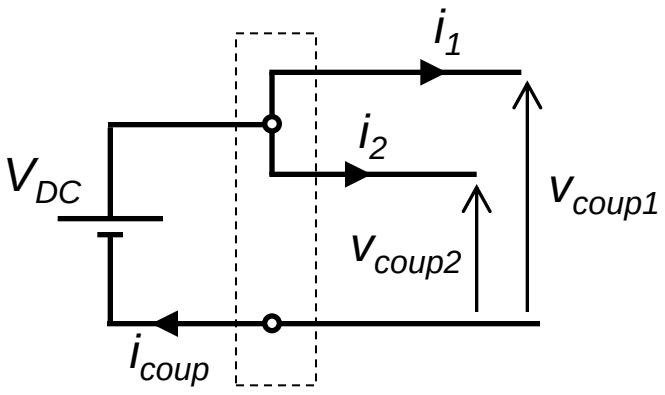
multiphysical coupling



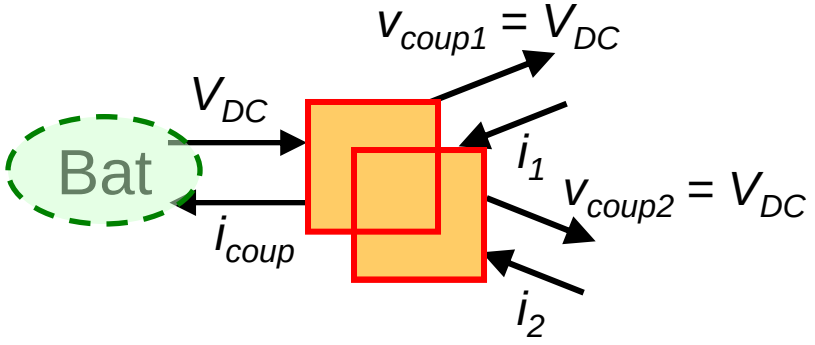
Monophysical coupling

distribution of energy

no tuning vector

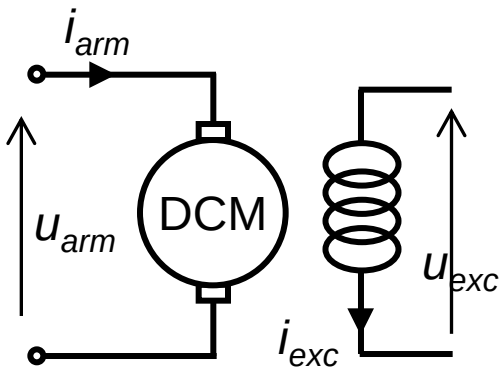


parallel connexion

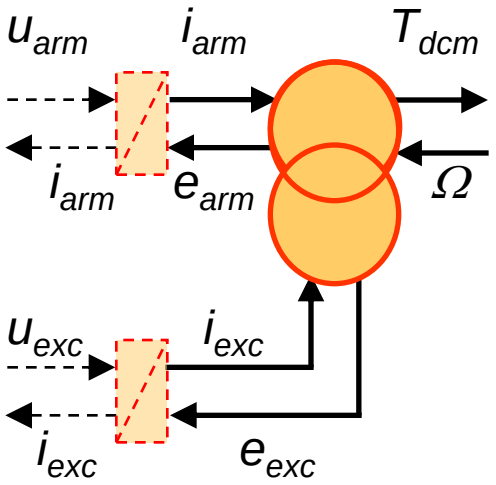


$$\begin{cases} V_{DC} \text{ common} \\ i_{coup} = i_1 + i_2 \end{cases}$$

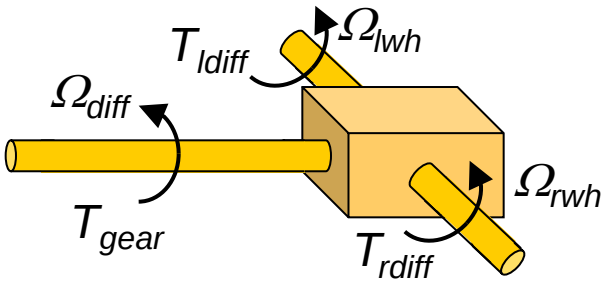
Field winding DC machine



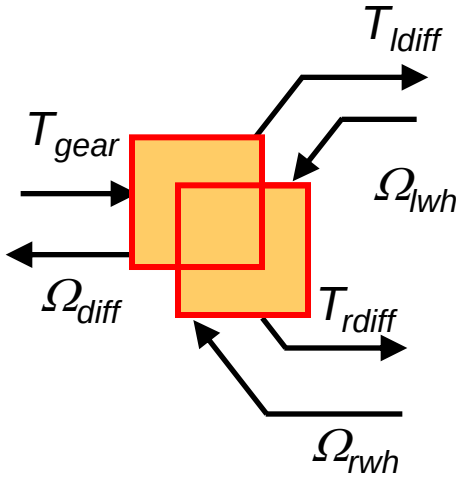
$$\begin{cases} T_{dcm} = k\, i_{exc}\; i_{arm} \\ e_{dcm} = k\, i_{exc}\; \Omega \end{cases}$$



Mechanical differential



$$\begin{cases} T_{ldif} = T_{rdif} = \dfrac{T_{gear}}{2} \\ \Omega_{diff} = \dfrac{\Omega_{lwh} + \Omega_{rwl}}{2} \end{cases}$$



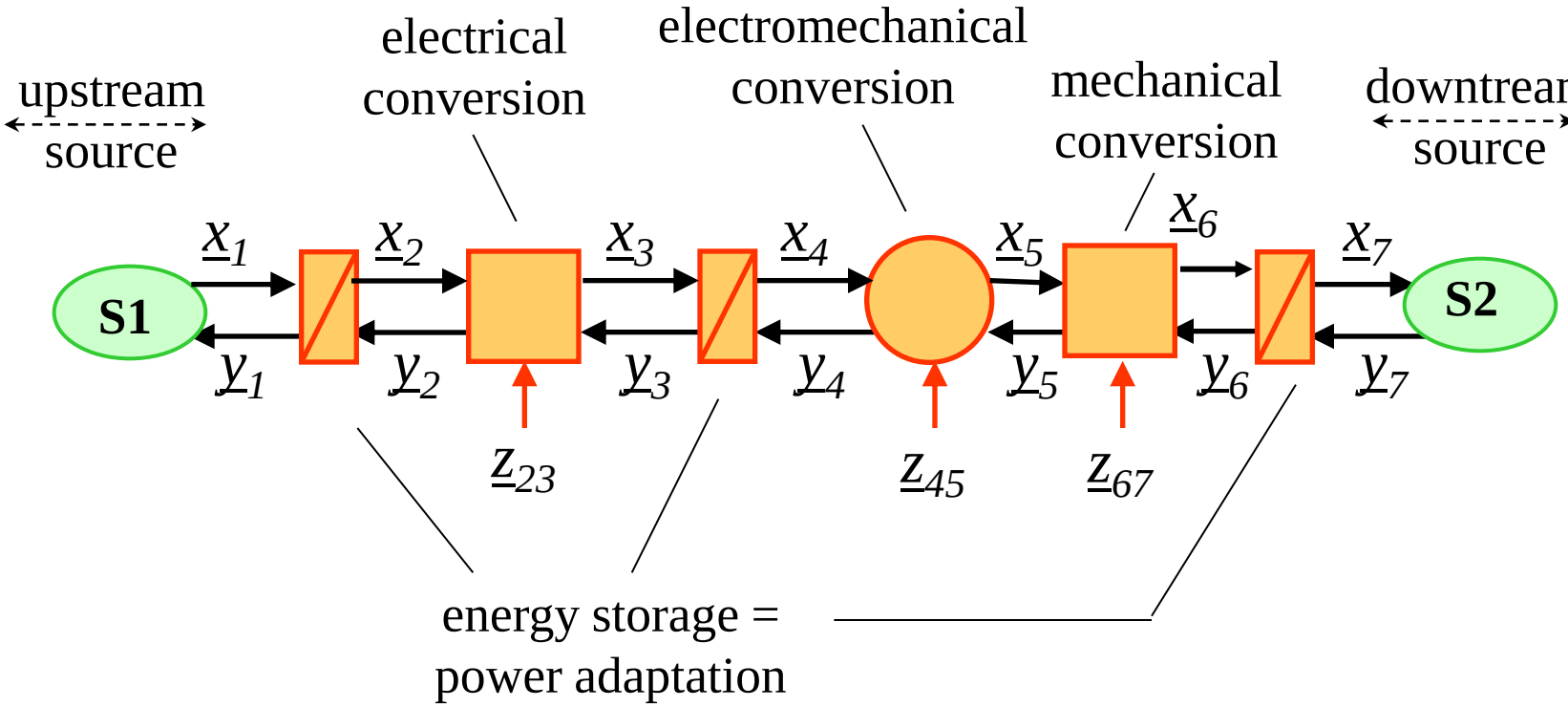
EMR'11
Lausanne
July 2011

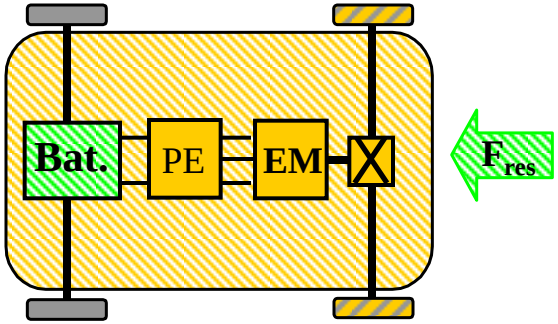
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Joint Summer School EMR'11
"Energetic Macroscopic Representation"

Université Lille1 Sciences et Technologies

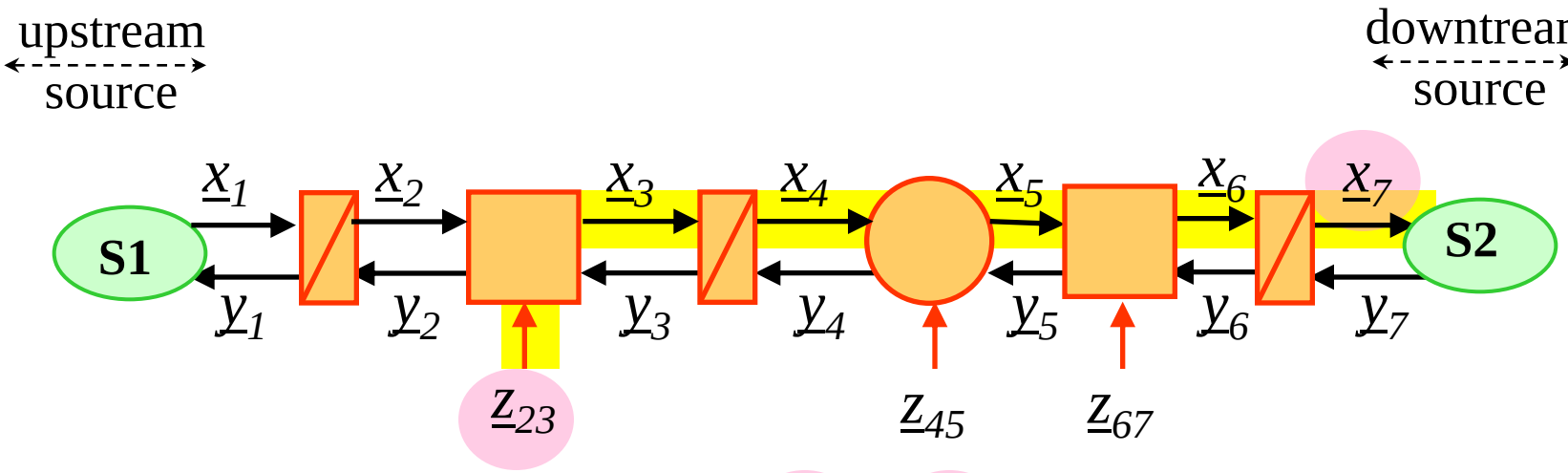
« EMR of a whole system »



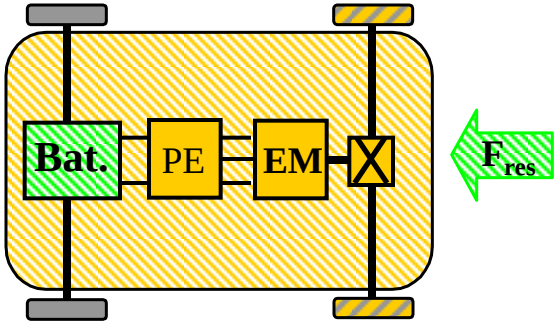


upstream source → downtream source

Convention: direction of positive power flow (could be negative for bidirectional system)



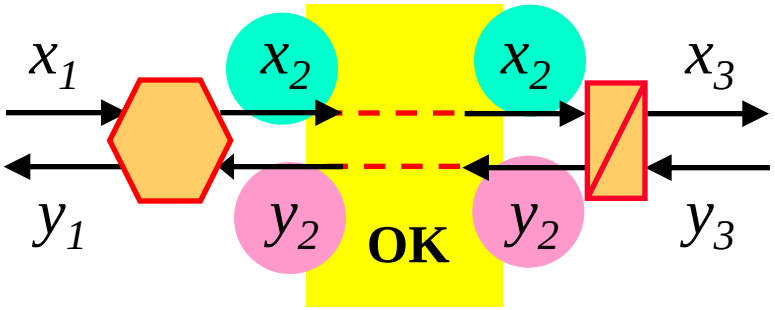
Technical requirements: action on $\underline{z}_{23}$ and $\underline{x}_7$ to be controlled



Tuning path: $\underline{z}_{23} \rightarrow \underline{x}_3 \rightarrow \underline{x}_4 \rightarrow \underline{x}_5 \rightarrow \underline{x}_6 \rightarrow \underline{x}_7$

The tuning path is **independent of the power flow direction**

(e.g. velocity control in acceleration AND regenerative braking)



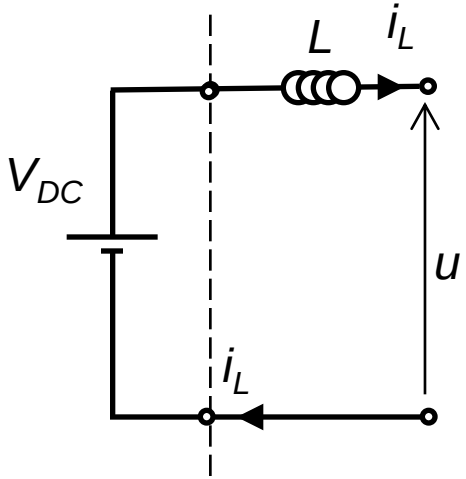
direct connection if:

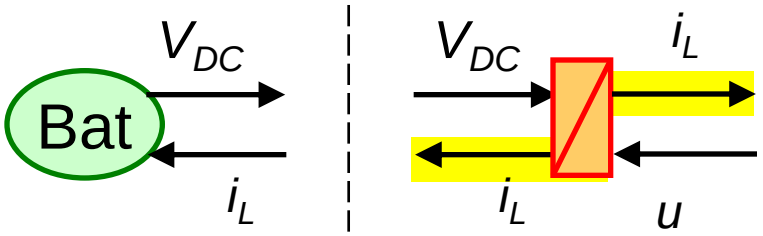
Out(S1) = In (S2)

In(S1) = Out(S2)

S1 and S2 any sub-systems

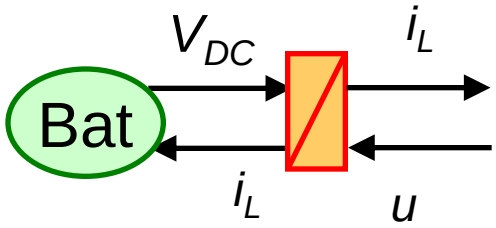
Example

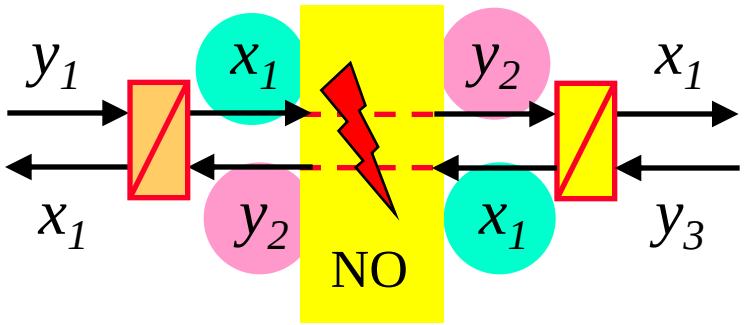




$$L\frac{d}{dt}i_L = V_{DC} - u$$

i state variable

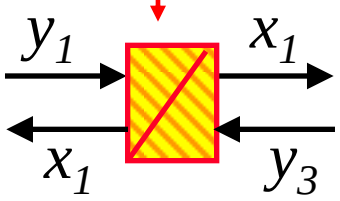




2 accumulation elements would impose the same state variable x_1

Conflict of association

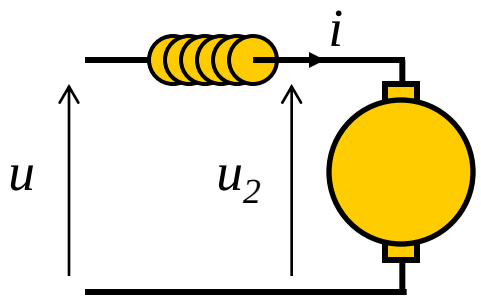
merging



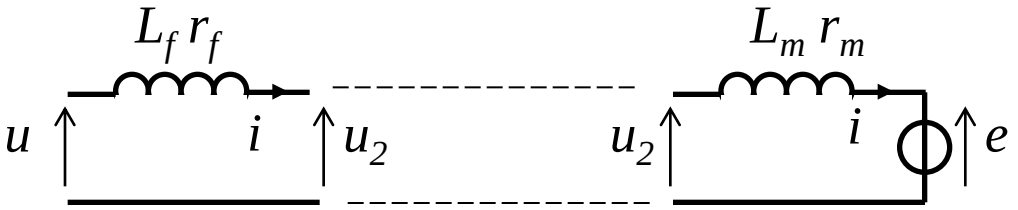
1 equivalent function for 2 elements / systemic

- Merging rule: example -

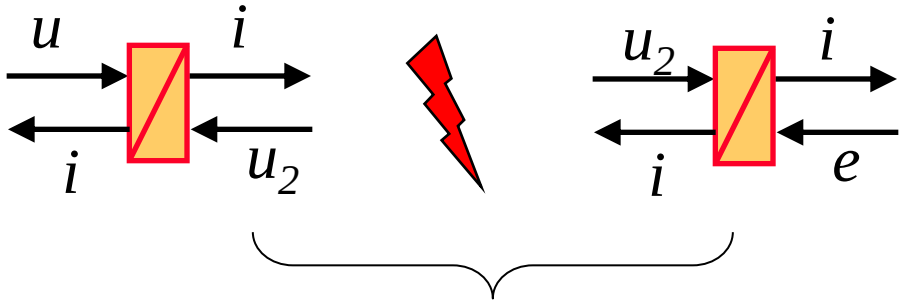
DC machine and smoothing inductor



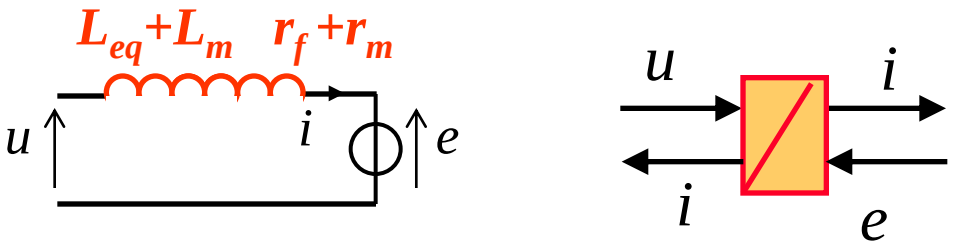
Assumption: L_f, L_m constant

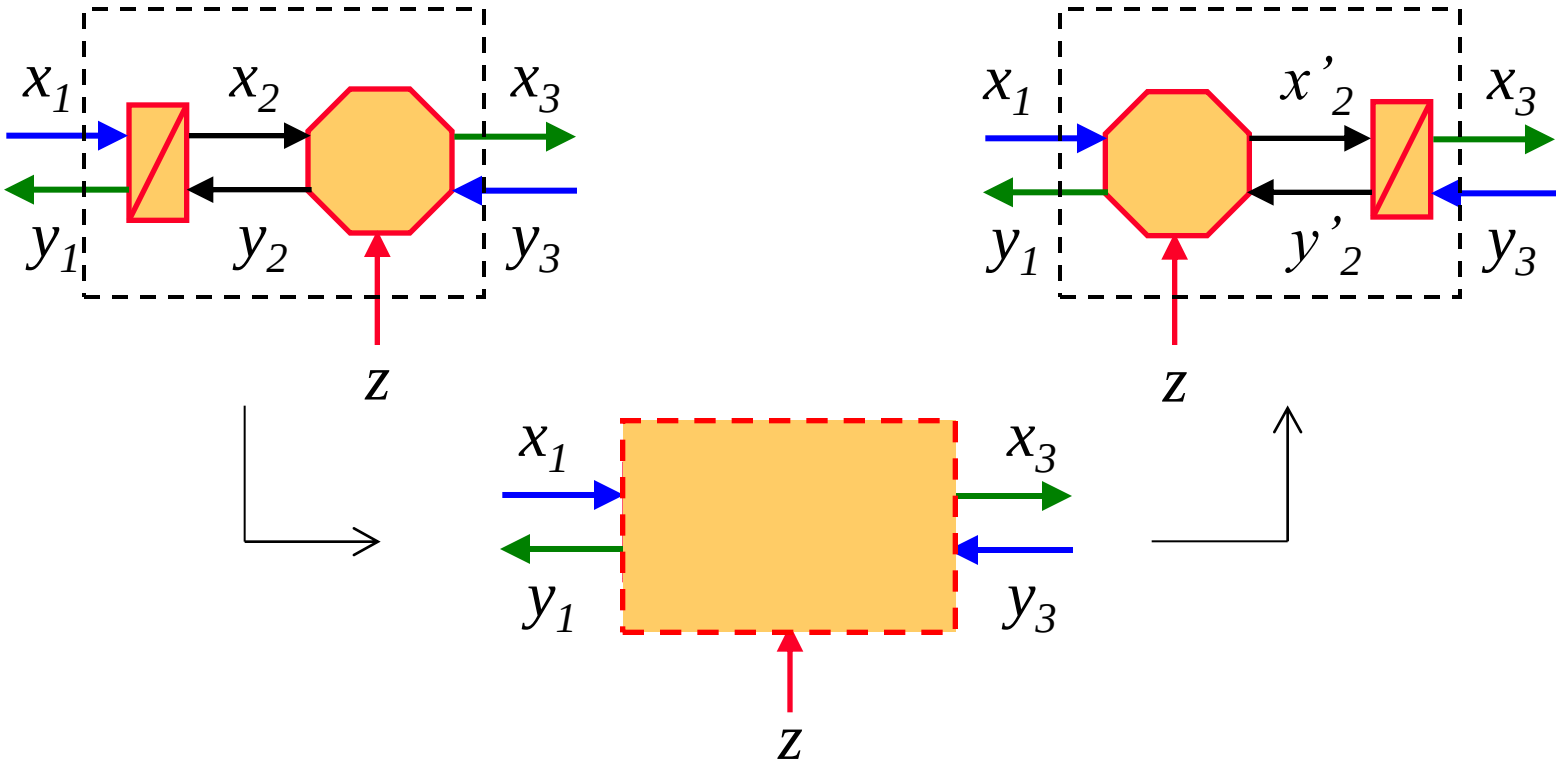


$$L_f \frac{di}{dt} = u - u_2 - r_f i \qquad L_m \frac{di}{dt} = u_2 - e - r_m i$$



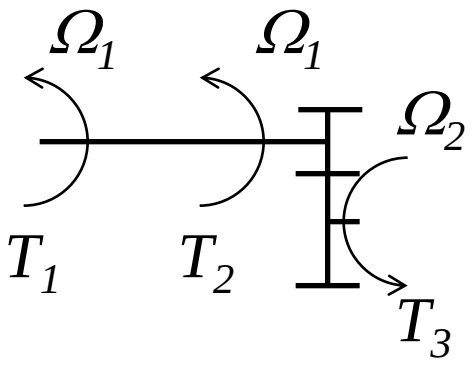
$$(L_f + L_m)\frac{di}{dt} = u - e - (r_f + r_m)i$$





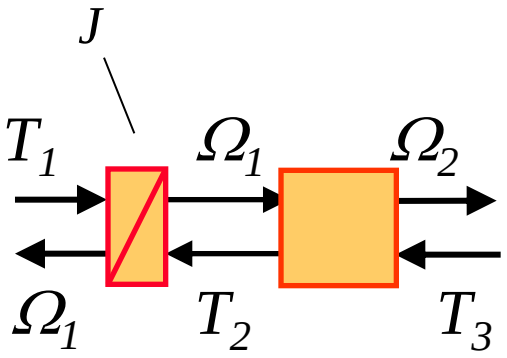
permutation possible if same global behavior:
strictly the same effects (y_1 and x_3) from the same causes (x_1 , y_3 and z)

- Permutation rule: example -



$$J\frac{d}{dt}\Omega_1 = T_1 - T_2$$

$$\begin{cases} T_2 = k\,T_3 \\ \Omega_2 = k\Omega_1 \end{cases}$$



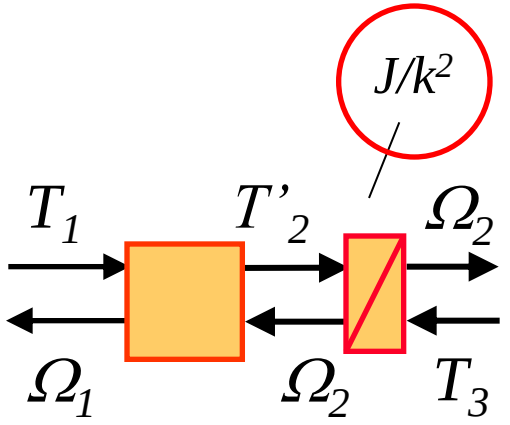
Shaft + gearbox

variable change

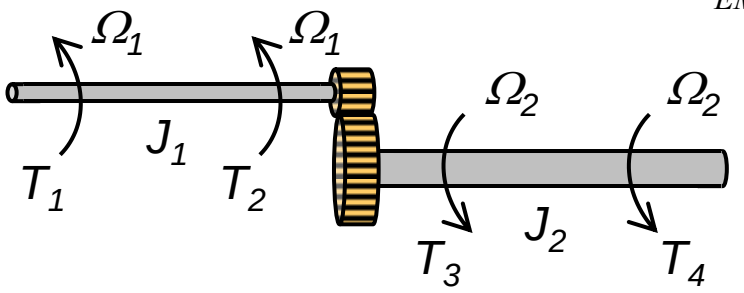
$$\frac{J}{k^2}\frac{d}{dt}\Omega_2 = T'_2 - T_3$$

$$\begin{cases} T_2' = \frac{1}{k}T_1 \\ \Omega_1 = \frac{1}{k}\Omega_2 \end{cases}$$

no assumption
strict equivalence
(same model)



- Interest of rules -



Assumptions:

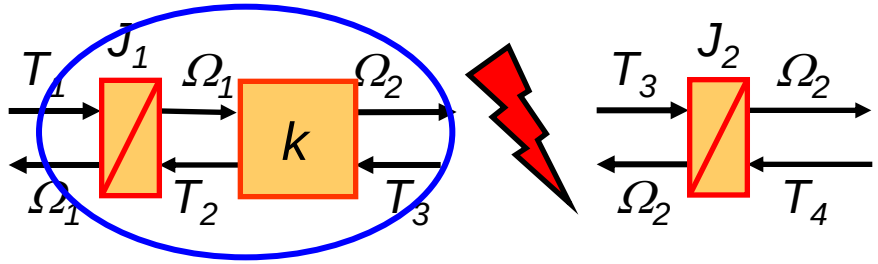
J_1 , J_2 constant

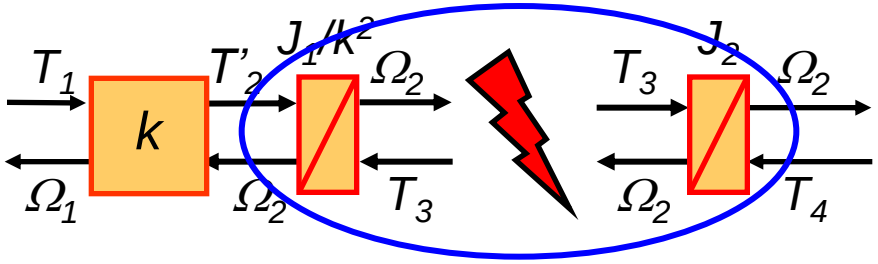
no backslash

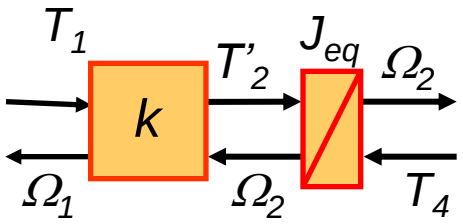
to solve conflict of association

permutation

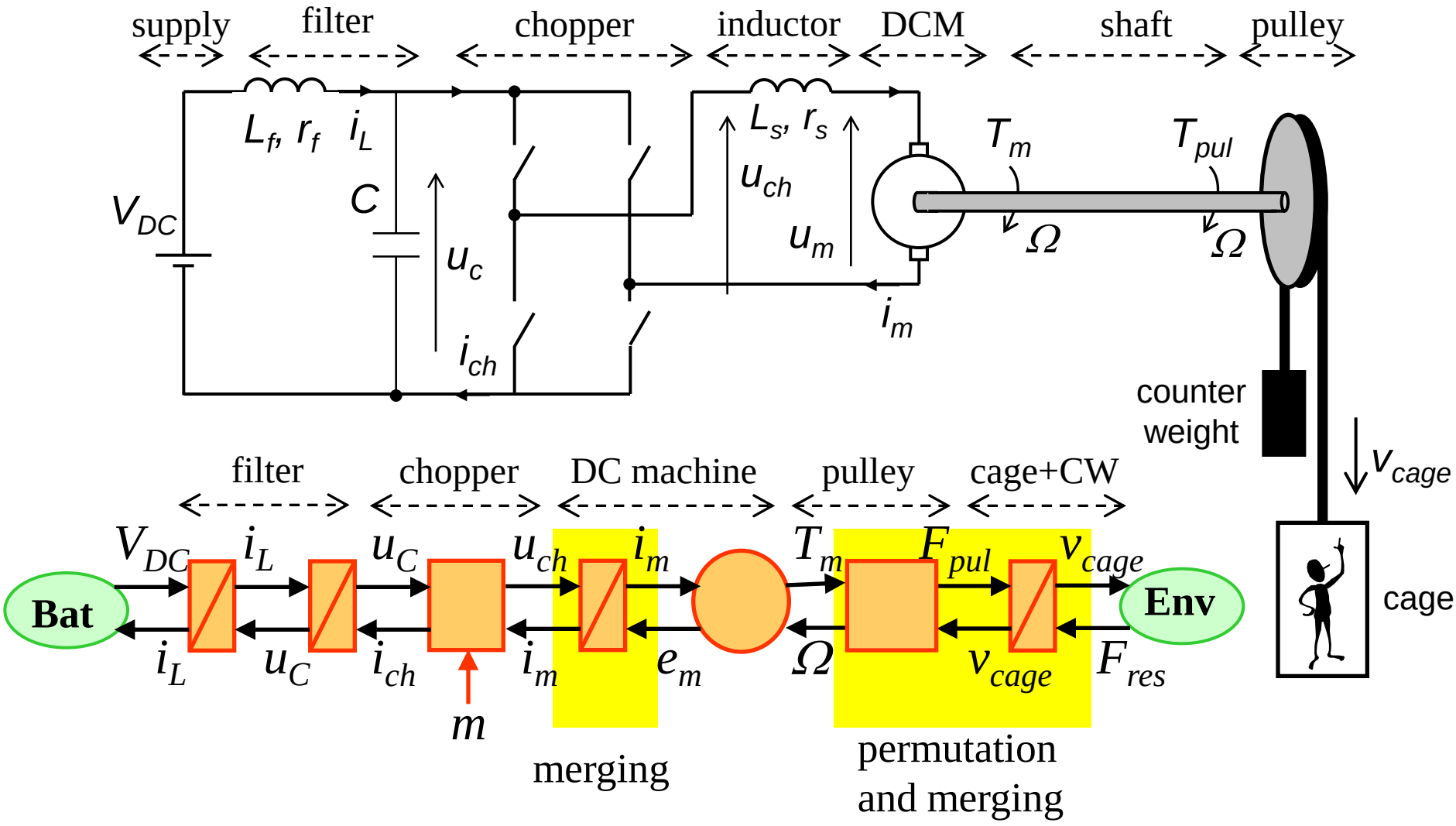
merging



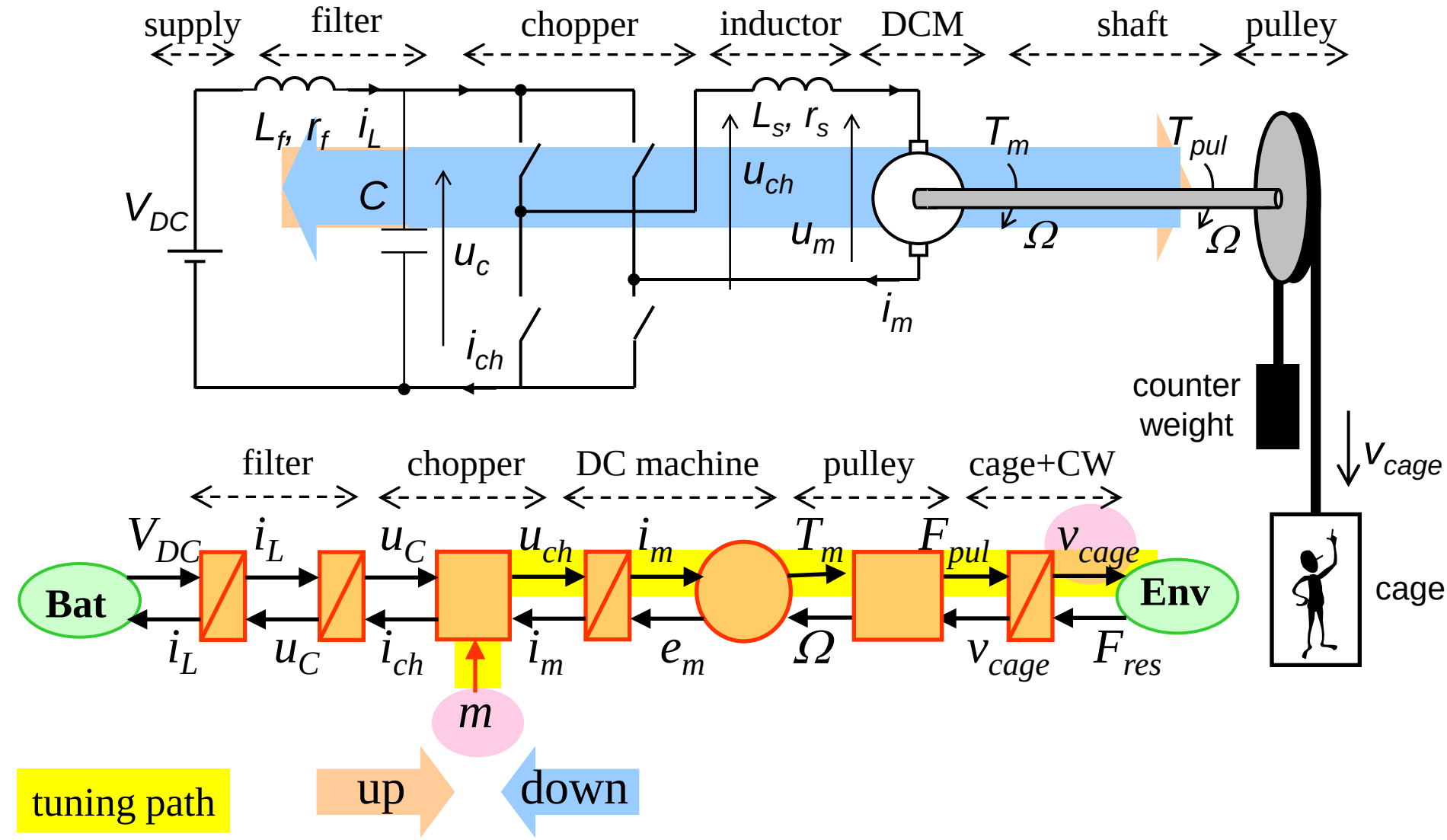




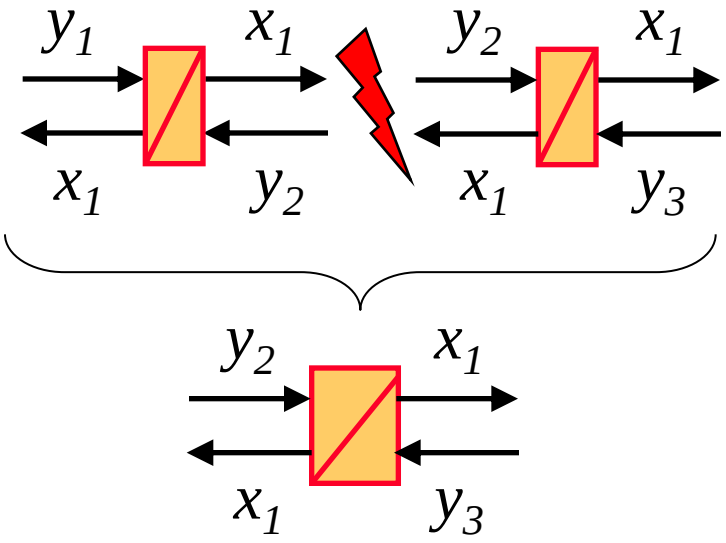
$$J_{eq} = \frac{J_1}{k^2} + J_2$$


supply
filter
chopper
inductor
DCM
shaft
pulley
L_f, r_f
i_L
V_{DC}
C
u_c
i_{ch}
L_s, r_s
u_{ch}
u_m
i_m
T_m
T_{pul}
Ω
Ω
counter weight
v_{cage}
filter
chopper
DC machine
pulley
cage+CW
V_{DC}
i_L
u_C
u_{ch}
i_m
T_m
F_{pul}
v_{cage}
Bat
Env
i_L
u_C
i_{ch}
i_m
e_m
Ω
v_{cage}
F_{res}
m
merging
permutation
and merging
cage

- Lift example: tuning path -



« Conclusion »



Priority to the function
by keeping the physical causality
(systemic)

EMR describes energetic functions

EMR respects natural integral causality

I/O are independent of power flows

Tuning paths:
- defined by the technical requirements
- independent of the power flow direction

EMR is adapted for control design

« BIOGRAPHIES AND REFERENCES »

« Energetic Macroscopic Representation »

- Authors -

Prof. Daniel HISSEL
University of Franche-Comte, FEMTO-ST, FCLAB, MEGEVH, France
Director, FCLAB CNRS Research Federation
Head, Hybrid & Fuel Cell Systems Research Team, FEMTO-ST
PhD in Electrical Engineering at University of Toulouse (1998)
Research topics: Modeling, control, diagnosis of hybrid and fuel cell systems

Dr. Walter LHOMME
L2EP, University Lille1, MEGEVH, France
PhD on Hybrid Electric Vehicles at University Lille1, 2007
Engineer at AVL (UK) (2007-2008) Associate Prof. at Univ. Lille1 (2008)
Research topics: EMR, EVs and HEVs

Prof. Alain BOUSCAYROL
University of Lille 1, L2EP, MEGEVH, France
PhD in Electrical Engineering at University of Toulouse (1995)
Research topics: EMR, EVs and HEVs

- References -

A. Bouscayrol, & al. "Multimachine Multiconverter System: application for electromechanical drives", *European Physics Journal - Applied Physics*, vol. 10, no. 2, May 2000, pp. 131-147 (common paper GREEN Nancy, L2EP Lille and LEEI Toulouse, according to the SMM project of the GDR-SDSE).

A. Bouscayrol, "Formalism of modelling and control of multimachine multiconverter electromechanical systems" (Texte in French), HDR report, University Lille1, Sciences & technologies, December 2003

A. Bouscayrol, M. Pietrzak-David, P. Delarue, R. Peña-Eguiluz, P. E. Vidal, X. Kestelyn, "Weighted control of traction drives with parallel-connected AC machines", IEEE Transactions on Industrial Electronics, December 2006, vol. 53, no. 6, p. 1799-1806 (common paper of L2EP Lille and LEEI Toulouse).

Boulon, L., Hissel, D., Bouscayrol, A., Pape, O., Péra, M.C., "Simulation model of a military HEV with a highly redundant architecture", IEEE Transactions on Vehicular Technology, vol. 59, n°6, pp. 2654-2663, 2010.

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

Boulon, L., Hissel, D., Bouscayrol, A., Péra, M.C., "From Modeling to Control of a PEM Fuel Cell Using Energetic Macroscopic Representation", IEEE Transactions on Industrial Electronics, vol. 57, n°6, pp. 1882-1891, 2010.

W. Lhomme, "Energy management of hybrid electric vehicles based on energetic macroscopic representation", PhD Dissertation, University of Lille (text in French), November 2007 (common work of L2EP Lille and LTE-INRETS according to MEGEVH network).