« ENERGY MANAGEMENT STRATEGIES OF HYBRID ELECTRIC VEHICLES (HEVs) »

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Coordination:
Prof. A. Bouscayrol

6 projects
4 PhDs in progress
11 PhDs defended

8 industrial partners
10 academic Labs

(Energy management of Hybrid and Electric Vehicles)

http://www.megevh.org/
- MEGEVH philosophy -

Theoretical developments

- MEGEVH-macro
- MEGEVH-strategy
- MEGEVH-optim

MEGEVH-FC

MEGEVH-store

Development of modeling and energy management methods independently of the kind of vehicle

Experimental plate-forms

Reference vehicles

Paper Prize Award of IEEE-VPPC’08

Paper Prize Award of IEEE-VPPC’12

Paper Award EPE’14 ECCE Europe

Best paper Award IET-EST journal 2015
Energetic Macroscopic Representation

= organization of models of complex systems

Systematic deduction of organization of control schemes

[Bouscayrol 00, 12]
IEEE - Institute of Electrical & Electronics Engineers

- Non-profit professional organization for advancing technological innovation and excellence
- **400,000 members from 160 countries** (30 % students)
- 38 societies on technical interest
- **Activities**
  - scientific workshop, conferences, publications, standards
  - database *IEEE Xplore*, 3.5 millions documents, etc

### IEEE – Vehicular Technology Society (VTS)

- **Technical topics**
  - land, airborne and maritime services
  - mobile communication, vehicle electro-technology
- **2 publications and 4 annual conferences**
- **Distinguished Lecturer Program**

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Prof. A. Bouscayrol

- HIL simulation
- EMR formalism
- EVs and HEVs

Hangzhou, 2016
1. Context of EVs and HEVs

2. Different Kinds of EVs and HEVs

3. Key Issues of EVs and HEVs

4. Energy Management of EVs and HEVs

5. Examples of Innovatives Vehicles

References
1. Context of EVs & HEVs

- Global warming
- Petroleum resources
- Thermal Vehicle
- Green House Gases -

France 2012

Road transport 80%

Transport

Industrial process

Agriculture

Residential / trade

Energy production

Waste (incl. deforestation)

http://www.statistiques.developpement-durable.gouv.fr/ [CGDD 15]
- Green House Gases (2) -

All GHG, World 2010

Transport
Industrial Process
Agricultural
Residential/trade
Energy production
Waste (incl. deforestation)

http://www.citepa.org/
(Centre Interprofessionnel Techniques d'Etudes de la Pollution Atmosphérique)
- Thermal Vehicle -

- Low efficiency
- Pollutant emission
- No energy recovery

Great autonomy
Fast energy charge

Fuel tank
IC engine
gearbox
differential
wheels
chassis

Fuel tank
accelerator
couch
gear ratio
steering wheel
road
- Gasoline engine -

\[ P_{\text{max}} = 60 \text{ ch (45 kW)} @ 3750 \text{ rpm} \]
\[ T_{\text{max}} = 119 \text{ Nm @ 3400 rpm} \]

(1700 cm³)

Iso specific consumption (g/kWh)

Efficiency map
- Future Vehicles? -

- Thermal vehicle with bio-fuels
  (coupling energy & food? water requirement? etc)
- Electric Vehicles
  (production of electricity? autonomy reduction? etc)
- Hybrid Electric vehicles
  (increase of prize? need of fossil fuel? etc)
- Fuel Cell Vehicle
  (increase of prize? hydrogen production? etc)
- Etc.

but also

- A more reasonable mobility!
  (reduction of travels? Increase of common transport? Etc.)
Example of an urban drive cycle

ICE Power (kW)

- Power of a thermal vehicle -

Interest of a system which:
• delivers peak power at high efficiency
• enables energy recovery

\[ P_{\text{max}} = 60 \text{ kW} \]
\[ P_{\text{mean}} = 15 \text{ kW} \]
\[ P < 0 \]
Energy loss
Pollution of a thermal vehicle

Example of a highway drive cycle

78% of pollutant emissions during 14% of the cycle

Interest of a system which:
- enables transients at high efficiency and low emission
- Operation of an ICE -

Urban drive cycle / iso-consumption map

Mean efficiency ~12%
(88% of losses!!)
- Operation of an ICE -

Extra-urban drive cycle / iso-consumption map

Mean efficiency ~20%
2. Different kinds of EVs & HEVs

- Electric Vehicles
- Hybrid Electric Vehicles
- Fuel Cell Vehicles
1830: first mini-electric-train

1890: 3 kinds of vehicles on the automotive market
  thermal / electric / steam

1899: « La Jamais contente » first vehicle
  to reach 100 km/h

1930: last productions of electric vehicles

- technological reasons (autonomy, charging time)
- economical reasons (reduction of the gasoline cost)
- societal reasons (extension of the required range)
- Electric Vehicle -

- Battery
- Power electronics
- Electric machine
- Differential
- Wheels
- Chassis

High efficiency
No local emission
Energy recovery
Low autonomy
Long energy charge

Switch orders
Steering wheel
Road
- Thermal and Electric Vehicles -

**Thermal Vehicle:**
- pollution
- low efficiency

**Electric Vehicle:**
- long charge
- low autonomy

_Nissan leaf_
- Hybrid Electric Vehicles -

Hybrid vehicle:
- advantage of each technology
- higher cost
- complex control

Various configurations:
- different power ratios $P_{ICE}/P_{EM}$
- different component organization

Toyota Prius 3
http://www.toyota.com/

Peugeot 3008 HY4
http://www.mpsa.com
- HEVs or EVs? -

**Range extender EV**

= EV + ICE for higher mileage range

**Plug-in HEV:**

= HEV + charger + plug

**BMW i3**

[Link to BMW i3](http://www.bmw.com/)

**Chevrolet Volt**

[Link to Chevrolet Volt](http://www.chevrolet.com/
- Fuel Cell vehicles? -

Fuel cell vehicle:
= EV with battery replaced by a fuel cell and a H2 tank

FC vehicle with hybrid storage
= another kind of RE-EV

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

Toyota Mirai
http://www.toyota.com/
- H2 production -

Example (Natural Gaz)

\[ \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{C}0 + 3 \text{H}_2 \]

H2 production

- Electrolysis
  \[ \text{H}_2\text{O} + \text{electricity} \rightarrow \frac{1}{2}\text{O}_2 + \text{H}_2 \]

- Thermo-chemistry
  \[ \text{H}_2\text{O} + \text{heat} \rightarrow \frac{1}{2}\text{O}_2 + \text{H}_2 \]

Sources of energy:
- Fossil fuel
- Coal
- Nuclear
- Biomass
- Renewable sources

Experimental processes:
- Electrolysis
- Thermo-chemistry

Electrolysis

96%
Fuel cell = inverse of the electrolysis water

Fuel cell: \[
\frac{1}{2} O_2 + H_2 \rightarrow H_2O + \text{electricity} + \text{heat}
\]

Electrolysis: \[
H_2O + \text{electricity} \rightarrow \frac{1}{2} O_2 + H_2
\]

Pros: no local pollution
Cons: high cost, low lifetime, H2 production

... and 50% efficiency, heat production
New technologies are also used in various vehicles in order to reduce the ecological footprint of transportation systems!
3. Key issues of EVs & HEVs

- Energy Storage Subsystems
- Energy Management
- Societal changes
- Toyota Prius, a success story -

Battery Ni-MH
High energy density

Complex control

High efficiency
Power electronics

Mechanical power path
Electrical power path

Generator
Inverter
Boost
Battery

ECU

Engine
Motor
Power split

Permanent Magnet
Synchronous Machines

Véhicule PRIUS II
http://www.toyota.com/
- Architecture bases -

**Series HEV**

- BAT
- EM
- ICE
- EG
- Fuel

**Parallel HEV**

- BAT
- EM
- ICE
- Fuel

**Series Parallel HEV**

- BAT
- EM
- ICE
- EG
- Fuel

- Electrical node
- Mechanical node
- Power flows
- Hybridization rate -

(power ratio associated with functionalities)

- TV
  - thermal traction
  - internal charge of battery
  - Stop & Go
  - regenerative braking
  - electrical boost

- μ HEV
  - thermal traction
  - internal charge of battery
  - Stop & Go
  - regenerative braking
  - electrical boost

- mild HEV
  - thermal traction
  - internal charge of battery
  - Stop & Go
  - regenerative braking
  - electrical boost

- full HEV
  - thermal traction
  - internal charge of battery
  - Stop & Go
  - regenerative braking
  - electrical boost
  - electrical traction

- EV
  - external charge (Plug-in HEV)
- Energy and Power -

Power density (W/kg)
~ acceleration, charge time

Energy density (Wh/kg)
~ mileage range

[Chan 2007]
### Different sources

<table>
<thead>
<tr>
<th>Mechanical interface</th>
<th>Non reversible</th>
<th>Reversible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel</td>
<td>Thermal engine</td>
<td>Compressed air</td>
</tr>
<tr>
<td>Hydraulics machine</td>
<td></td>
<td>Hydraulic machine</td>
</tr>
<tr>
<td>Fly wheel</td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrical interface</th>
<th>H2</th>
<th>Electrochemical batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell</td>
<td></td>
<td>SuperCapacitors</td>
</tr>
</tbody>
</table>
- Series hybrid topologies -

- Electric coupling

- DC bus

- Electric traction

- Fuel cell

- H2

- Battery

- superC

- Fuel Cell

- Electric machine

- Power electronics

- Thermal engine

- Hydraulic machine

- Compressed air

- Flywheel
Parallel hybrid topologies -

- Mechanical coupling
  - belts
  - Planetary trains etc.

- Fuelled thermal engine
  - CVT / gearbox (manual, automated…)
  - PSA HybridAir

- Compressed air
  - Hydraulic machine

- Flywheel

- H2
  - Fuel Cell

- Battery

- superC

Hangzhou, 2016
 Various solutions...

- Split hybrid topologies -

Electrical AND mechanical coupling

Fuel

Thermal engine

DC bus

Battery

ICE

EM1

EM2

Optimal point for ICE

Operation point requested by the vehicle

More fuel optimization...

... more complex control
- Well to Wheel analysis -

<table>
<thead>
<tr>
<th>Fuel Source</th>
<th>g CO² / km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Megane 1.6 115ch</td>
<td>163</td>
</tr>
<tr>
<td>Megane 1.6 115ch</td>
<td>192</td>
</tr>
<tr>
<td>Gaz Nat. (mix Europe)</td>
<td>139</td>
</tr>
<tr>
<td>Megane 1.5 dCi 85ch</td>
<td></td>
</tr>
<tr>
<td>Coal (w/o CCS*)</td>
<td>121</td>
</tr>
<tr>
<td>Coal (IGCC*)</td>
<td>108</td>
</tr>
<tr>
<td>Mix Européen</td>
<td>58</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>57</td>
</tr>
<tr>
<td>wood</td>
<td>9</td>
</tr>
<tr>
<td>Nuclear</td>
<td>2</td>
</tr>
<tr>
<td>Wind</td>
<td>0</td>
</tr>
<tr>
<td>HEV</td>
<td>122</td>
</tr>
</tbody>
</table>

(HEV: Hybrid Electric Vehicle, EV: Electric Vehicle)
- Evolution of batteries -

11 000 Wh/kg

Most promising Technology for EVs and HEVs

<table>
<thead>
<tr>
<th>Technology</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead acid</td>
<td>in commerce</td>
</tr>
<tr>
<td>NiCd</td>
<td>in development</td>
</tr>
<tr>
<td>NiMH</td>
<td>in development</td>
</tr>
<tr>
<td>Li-ion</td>
<td>in commerce</td>
</tr>
<tr>
<td>Technologies long terme Zn-air, Li-air, Li-S ... ?</td>
<td>in research</td>
</tr>
</tbody>
</table>

but

Fossil fuel
- Energy charge -

• slow charge at home / at work (4-8h?)
  (plug or induction)
• ultra-fast charge at specific station (1/2h?)
• battery swap station (5-10 min?)

New technologies and developments? “Smart” charge?
but also
A new way to manage our energy charge?

http://france.betterplace.com/
New concepts for grid management?

but also

A new way to manage our energy prize?
- Day trip analysis -

Average values of daily trips in Europe in 2007:

- **daily trip > 60 km**: 20%
- **daily trip < 20 km**: 30%
- **20 km < daily trip < 60 km**: 50%

Mileage range of a classical EV: 100 to 150 km

Possible uses of EVs?

*but*

A new way to manage our mobility?
- Challenge EVs and HEVs -

**EVs**
- battery cost and lifetime
- charging time, range
- cabin thermal management

**HEVs**
- ZEV mode
- topology and design
- energy management

**FCs**
- topology and design
- energy management
- FC cost and lifetime
- H2 production and distribution

**Driving conditions**

Energy Storage Subsystem
- balanced design
- complex control

Hangzhou, 2016
Controls of TVs and EVs: mono-objective (no optimization) ensure the driving cycle
- Challenge of HEV Control -

Controls of HEVs:
- multi-objective: ensure the driving cycle AND reduce the fuel consumption
- various modes: pure electric, pure thermal, hybrid, etc.

How to achieve the objectives?
Which mode and when? How to switch between modes?
Etc.
Organization of HEV control

- Energy Management Strategy (EMS)
  - EM control
  - ICE control
  - Trans control

How to split the control?
How to develop efficient EMS?

Fast subsystem controls
Slow system supervision (subsystem coordination)

Driver requests
4. Energy Management Strategies (EMS) of EVs and HEVs

- EMS classification
- ruled-based EMS
- optimization-based EMS
Basic example: Battery / Supercapacitors (SCs) EV
Main objective: to increase the battery lifetime

How to manage such a system?
- Organization of vehicle control -

SCS. \hspace{2cm} \text{power electronics} \\
\hspace{2cm} \text{Bat.} \\
\hspace{2cm} \text{power electronics} \hspace{1cm} \text{Electric machine} \\
\hspace{1cm} \text{PE control} \hspace{1cm} \text{PE control} \hspace{1cm} \text{EM control} \\
\hspace{6cm} \text{Energy Management Strategy (EMS)} \\
\hspace{4cm} \text{Trans.} \\
\hspace{6cm} \text{driver requests}
- Organization of vehicle control -
Using EMR approach

Battery current reference as control variable

Focus on EMSs
- Classification -

[Sciaretta 2007], [Salmasi 2007], [Trigui 2011]

**Rule-based**
- Deterministic rules
  - Filtering, Thermostat control …
- Fuzzy rules
  - Fuzzy logic, Neural networks …

**Optimization-based**
- Global optimization
  - Dynamic programming, Pontryagin’s minimum
- Real-time optimization - based
  - $\lambda$-control, Predictive control …
- Classification -

Rule-based

- Deterministic rules
  - Filtering, Thermostat control …

- Fuzzy rules
  - Fuzzy logic, Neural networks …

Real-time implementation

No optimal performances
Optimization-based

Global optimization

Real-time optimization-based

Optimal performances
Real-time implementation
Benchmarking use

Compromise between performances and real-time implementation
-Application: Filtering – (Rule-based)

Traction current

Current (p.u)

Low dynamics for the battery

High dynamic for the SCs
-Application: Filtering – (Rule-based)

Performance criterion:
Battery current RMS value (lifetime)

Real-time
Driving cycle not required
No optimal

Energy sources
EMS

Traction current

Low-pass filter

\( i_{b\text{-ref}} \rightarrow f_0 \rightarrow i_{t\text{-meas}} \)
Bellman’s optimality principle –
If a-b-e is an optimal way from a to e, then b-e is the optimal way from b to e.

Dynamic programming –
Recurrence relationship

\[ x(k) = \min (x(k-1) + x_{1,k}) \]

To find the optimal trajectory
- Application: Dynamic programming – (global optimization)

Backward simplified model

DP algorithm

Energy sources EMS

Driving cycle requested

$\dot{i}_{b-ref}$

Optimal
Off-line

Driving cycle
SCs voltage
Minimization of a Hamiltonian function:

\[ H = i_{b-ref}^2(t) - \lambda_{ref}(OCV - r_b i_{b-ref})(i_p - i_{b-ref})\eta_g \gamma_g \]

**Criterion**

System to optimize

State variables constraints

Control variable expression by solving:

\[ \frac{\partial H}{\partial i_{b-ref}} = 0 \]

\[ i_{b-ref}^*(t) = \frac{\lambda_{ref}\eta_g \gamma_g (OCV + r_b i_p)}{2(\lambda_{ref}r_b \eta_g \gamma_g - 1)} \]
Control variable expression

\[ i_{b-ref}(t) = \frac{\lambda_{ref} \eta \gamma (OCV + r_b i_p)}{2(\lambda_{ref} r_b \eta \gamma - 1)} \]

- Application: Calculus of Variations-
  (Real-time optimization-based)

Energy sources
EMS

Optimal
Real-time
Driving cycle requested

Driving cycle requested
SCs voltage
- Application: $\lambda$-control -
(Real-time optimisation-based)

Minimization of a Hamiltonian function:

$$H = i_{b-ref}^2(t) - \lambda_{ref} (OCV - r_b i_{b-ref}) (i_p - i_{b-ref}) \eta_g \gamma_g$$

Based on Calculus of Variations

Feedback control to face driving conditions variations

Control variable expression by solving:

$$\frac{\partial H}{\partial i_{b-ref}^*} = 0$$

$$i_{b-ref}^*(t) = \frac{\lambda_{ref} \eta_g \gamma_g (OCV + r_b i_p)}{2(\lambda_{ref} r_b \eta_g \gamma_g - 1)}$$
- Application: Calculus of Variations - (Real-time optimization-based)

Limitations of $u_{sc}$

Suboptimal
Real-time
Driving cycle not requested

Energy sources
EMS
SCs voltage
- Simulations results -

B-EV case

Real driving cycle

Velocity (km/h)

Current (p.u.)

Battery current
- Simulation results -

Battery-SCs vehicle

Battery current

Current (p.u)

- $i_b$ (λ-ctrl)
- $i_b$ (Filter.)
- $i_b$ (DP.)

(t)
Battery-SCs vehicle

**Performance criterion**

- Criterion: 
  - $\lambda$-control: -25 %
  - Filtering: -20 %

**RMS value of battery current**

- DP strategy (theoretical optimal i.e. benchmark)
- $\lambda$-control strategy
- Filtering strategy
- Pure battery EV

**Criterion:**

- $\lambda$-control: -25 %
- Filtering: -20 %
Fuel Cell (FC) – Battery – Supercapacitors (SCs) vehicle

Experimental implementation

WLTC driving cycle (low speed)

Decomposed \(\lambda\)-control

More details in Special session SS5

Vehicle velocity (km/h)

Battery and SCs currents (p.u)

FC conv - Traction

SCs

Bat

Fuel Cell (FC) – Battery – Supercapacitors (SCs) vehicle

- More complex system -
5. Examples of Innovative Vehicles

Non available on the pdf version
Conclusion

HEVs and EVs could be valuable alternative vehicles

but

Design and Energy Management Strategies are key issues for their development…
tutorial « Energy Management of Evs and HEVs »
Monday October 17, 14:00-16:00, room E
Prof. Alain BOUSCAYROL, Dr. Ali CASTAINGS (Univ. Lille1, MEGEVH, France)
Dr. Rochdi TRIGUI (IFSTTAR, MEGEVH, France)

Monday October 17, 14:00-16:00, room F
Prof. Daniel HISSEL, Prof. Marie-Cécile PERA (Univ. Bourgogne Franche-Comté, MEGEVH, France)

SS « Energy Management of Electrical Hybrid Energy Sources »
Wednesday October 19, 10:30-11:30, room D
Dr. Ronan GERMAN, Dr. Walter LHOMME (Univ. Lille1, MEGEVH, France)
Dr. Joao TROVAO (Univ. Sherbrooke, Canada)

SS « Energetic Macroscopic Representation and other graphical descriptions »
Wednesday October 19, 14:00-15:30, room D
Dr. Clément MAYET (Univ. Lille1, MEGEVH, France)
Prof. MINH C. TA (Hanoi Univ. Of Science and Tech., Vietnam)
References


