Joint Summer School EMR’12
“Energetic Macroscopic Representation”

« Energetic Macroscopic Representation (EMR) »

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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
EMR basic elements
**Interaction principle**
Each action induces a reaction

Power exchanged between S1 and S2 = action x reaction

**Example**

\[ P = V_{bat} i_{load} \]
Principle of causality
physical causality is integral

\[ \int x \, dt \quad \rightarrow \quad \text{area} \]

OK in real-time

\[ \text{knowledge of past evolution} \]

\[ t_1 \]

\[ \text{slope} \]

\[ \frac{dx}{dt} \]

impossible in real-time

knowledge of future evolution

input

cause

output

effect
Energy is the integrative of power

\[ Energie(t) = \int_{0}^{t} Power(\tau) d\tau \]

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

Energy cannot vary instantaneously!

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

\( \Rightarrow \) 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):

\[ E = \frac{1}{2} C V^2 \]

\[ \text{variable linked to energy} = \text{voltage } V \]
\[ \text{the voltage } V \text{ of a capacitor cannot vary instantaneously} \]
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 $\Omega$
- angular speed $\Omega$ 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
terminal elements which represent the environment of the studied system
generator and/or receptor of energy

Source

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

- Energetic sources -

power system

upstream source

action

reaction

\[ p_1 = x_1 \cdot y_1 = \sum_{i=1}^{n} x_{1i} y_{1i} \]

direction of positive power (convention)

\[ p_2 = x_2 \cdot y_2 \]
- Energetic sources: examples (1) -

**Battery**

- Structural description
  - $V_{DC}$
  - $i$

- EMR (functional description)
  - $p = V_{DC} i$

**Electrical grid**

- 2 independent currents
  - $i_1$
  - $i_2$

- 2 independent voltages
  - $u_{13}$
  - $u_{23}$

- $u = \begin{bmatrix} u_{13} \\ u_{23} \end{bmatrix}$
- $i = \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}$
Battery
(voltage source)
generator and
receptor of energy

Energetic sources: examples (2)

Battery
(voltage source)
generator and
receptor of energy

IC engine
(torque source)
Energy generator

Lighting bulb
Energy receptor

Wind
(air flow source)
Energy generator

\( V_{DC} \)

\( T_{ice} \)

\( \Omega \)

\( u \)

\( P_{load} \)

\( q_{wind} \)

\( i \)

\( T_{ice} \)

\( \Omega \)

\( P_{load} \)

\( q_{wind} \)
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

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

\[ y \propto \int f(x_1, x_2) dt \]

\( y = \text{output, delayed from input changes} \)

\( p_1 = x_1 \cdot y \)
\( p_2 = x_2 \cdot y \)
- Accumulation elements: examples (1) -

**inductor**

\[ L \frac{d}{dt} i + r_L i = v_1 - v_2 \]

**3-phase line**

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

**Structural description**

**Mathematical model**

**EMR (causal representation)**
- Accumulation elements: examples (2) -

**Inductor**

\[ E = \frac{1}{2} L i^2 \]

**Capacitor**

\[ E = \frac{1}{2} C v^2 \]

**Inertia**

\[ E = \frac{1}{2} J \Omega^2 \]

**Stiffness**

\[ E = \frac{1}{2} k T^2 \]
- Conversion elements -

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)

no delay!

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

action / reaction

$$P_1 = x_1 \cdot y_1$$

$$P_2 = x_2 \cdot y_2$$

$$y_2 = f(x_1, z)$$

$$y_1 = f(x_2, z)$$
Conversion element pictograms -

Square = electrical conversion

Circle = electromechanical conversion

Triangle = mechanical conversion

For multiphysical systems

Square = monophysicial conversion

Circle = multiphysical conversion
Square = monophysical conversion

Circle = multiphysical conversion

\[ V_{DC} \]

\[ i_{conv} \]
\[ u_{conv} \]
\[ i_{load} \]

\[ \begin{cases} u_{conv} = m \cdot V_{DC} \\ i_{conv} = m \cdot i_{load} \end{cases} \]

\[ m : \text{ modulation function of the converter} \]
\[ \langle m \rangle = D = \text{duty cycle} \]
\[ V_{\text{DC}} \]

Energetic Macroscopic Representation

- Conversion elements: examples -

\[
\begin{align*}
L \frac{d}{dt} i_{\text{dcm}} + r i_{\text{dcm}} &= u - e_{\text{dcm}} \\
T_{\text{dcm}} &= k_\Phi i_{\text{dcm}} \\
e_{\text{dcm}} &= k_\Phi \Omega \\
J \frac{d}{dt} \Omega_2 &= T_{\text{gear}} - T_3
\end{align*}
\]
« Energetic Macroscopic Representation »

- Coupling elements -

coupling elements

- overlapped pictograms
- background: orange
- contour: red

electro mechanical coupling

mechanical coupling

distribution of energy

no tuning vector

More general pictograms

Monophysical coupling

multiphysical coupling

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Multiphysical coupling elements

- Overlapped pictograms
  - Background: orange
  - Contour: red

Monophysical coupling

Parallel connexion

\[
\begin{align*}
V_{DC} & \quad i_1 \\
i_{coup} & \quad v_{coup1} \\
i_2 & \quad v_{coup2}
\end{align*}
\]

\[
\begin{align*}
V_{coup1} &= V_{DC} \\
v_{coup2} &= V_{DC} \\
i_{coup} &= i_1 + i_2
\end{align*}
\]
Field winding DC machine

\[ \begin{align*}
T_{dcm} &= k i_{exc} i_{arm} \\
e_{dcm} &= k i_{exc} \Omega
\end{align*} \]

Mechanical differential

\[ \begin{align*}
T_{ldiff} &= T_{rdiff} = \frac{T_{gear}}{2} \\
\Omega_{diff} &= \frac{\Omega_{lwh} + \Omega_{rwh}}{2}
\end{align*} \]
« EMR of a whole system »
- Example of an electromechanical conversion system -

**CONVENTION:** direction of positive power flow (could be negative for bidirectional system)
Technical requirements: action on $z_{23}$ and $x_7$ to be controlled

Tuning path: $x_3 \rightarrow x_4 \rightarrow x_5 \rightarrow x_6 \rightarrow x_7$

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**

\[
\frac{d}{dt} i_L = V_{DC} - u
\]

\(i\) state variable
Association rules: merging rule

2 accumulation elements would impose the same state variable $x_1$

Conflict of association

merging

1 equivalent function for 2 elements / systemic
DC machine and smoothing inductor

\[ L_f \frac{di}{dt} = u - u_2 - r_f i \]

\[ L_m \frac{di}{dt} = u_2 - e - r_m i \]

Assumption: \( L_f, L_m \) constant

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

Shaft + gearbox

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

\[
\begin{align*}
T_2 &= k T_3 \\
\Omega_2 &= k \Omega_1
\end{align*}
\]

\[
\frac{J}{k^2} \frac{d}{dt} \frac{1}{\Omega_2} = T'_2 - T_3
\]

\[
\begin{align*}
T_2' &= \frac{1}{k} T_1 \\
\Omega_1 &= \frac{1}{k} \Omega_2
\end{align*}
\]

no assumption
strict equivalence (same model)
Assumptions:

- \( J_1, J_2 \) constant
- no backslash

To solve conflict of association

Permutation

Merging

\[ J_{eq} = \frac{J_1}{k^2} + J_2 \]
Energetic Macroscopic Representation

- Lift example: EMR -

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- Lift example: tuning path -

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Conclusion
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

Priority to the function by keeping the physical causality (systemic)
« BIOGRAPHIES AND REFERENCES »
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