« Study of Energetic Systems using Energetic Macroscopic Representation »

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(University Lille1, L2EP, MEGEVH, France)

http://emrwebsite.org/

based on the works of “eV” group of Control team of L2EP Lille
1. Research at L2EP / Univ. Lille1

2. Requirements for study of EVs and HEVs

3. EMR and Inversion-based control

4. Example of an EV

5. More advanced Example

Simulation of an EV
at the crossroad of Paris, London and Brussels

Lille and suburbs more than 1.5 million inhabitants
4 universities
(150,000 students)
University of Lille 1
(30,000 students)
Laboratory of Electrical Engineering and Power (L2EP)

http://l2ep.univ-lille1.fr/

28 professors and associate professors, 41 PhD students, 12 technical and administrative staff
« Study of energetic systems using EMR »

- Research at L2EP -

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« Numerical Modelling »
Prof. S. Clénet

« Optimisation »
Prof. M. Hecquet

« Control »
Prof. B. Lemaire-Semail

« Electrical grid »
Prof. B. Robyns

« Power Electronics »
Prof. P. Le Moigne
« Study of energetic systems using EMR »

- “Control” team of L2EP -

Prof. B. Lemaire-Semal

Modelling and control tools
(COG, EMR, BMC, resonant controllers..)

Formalisms bring solutions for new applications

New applications lead to the improvement of formalisms
« Study of energetic systems using EMR »

- Modeling and control tools -

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1980 1990 2000 2010

Power Electronics  Electric Drives  Electromechanical Systems

[Petri Nets (use)]  [COG] Causal Ordering Graph  [LEEI Toulouse (France)]

[LEEI / GREEN LESiR / GE44 GdR SDSE-ME₂MS (France)]

[LEEI / GREEN LESiR / GE44 GdR SDSE-ME₂MS (France)]

[MMS] Multimachine Multiconverter System description

[Univ. Trois Rivières (Ca)]
[EPF Lausanne (CH)]
[FEMTO-ST]
[MEGEVH network]

[EMR] Energetic Macroscopic Representation

[Lei]  [Hautier 1996]  [SMM 2000]  [Bouscayrol 2003]
Study of energetic systems using EMR

- Graphical description and Education -

• University of Lille, Polytech Lille, EC Lille
  – Master 1: COG - EMR initiation
  – Master 2: COG - EMR further development

• Other French Universities and Engineering Schools
  – COG: Toulouse, Cachan, Belfort, CNAM Paris

• Universities abroad France
  – Univ. de Québec Trois-Rivières (since 2002)
  – EPF Lausanne (since 2005)

• EMR Summer Schools
  – EMR’06, Lille (France) / EMR’08, Harbin (China)
  – EMR’09, Trois Rivières (Canada)
  – EMR’11, Lausanne (Switzerland) / EMR’12, Madrid (Spain)
  – EMR’13 Lille (France) / EMR’14 Coimbra (Portugal)
Study of energetic systems using EMR

- Collaborations using graphical descriptions -

Industries: EADS, ETEL, Nexter System, PSA Peugeot Citroën, ST-micro, SNCF, Siemens Transportation Systems, Valéo …
- Scientific Influence -

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1. Special sessions in Conferences
   “Graphical descriptions for modelling and control”
   - *IEEE-IECON’06* (Paris), *ElectriMACS’08* (Québec), *IEEE-VPPC’09* (Detroit),
   - *IEEE-VPPC’10* (Lille), *IEEE-VPPC’11* (Chicago)
   “HEVs modelling and control” (within the framework of *MEGEVH*)
   - *IEEE-VPPC’06* (Windsor, UK), *IEEE-VPPC’08* (Harbin, China), *IEEE-VPPC’10* (Lille)
   “Hardware-In-the-Loop simulation” (within the framework of *MEGEVH*)
   - *IEEE-VPPC’07* (Dallas), *IEEE-VPPC’08* (Harbin, China), *IEEE-ISIE’08* (Cambridge, UK)
   “Multiphase drives”
   - *IEEE-VPPC’10* (Lille)

2. Tutorials & Keynotes in international conferences
   “Tactile actuators”, *EuroHaptics’06* (Paris), *ECCE-EPE’11* (Birmingham)
   “Hardware-In-the-Loop simulation”, *EVS’24* (Stavanger, Norway, 2009)
   “HEVs energy management”, *IEEE-VPPC’09* (Detroit), *IEEE-IECON’09* (Porto)
   “HEV and EMR”, *IEEE-VPPC’13* (Beijing)

3. Guest Editors of archival journals
   “Hardware-In-the-Loop simulation”, IEEE trans. on Industrial Electronics (2010)
   “Advanced transportation systems”, IEEE trans. on Vehicular Technology (2011)

4. Conference organizations
   - *IEEE-VPPC 2010* (Lille) *EPE-ECCE 2013* (Lille)
2. Requirement for the study of EVs and HEVs

Based on the works of MEGEVH, French network on HEVs
MEGEVH

- MEGEVH network -

Coordination:
Prof. A. Bouscayrol

6 projects
7 PhDs in progress
6 PhDs defended
8 industrial partners
10 academic Labs

http://l2ep.univ-lille1.fr/megevh.htm

MEGEVH
French network on HEV's

(Energy management of Hybrid Electric Vehicles)
- MEGEVH philosophy -

**theoretical developments**

<table>
<thead>
<tr>
<th>MEGEVH-macro</th>
<th>MEGEVH-strategy</th>
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<tbody>
<tr>
<td>MEGEVH-optim</td>
<td>MEGEVH-FC</td>
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<tr>
<td>MEGEVH-store</td>
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Development of modelling and energy management methods independently of the kind of vehicle

**experimental platforms**

Reference vehicle

**Paper Prize Award of IEEE-VPPC’08**

**Paper Prize Award of IEEE-VPPC’12**

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Thermal vehicle:
- fossil fuel
- pollution
- low efficiency

Electric Vehicle:
- long charging time
- low range
- battery cost

Fuel Cell vehicle:
- H2 production
- Fuel Cell cost
- Fuel cell lifetime

Think city
http://www.thinkev.com/

Honda Clarity FX
http://www.honda.com/
Hybrid vehicle:

- several source of energy
- advantage of each technology
- important cost
- complex control

Key issues for HEVs:

1. topologies of the power train
2. design of sources and components
3. control and energy management
« Study of energetic systems using EMR »

- HEV topologies -

Parallel HEV

Series HEV

Series Parallel HEV
A lot of operation modes to deals with the control design must include energy management
Studies of energetic systems using EMR

- Control and energy management -

**Parallel HEV**

- **Fast subsystem controls**
  - EM1 control
  - ICE control
  - Trans control

- **Slow system supervision**
  - Energy management (supervision/strategy)

**Driver request**
« Study of energetic systems using EMR »

- How to study HEVs? -

• low energy consumption
• low pollutant emissions
• large drive range

• adapted topology
• balanced design
• structure control

to achieve together

But more complex than for Thermal Vehicle or Electric Vehicle
• multi-physical devices
• more power flows
• various interconnected subsystems

An energetic modeling is required
to take into account the different power flows and the subsystems interactions

(for model-based control)
Based on the works of “control team” of L2EP
Simulation for ever!
Launching Matlab/Simulink is more and more a “Pavlov reflex”

But:
• Why simulation?
• Which constraints and objectives?
• Which level of accuracy?
• How to be sure of the results?
« Study of energetic systems using EMR »

- From real system to simulation -

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Intermediary steps are required for complex systems

real system

Limitation to main phenomena in function of the objective

Organization of the model to highlight some properties

From real system to simulation

assumptions

system model

no assumption

system representation

assumptions

system simulation
« Study of energetic systems using EMR »

- Basic example -

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Real system → Assumptions → System model  

→ Assumptions → System representation  

→ Assumptions → System simulation

\[ v_I = L \frac{d}{dt} i_L + R i_L \]

(Velocity of the inductor)

\[ V_L = \frac{I}{R + L s} \]

(Voltage of the inductor)

Smoothing inductor  

(low frequency dynamical model)  

(bloc diagram + Laplace)  

(Simulink © + Runge Kutta)
Different possibilities at each step in function of the objective
EUREKA!

Fingers in the pockets!

But block diagrams:
- can be confusing for complex systems
- are limited to continuous and linear systems
- do not highlight energy properties
- do not highlight interaction between subsystems
System = interconnected subsystems organized for a common goal

Systemic approach
Study of subsystems and their interactions
Holistic property: associations of subsystem induce new global properties.

Cartesian approach
The study of subsystems is sufficient to know the system behaviour.

Cybernetic systemic
black box approach. behaviour model

Cognitive systemic
physical laws knowledge model

For better performances of a system
Interactions and physical laws must be considered!
Interaction principle
Each action induces a reaction

Example

Power exchanged by S1 and S2 = action x réaction

\[ P = V_{bat} i_{load} \]
If the interaction principle is not respected for 1 subsystem

Error in the energy analysis for the whole system

(reaction = 0)

Power = 0
Principle of causality
physical causality is integral

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

OK in real-time

knowledge of past evolution

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

impossible in real-time

knowledge of future evolution

input cause

output effect

slope

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Example

\[ i_c = C \frac{d}{dt} v_c \]

\[ E_c = \frac{1}{2} Cv_c^2 \]

For energetic systems
physical causality is VITAL
If the causality principle is not respected for 1 subsystem

Risk of damage!
No real-time management
« 3a. Energetic Macroscopic Representation »

Based on the works of “control team” of L2EP
- The different elements -

An energetic system:

Energy sources
Energy storage elements
Energy conversion elements
Energy distribution elements

Key elements are:

• energy storage element
  
  (delay, state variable, closed-loop control)

• energy distribution element
  
  (power flow coupling, control with criteria)


- Energetic sources -

Terminal elements which represent the environment of the studied system generator and/or receptor of energy

Source

Oval pictogram
- Background: light green
- Contours: dark green
- 1 input vector (dim n)
- 1 output vector (dim n)

Power System

\[ p_1 = x_1 \cdot y_1 = \sum_{i=1}^{n} x_i y_i \]
\[ p_2 = x_2 \cdot y_2 \]

Direction of positive power (convention)

Action

Upstream source

Reaction

Downstream source
- Energetic sources: examples (1) -

**Battery**

\[ V_{DC} \]

\[ i \]

\[ p = V_{DC} i \]

**Electrical grid**

\[ u_{13} \]

\[ u_{23} \]

\[ i_1 \]

\[ i_2 \]

\[ u = \begin{bmatrix} u_{13} \\ u_{23} \end{bmatrix} \]

\[ i = \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \]

2 independent currents!

2 independent voltages!
Battery
(voltage source)
generator and receptor of energy

Battery
(voltage source)
generator and receptor of energy

IC engine
(torque source)
generator of energy

Wind
(air flow source)
generator of energy

Ligthing bulb
receptor of energy
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- Accumulation elements -

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internal accumulation of energy (with or without losses)

causality principle

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

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

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

fixed I/O (causal description)

- Accumulator

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

action

reaction

\[ p_1 = x_1 \cdot y \]

\[ p_2 = x_2 \cdot y \]
« Study of energetic systems using EMR »

- Accumulation elements: examples (1) -

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**Inductor**

Structural description:

\[
\begin{align*}
L \frac{di}{dt} + r_L i &= v_1 - v_2 \\
\end{align*}
\]

Mathematical model:

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

EMR (causal representation):

- Accumulation elements: examples (1) -
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 elements -

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

Various pictograms
- background: orange
- contour: red

- upstream I/O vectors (dim n)
- downstream I/O vectors (dim p)

Possible tuning input vector (dim q)

Action / reaction

\[
\begin{align*}
    z &= \begin{cases}
        y_2 = f(x_1, z) \\
        y_1 = f(x_2, z)
    \end{cases} \\
    p_1 &= x_1 \cdot y_1 \\
    p_2 &= x_2 \cdot y_2
\end{align*}
\]

No delay!

Upstream and downstream I/O can be permuted
(floating I/O)
Circle = multiphysical conversion

Circle = multiphysical conversion

Square = monophysical conversion

\[ m: \text{ modulation function of the converter} \]

\[ \langle m \rangle = D = \text{duty cycle} \]
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- Conversion elements: examples -

\[ V_{DC} \]

\[ s \]

\[ u_{conv} \]

\[ i_{load} \]

\[ i_{conv} \]

\[ V_{DC} \]

\[ u_{conv} \]

\[ i_{load} \]

\[ i_{conv} \]

\[ V_{DC} \]

\[ u_{conv} \]

\[ i_{load} \]

\[ i_{conv} \]

\[ m \]

\[ \begin{align*}
  u_{conv} &= m \ V_{DC} \\
  i_{conv} &= m \ i_{load}
\end{align*} \]

\[ \begin{align*}
  L \ \frac{d}{dt} i_{dcm} + r \ i_{dcm} &= u - e_{dcm} \\
  T_{dcm} &= k_\Phi \ i_{dcm} \\
  e_{dcm} &= k_\Phi \ \Omega
\end{align*} \]

\[ \begin{align*}
  T_{gear} &= k_{gear} \ T_1 \\
  \Omega_{gear} &= k_{gear} \ \Omega_2 \\
  J \ \frac{d}{dt} \ \Omega_2 &= T_{gear} - T_3
\end{align*} \]
Study of energetic systems using EMR

- Coupling elements -

Bat

coupling elements

overlapped pictograms
background: orange
contour: red

Monophysical coupling

distribution of energy

no tuning vector

parallel connexion

\[ V_{DC} \]

\[ i_1 \]

\[ i_2 \]

\[ v_{coup1} \]

\[ v_{coup2} \]

\[ i_{coup} \]

\[ \begin{align*}
V_{DC} & = V_{DC} \\
vcoup1 & = V_{DC} \\
vcoup2 & = V_{DC} \\
i_{coup} & = i_1 + i_2
\end{align*} \]
Field winding DC machine

\[ T_{dcm} = k i_{exc} i_{arm} \]
\[ e_{dcm} = k i_{exc} \Omega \]

Mechanical differential

\[ T_{ldiff} = \frac{T_{rdiff}}{2} \]
\[ \Omega_{diff} = \frac{\Omega_{lwh} + \Omega_{rwh}}{2} \]
« 3b. Inversion-based control »

Based on the works of “control team” of L2EP
In collaboration with Prof. P. Sicard
(Univ. Quebec Trois Rivières, Canada)
« Study of energetic systems using EMR »

- Principle of Inversion-based methodology -

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System

cause

effect

Control

right cause

desired effect

input

output

measurements?

control = inversion of the causal path

[Hautier 96]

1. Which algorithm? (how many controllers)
2. Which variables to measure?
3. How to tune controllers?
4. How to implement the control?

Inversion-based methodology

automatic control

industrial electronics
EMR = system decomposition in basic energetic subsystems (SSs)

Inversion-based control: systematic inversion of each subsystems using open-loop or closed-loop control.
output depends on a single input without delay

**Example:**

\[ y(t) = K u(t) \]

**Example: Resistance**

\[ i(t) = \frac{1}{R} v(t) \]

1. no measurement
2. no controller
   (open-loop control)

Assumption: \( K \) well-know and constant
Output depends on several inputs without delay

Example:

\[ y(t) = u_1(t) + u_2(t) \]

- \( u_1 \) is chosen to act on the output \( y \)
- \( u_2 \) becomes a disturbance input

Assumption: \( u_2 \) well-know and can be measured

1. measurement of the disturbance input
2. no controller (open-loop control)
Example:

- Inversion 3: single-input causal relationship -

output depends on a single input and time (delay) → causality principle

\[ y(t) = \int u(t) dt \]

1. measurement of output
2. a controller is required (closed-loop control)

\[ u(t) = \frac{d}{dt} y_{ref}(t) \]

\[ u(t) = C(t) \left[ y_{ref}(t) - y_{meas}(t) \right] \]

closed loop controller
multi-input causal relationship

\[ \Delta u = u - e \]

\[ L_m \frac{di}{dt} = \Delta u - r_m i \]

direct inversion

closed-loop
Objective: to control $y_2$

\[ y_2 = f(u_1, u_{21}) \]

Manipulate $u_{21}$ → $u_1$ is a disturbance

**Ex**: H-bridge chopper

\[
\begin{align*}
    u_{Hb} &= m_{Hb} V_{DC} \\
    i_{Hb} &= m_{Hb} i_{dcm}
\end{align*}
\]

\[ m_{Hb} = \frac{u_{Hb\_ref}}{V_{DC\_meas}} \]
Objective: to control $y_2$

$y_2 = f(u_1)$

Example: pulley or roller

\begin{align*}
V_{trans} &= r_{pull} \Omega_1 \\
T_{trans} &= r_{tpull} F_{load}
\end{align*}

$$\Omega_{1_{-ref}} = \frac{\Omega_{trans_{-ref}}}{r_{tpull}}$$

$\Omega_{1_{-ref}}$ $V_{trans_{-ref}}$
Objective: to control $y_2$

$y_2 = f(u_1, u_2)$

$f$ is in integral form

Direct inversion is in derivative form

Approximate inversion by closed loop control

 Manipulate $u_1$  $u_2$ is a disturbance

Ex : rotating shaft

\[ J \frac{d}{dt} \Omega + f \Omega = T_{em} - T_{load} \]

\[ T_{em\_ref} = C(t)(\Omega_{ref} - \Omega_{meas}) + T_{load\_meas} \]

\[ \Omega_{meas} \]

\[ \Omega_{ref} \]

\[ T_{load\_meas} \]
Example: chassis of a train

\[
\begin{align*}
F_{\text{bog}1} & \quad v_{\text{train}} \\
F_{\text{bog}2} & \quad v_{\text{train}} \\
F_{\text{bog}3} & \quad v_{\text{train}} \\
F_{\text{bog}4} & \quad v_{\text{train}} \\
\end{align*}
\]

no measurement
no controller
(m - p) distribution variables

\[
\begin{align*}
\begin{cases}
    u_{11} = k_{D1} y_{2-ref} \\
    \vdots \\
    u_{1m} = k_{Dm} y_{2-ref}
\end{cases}
\end{align*}
\]
1. EMR of the system
2. Tuning path
3. Inversion step-by-step

Strong assumption: all variables can be measured!

Maximal Control Scheme:
- maximum of sensors
- maximum of operations
1. EMR of the system
2. Tuning path
3. Inversion step-by-step
4. Simplification of the control scheme
5. Estimation of non-measured variables
6. Tuning of controllers

Simple tuning is possible by time coordination/separation of the control loops

3b. Strategy

PID controller
Calculation of $k_p, k_i, k_d$
Specific pictograms for the analysis of power flows:
• source of energy (green oval)
• accumulation of energy (orange crossed rectangle)
• conversion of energy (orange square or circle)
• distribution of energy (overlapped pictograms)

Better understanding, efficient energy management
Remember, Divide and conquer!
« 4. Inversion-based control of an EV »

T. Letrouvé, with the preparation of W. Lhomme
based on the works of “control team” of L2EP
« Study of energetic systems using EMR »

- System Modeling using EMR -

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Study of energetic systems using EMR

- System Modeling using EMR -

Battery \[ u_{bat} \] to chopper \[ u_{cha} \] using \[ m_{cha} \].

\[
\begin{align*}
u_{cha} &= m_{cha} u_{bat} \\
i_{cha} &= m_{cha} i_{a}
\end{align*}
\]
without saturation of the DC machine
« Study of energetic systems using EMR »

- System Modeling using EMR -

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\[ T_{em} = k_\Phi i_a \]

\[ e_a = k_\Phi \Omega_{em} \]
neither the contact law nor curving road
Study of energetic systems using EMR

- System Modeling using EMR -

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battery

chopper

DC machine

Trans-wheels

chassis

\[ u_{bat} \rightarrow i_{tot} \rightarrow i_{cha} \rightarrow u_{cha} \rightarrow i_a \rightarrow \Omega_{em} \rightarrow T_{em} \rightarrow \Omega_{dif} \rightarrow T_{dif} \rightarrow \Omega_{w1} \rightarrow T_{red} \rightarrow v_{ev} \rightarrow F_{res} \]

\[ E_\text{s} \]

\[ u_{bat} \rightarrow u_{cha} \rightarrow i_a \rightarrow e_a \rightarrow T_{em} \rightarrow F_{tran} \rightarrow v_{ev} \rightarrow F_{res} \]

\[ M \frac{d}{dt} v_{ev} = F_{tran} - F_{res} \]
\[ F_{\text{res}} \approx F_{\text{drag}} + F_{\text{slope}} \]

\[ F_{\text{drag}} = \frac{1}{2} \rho_{\text{air}} S_{\text{front}} C_x v_{\text{ev}}^2 \]

\[ F_{\text{slope}} = M g \sin(\alpha) \]

« Study of energetic systems using EMR »

- System Modeling using EMR -

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« Study of energetic systems using EMR »

- System Modeling using EMR -

Barcelona, November 2013

battery

chopper

DC machine

Trans- wheels

chassis

environ.

$u_{bat}$

$i_{tot}$

$u_{cha}$

$i_a$

$T_{em}$

$F_{tran}$

$v_{ev}$

$F_{res}$

$E_{S}$

$M_{cha}$

$e_a$

$\Omega_{em}$

$v_{ev}$
Step 3a: By inversion of tuning path, obtain control path

- Inversion-based Control -

```
\text{battery} \quad \text{chopper} \quad \text{DC machine} \quad \text{Trans- wheels} \quad \text{chassis} \quad \text{environ.}
```

```
\text{ES} \quad \text{chopper} \quad \text{DC machine} \quad \text{Trans- wheels} \quad \text{chassis} \quad \text{environ.}
```

```
\text{ES} \quad \text{chopper} \quad \text{DC machine} \quad \text{Trans- wheels} \quad \text{chassis} \quad \text{environ.}
```

```
\text{ES} \quad \text{chopper} \quad \text{DC machine} \quad \text{Trans- wheels} \quad \text{chassis} \quad \text{environ.}
```
Step 3b: Maximum Control Structure

\[ M \frac{d}{dt} v_e = F_{\text{tran}} - F_{\text{res}} \]

\[ F_{\text{tran}} \quad + \quad \frac{1}{M} \quad \frac{d}{dt} \quad v_e \quad + \quad v_e \]

\[ F_{\text{res}} \quad - \quad F_{\text{res\_mea}} \quad + \quad v_{e\_\text{mea}} \]

\[ F_{\text{tran\_ref}} \quad + \quad + \quad C(s) \quad - \quad + \quad v_{e\_\text{ref}} \]

Battery \quad \rightarrow \quad Chopper \quad \rightarrow \quad DC \, machine \quad \rightarrow \quad Trans-\, wheels \quad \rightarrow \quad Chassis \quad \rightarrow \quad Environ.
Step 3b: Maximum Control Structure

- Inversion-based Control -

\[ T_{\text{em}} \]
\[ \Omega_{\text{em}} \]
\[ F_{\text{tran}} \]
\[ k_{\text{red}} \]
\[ R_{\text{wh}} \]
\[ \frac{k_{\text{red}}}{R_{\text{wh}}} \]

Battery
Chopper
DC machine
Trans-wheels
Chassis
Environment

\[ F_{\text{tran}} = \frac{k_{\text{red}}}{R_{\text{wh}}} \]
\[ \Omega_{\text{em}} = \frac{k_{\text{red}}}{R_{\text{wh}}} v_{\text{ev}} \]

\[ T_{\text{em}} \]
\[ F_{\text{tran}} \]
\[ v_{\text{ev}} \]
\[ F_{\text{res}} \]

\[ k_{\text{red}} \]
\[ R_{\text{wh}} \]

\[ T_{\text{em\_ref}} \]
\[ F_{\text{tran\_ref}} \]
\[ v_{\text{ev\_ref}} \]
Step 3b: Maximum Control Structure

- Inversion-based Control -

$$T_{em} = k_\Phi I_a$$
$$e_a = k_\Phi \Omega_{em} e_v$$
Step 3b: Maximum Control Structure

- Inversion-based Control -

batterychopperDC machineTrans-wheelschassis environ.

$\text{battery} \rightarrow \text{chopper} \rightarrow \text{DC machine} \rightarrow \text{Trans-wheels} \rightarrow \text{chassis} \rightarrow \text{environ.}$

\[ u_{bat} \quad i_a \quad T_{em} \quad F_{tran} \quad v_{ev} \]

\[ v_{ev} = \frac{1}{R} \left( \frac{i_a}{1 + L / Rs} \right) \]

\[ u_{cha} = u_{cha_{ref}} \quad e_a = e_a_{mea} \quad C(s) \quad i_{a_{ref}} \]
Step 3b: Maximum Control Structure

\[
\begin{align*}
    u_{bat} & \quad \rightarrow \quad u_{cha} \\
    i_{tot} & \quad \rightarrow \quad i_{a} \\
    & \quad \rightarrow \quad e_{a} \\
    & \quad \rightarrow \quad T_{em} \\
    & \quad \rightarrow \quad F_{tran} \\
    & \quad \rightarrow \quad v_{ev} \\
    & \quad \rightarrow \quad F_{res} \\
\end{align*}
\]

**Battery** \( u_{bat} \) \( \rightarrow \) **Chopper** \( u_{cha} \) \( \rightarrow \) **DC Machine** \( i_{a} \) \( \rightarrow \) **Transmission Wheels** \( T_{em} \) \( \rightarrow \) **Chassis** \( F_{tran} \) \( \rightarrow \) **Environment** \( v_{ev} \) \( \rightarrow \) **Motor System** \( F_{res} \)

**PWM**

\[
\begin{align*}
    u_{cha} & = m_{cha} u_{bat} \\
    i_{cha} & = m_{cha} i_{a} \\
    m_{cha} & \quad \rightarrow \quad u_{cha_ref} \\
    u_{cha_ref} & \quad \rightarrow \quad i_{a_ref} \\
    T_{em_ref} & \quad \rightarrow \quad F_{tran_ref} \\
    v_{ev_ref} & \quad \rightarrow \quad u_{cha_ref} \\
\end{align*}
\]
Step 3b: Maximum Control Structure

Inversion-based Control

Battery \rightarrow Chopper \rightarrow DC Machine \rightarrow Transmission Wheels \rightarrow Chassis \rightarrow Environment

$u_{bat}$ $i_{tot}$ $u_{cha}$ $i_a$ $T_{em}$ $F_{tran}$ $v_{ev}$

$m_{cha}$

$m_{cha\text{\_ref}}$ $u_{cha\text{\_ref}}$ $i_{a\text{\_ref}}$ $T_{em\text{\_ref}}$ $F_{tran\text{\_ref}}$ $v_{ev\text{\_ref}}$
Step 4: Practical control structure - simplification
« Study of energetic systems using EMR »

- Inversion-based Control -

Step 4: Practical control structure - estimation
- Inversion-based Control -

Step 6: Control tuning – Step 7: implementation

- Diagram of energetic system control unit with labels:
  - Battery
  - Power electronics
  - Electric machine
  - Control unit

- Variables:
  - $m_{cha}$
  - $m_{cha_{ref}}$
  - $u_{cha_{ref}}$
  - $i_{a_{ref}}$
  - $T_{em}$
  - $T_{em_{ref}}$
  - $F_{tran}$
  - $F_{tran_{ref}}$
  - $v_{ev}$
  - $v_{ev_{ref}}$
  - $\Omega_{em}$
  - $\Omega_{em_{ref}}$
« 5b. Application to other innovative systems »

Based on the works of “control team” of L2EP and on MEGEVH
Objective of the “electricity & vehicle” (eV) platform of the control team: real-time validation of energy management of new vehicle concepts for more efficient and less pollutant transportation systems.

- **pre-validation on the “eV” platform**
  - flexible power and control devices
  - HIL simulation

- **validation on a real prototype**
  - real vehicle
  - IBC and EMS integration

Ex: PhD of T. Letrouvé (double parallel HEV of PSA)

Simulation of the 3008 HY4 using EMR
HIL simulation of the 3008 HY4 traction system (« ev » platform)
Validation of the control on the 3008 HY4 prototype
**Flexibility**: “eV” is the open platform of MEGEVH for the real-time validation of various concepts of new vehicles.

- **dSPACE 1103**: 10 kW converters
- **dSPACE 1005**: 50 kW converters
- **10 kW PMSM+DCM**
- **20 kW MSAP+IM**
- **2 kW MS+IM+DCM**
- **2 kW MS+IM+DCM**
- **2 kW MS+IM+DCM**
- **10 kW MS+IM+DCM**

**Studied Vehicle**: (power components + HIL simulations)

- **Pb Bat**
- **NiMH Bat**
- **Li-ion Bat**
- **DP geartrain + machines**
- **e-bike (Li-ion)**
- **e-scooter (NiMH)**
- **EV Tazzari Zero**

**Flexibility**: eV is the open platform of MEGEVH for the real-time validation of various concepts of new vehicles.
Collaboration: a valuable platform for industrial and international collaborations with the framework of EMR methodology.
« Study of energetic systems using EMR »

- Control of subway VAL 206 traction system -

Barcelona, November 2013

rail  power electronics  DC machines  mechanical power train  environ.

EMR

control

simplifications [Verhille & al. 2007]
New strategy: slip detection

Reduction of torque of the slipping wheel

Increase of other torques

experimental validation using HIL simulation

[Verhille & al. 2007]
Master of T. Bossman, 2006

« Study of energetic systems using EMR »
- EMR of a hybrid storage system -

PV panel
DC/DC
DC/AC
supercapacitor bank
DC/DC
DC/AC
PMSM
air compressed accumulators
hydraulic machine
oil tank
(Switzerland)
EPFL [Bossmann & al. 2007]
« Study of energetic systems using EMR »

- EMR of a hybrid storage system -

Master of T. Bossman, 2006

(Switzerland)

EPFL [Bossmann & al. 2007]
« Study of energetic systems using EMR »

- EMR of a hybrid storage system -

Barcelona, November 2013
Automatic subway VAL supplied by a DC rail

- energy savings
- cost reduction
- safety operation
- modern product

Supercapacitor storage system without supply rail

1. Sizing of on-board energy
2. Sizing of Supercaps bank
3. Different topologies of power electronics
4. Simulation of the global system using EMR

Matlab-Simulink model of VAL 206

Supercapacitor bank of L2EP

[Allègre & al. 2010]
« Study of energetic systems using EMR »

- Subway NeoVAL using supercapacitor -

ESS in station

1. Grid
2. Computer
3. Fibre optique
4. SMES in station
5. On-board ESS

ESS in station

1. Slow charge of SC1
2. Fast transfer to SC2
3. Traction operation
4. Energy recovery

Next steps:
- Full-scale HIL simulation test on a real vehicle

Barcelona, November 2013
High-redundancy HEV

[Boulon & al. 2010]
Strategy = coordination of subsystems

[Boulon & al. 2013]

- High-redundancy HEV -
Series–Parallel HEVs:
• high efficiency for cars (e.g. Toyota Prius)
• use of a single planetary geartrain (SPG)
• use of 1 ICE and 2 Electric Machines (EMs)

new topology using a EVT
• integration of EMs and SPG

no real comparison between EVT-based and SPG-based HEVs
EMR for the development of the control

**Simulation of a drive cycle (EUDC)**

**Comparison of the EVT-based HEV with Toyota Prius II:**
- EVT-based vehicle has more consumption
- all operation modes and dynamics are possible
- efficiency should be increased at high velocity
- EVT has to be re-design in that objective

[Cheng & al. 2011]
Energetic systems require new tools and more interactions.

A graphical description could be a valuable step to respect physics’ principle and to organize the control … such as EMR.

Interaction between Academics and Industry is a key issue… such as MEGEVH.
IEEE Vehicle Power and Propulsion Conference
“Spreading E-Mobility Everywhere”

Coimbra - Portugal
UNESCO World Heritage
October 27-30, 2014

Digests deadline: 31 March 2014
Notification deadline: 18 May 2014
Final paper deadline: 1 July 2014

Organization:

Supported by:

We will be pleased to Welcome you in Coimbra!
References


- References (1) -


