FR CNRS 3539

FC LAB

Research

Energy Management Strategies for Hybrid Electric Vehicle

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femto-st SCIENCES & TECHNOLOGIES

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www.fclab.fr

Outline

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1. **Introduction**
   - FR FCLAB, goals and objectives
2. **Hybrid Electric Locomotive**
   - Modeling of the HEL
   - Otimal Fuzzy Logic Energy Management Strategy
3. **Hybrid Electric Heavy Duty Truck**
   - Wavelet Transform
   - Energy Management Strategy : ARIMA & NARNN
5. **Conclusions.**

Belfort and Fuel Cells

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- 1999 : First Fuel Cell research activities
- 2000 : CNRT on Fuel Cell Systems
- 2003 : National Test Platform for Fuel Cell Systems
- 2006 – 2011 : FCLAB “Joined laboratory”
  - ➔ CNRS, CEA, Univ. Franche-Comté,
  - ➔ UTBM, INPL, UHP Nancy, INRETS
- 2011 : FCLAB2 “CNRS Research Federation” Project
  - ➔ CNRS, Univ. Franche-Comté, UTBM, IFSTTAR, ENSMM

The test facility (scale 1)

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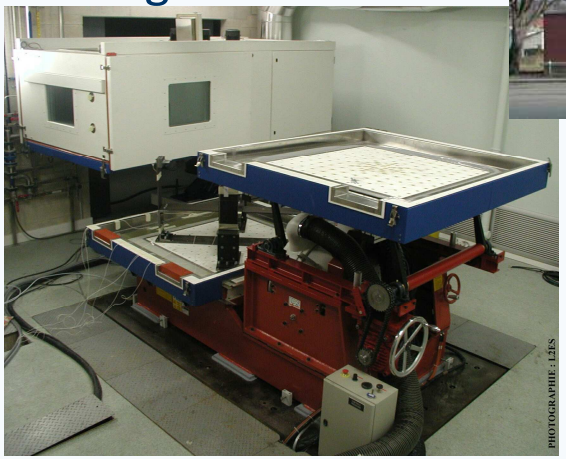
Mobile testbenches

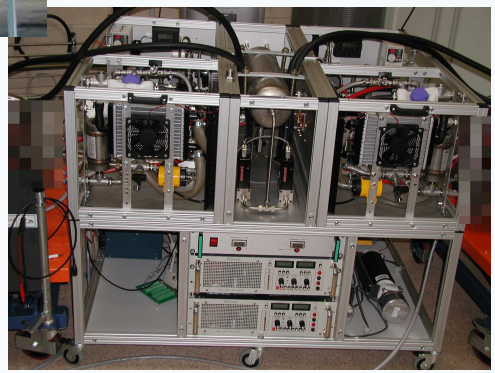
Loads
(machines, batteries,
ultracapacitors…)

Test benches
1kW, 10kW, 25kW, …

Vibrating table &
Climatic chamber
200kg – 2.3 m3



PEMFC
SOFC
Stacks & systems



Scientific & technological bolts

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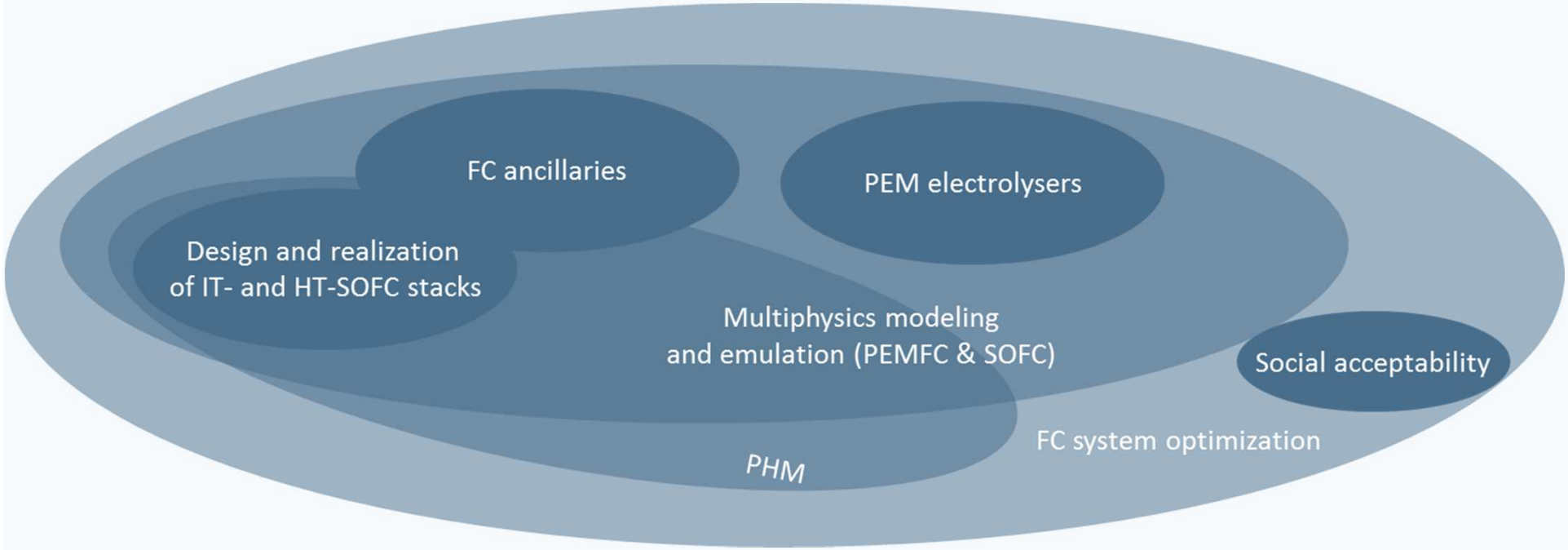
- Fuel cell system efficiency
  - Increase it from about 25-30% to about 35-40%
- Fuel cell system durability
  - Increase it from about 2000h to 5000h (transportation applications), up to 100000h (stationary applications)
- Public acceptance
- Cost ➔ linked to industrial deployment

7 research axes

- Complementary research issues, from FC stacks to FC systems
- Application fields : transportation applications and stationary power plants



Introduction

Development model out of date :

Economic growth:
- Industrial activity
- incomes
- consumption

Effect on mobility:
- longer distances
- energetic needs

Economic & environment impacts :
- energetic consumption
- global emissions (greenhouse gases) & global warming

What has to be done ?

- Reduction of energy consumption (especially in transportation area)
- Reduction of GHG emissions
- Reduction of our depency to fossil fuels

Introduction

- Coal : several hundred years (Except Europe & Japan)
- Natural Gas : 70 years @ constant production
- Oïl : 30 – 40 years

+

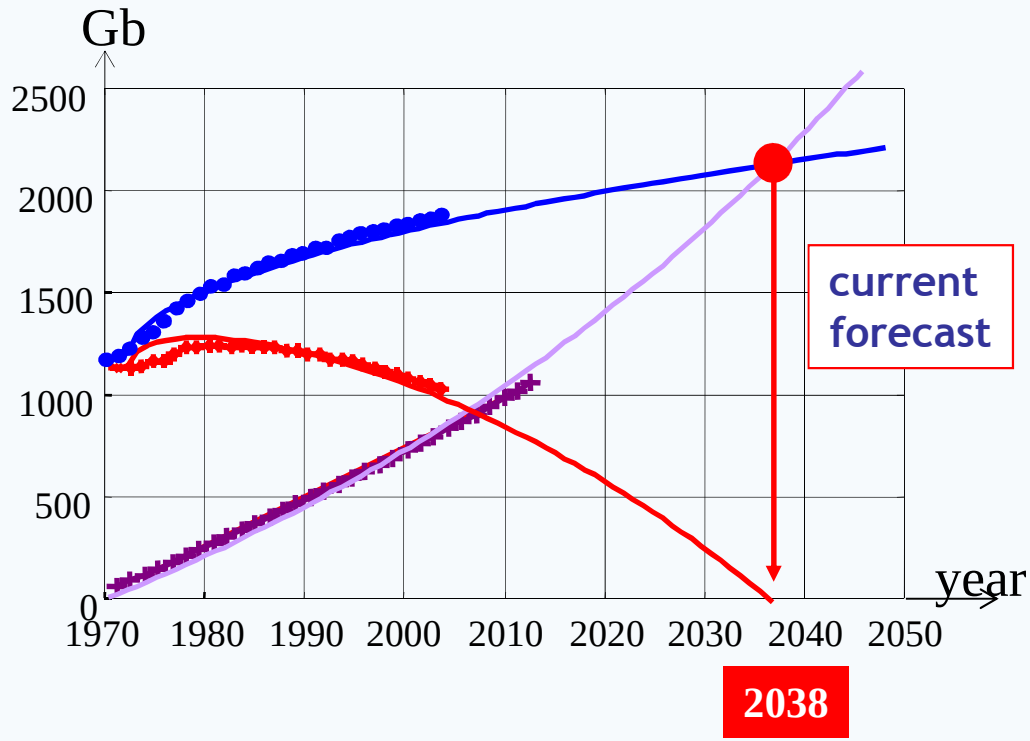
Discovery reserves

—

Cumulative Consumption

=

Remaining reserves

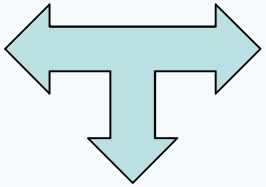


[Ehsani & al 2005]

Introduction

Conventional vehicles

- Internal Combustion Engine



Electric Vehicles (EV)

- Storage components (electrochemical, …)

Hybrid Electric Vehicle (HEV)

ICE
+
Storage components

Introduction

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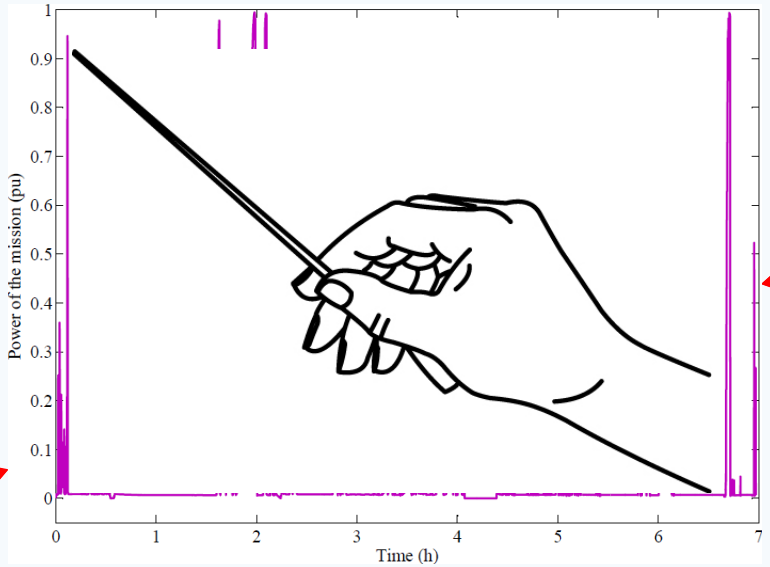
Goal: To share the power required on the driving cycle performed by the vehicle between the different on-board sources, taking into account their own specifications.



Introduction

Two applications considered

Introduction

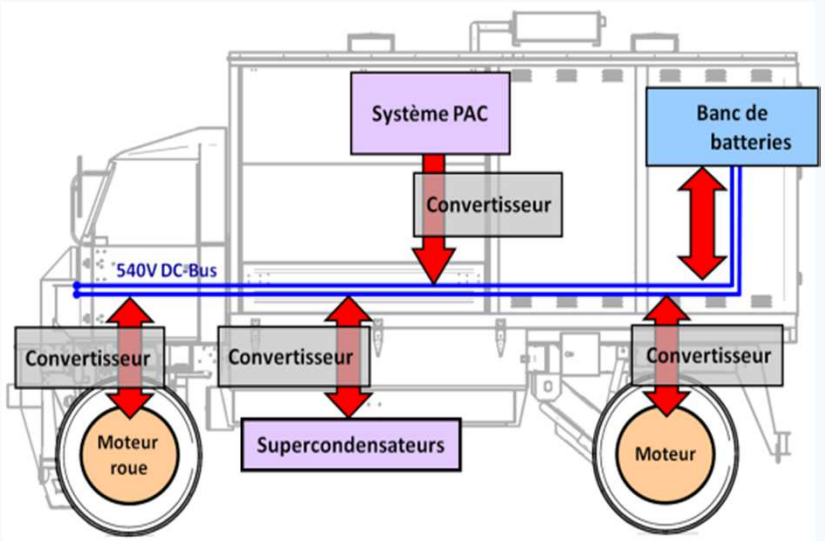
Hybrid Electric Locomotive

- 60% less particles
- 40% less NO
- 15% less maintenance

Introduction

Electrical Chain Components Evaluation

ECCE Vehicle



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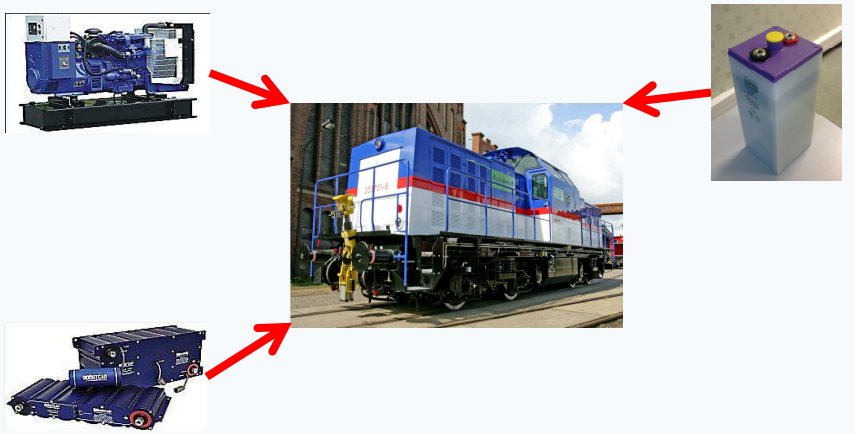
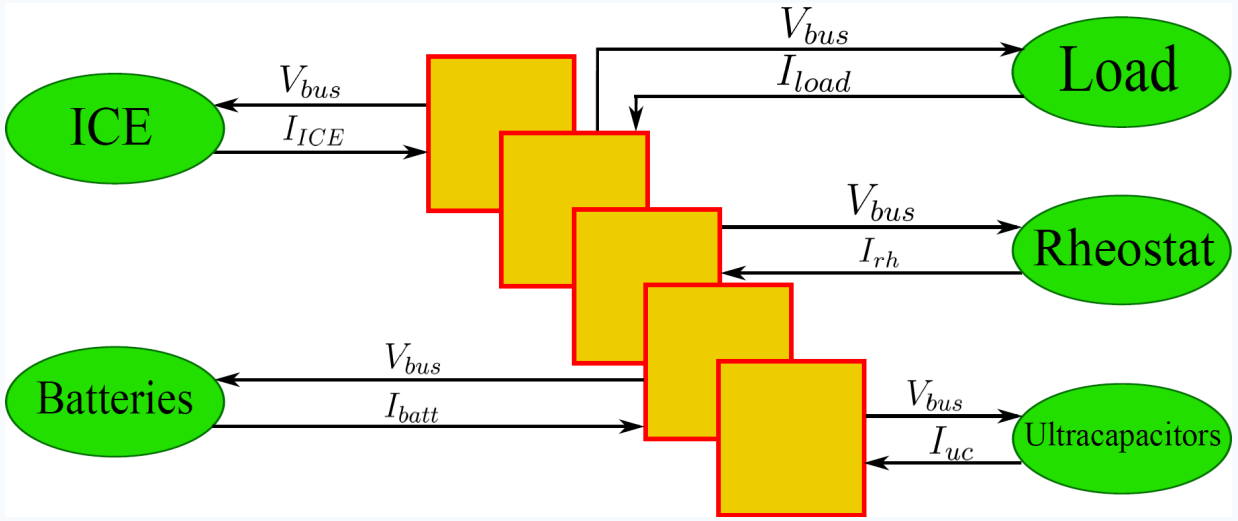
Hybrid Electric Locomotive (Model)

Energetic Macroscopic Representation approach

Advantages:

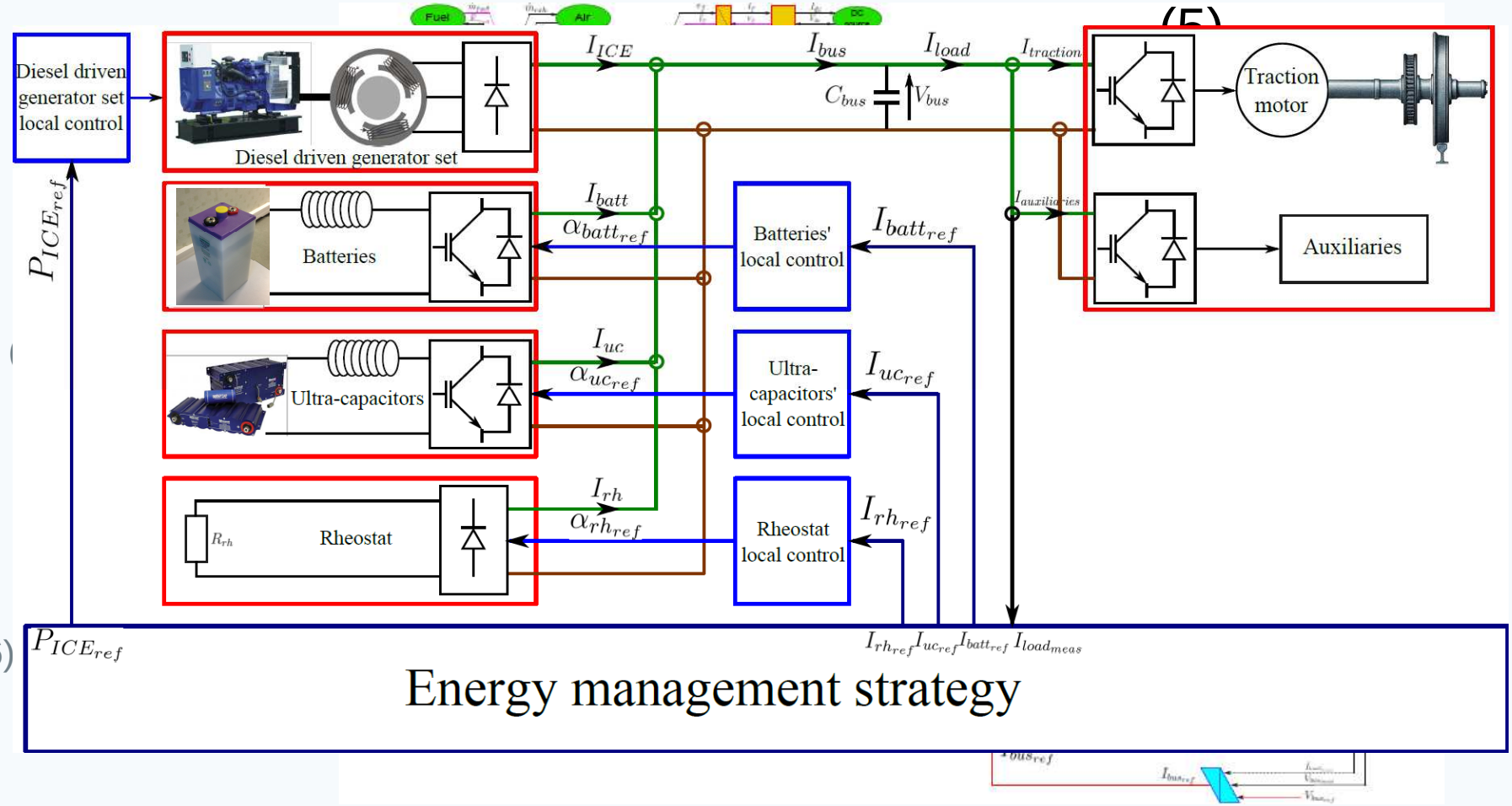
- Physical causality
- Highlight measures and sensors
- Control structure identification
- Implementation under Matlab / Simulink





Hybrid Electric Locomotive

Global structure



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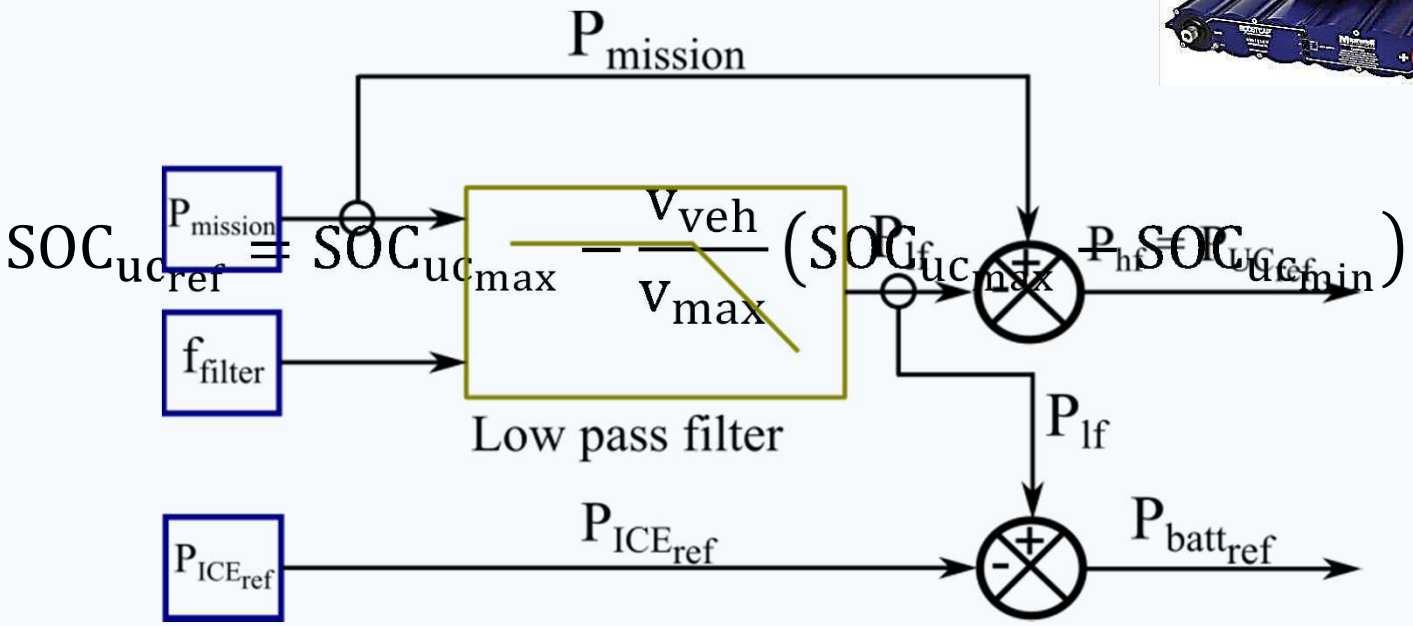
Hybrid Electric Locomotive (EMS)

Ultra-capacitors:

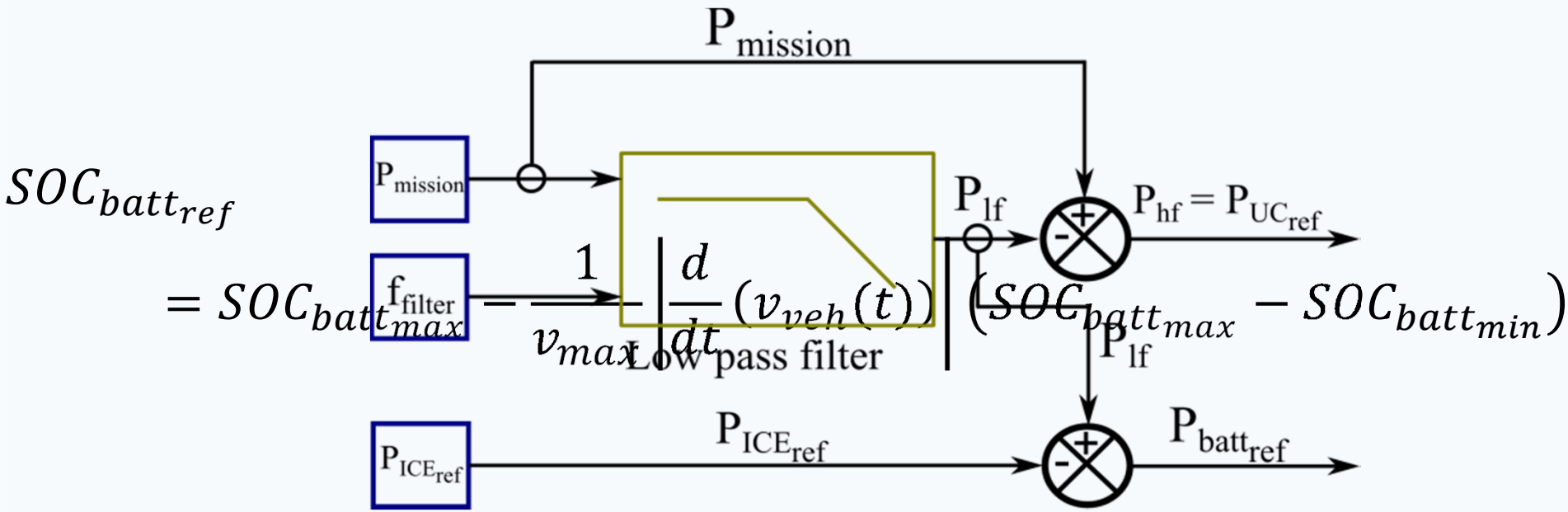
- Limitation of the State Of Charge (SOC) between 50% and 100%,
- control of the SOC according to the speed of the vehicle,
- supply the high frequencies of the power mission.



Hybrid Electric Locomotive (EMS)

Batteries:

- Limitation of the SOC between 70% and 90%,
- control of the SOC according to the acceleration of the vehicle,
- supply the LF of the power mission with the diesel driven generator set.



Hybrid Electric Locomotive (EMS)

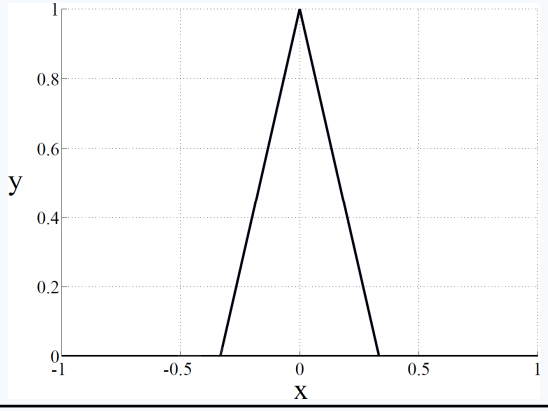
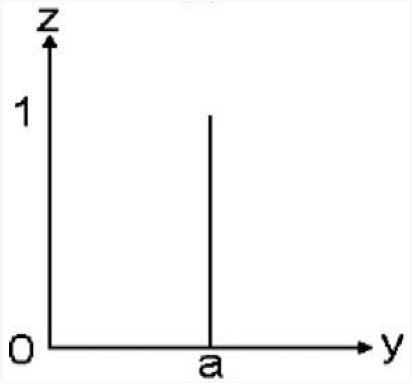
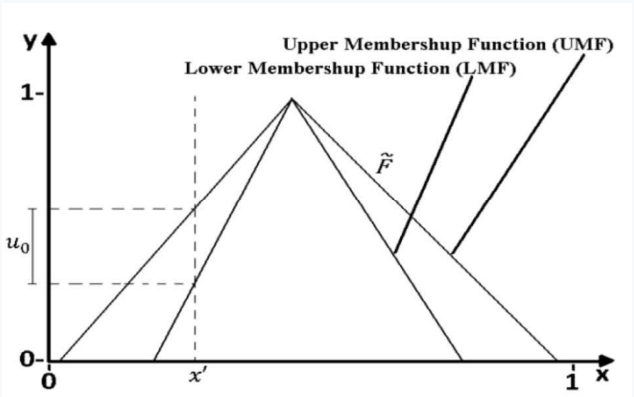
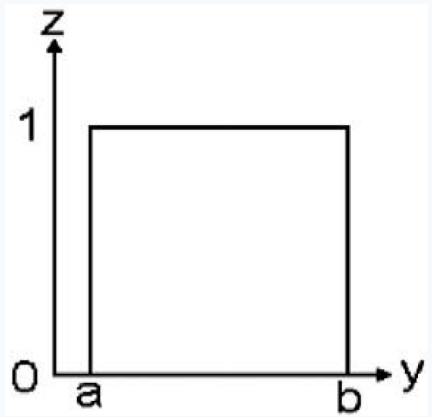
Diesel driven generator set:

- Use of a Fuzzy Logic Controller to determine the power delivered by this source,
- Supply the low frequencies of the power mission with the batteries.

Hybrid Electric Locomotive (EMS – FL)

Fuzzy Logic Controller design

Improve uncertainties modeling

	Primary Membership Function	Secondary Membership Function
Type-1		
Interval Type-2		

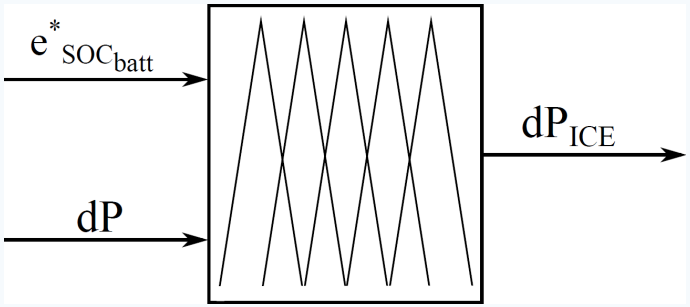
Hybrid Electric Locomotive (EMS – FL)

Fuzzy Logic Controller design

Fuzzy Logic Controller of the implemented EMS

7 linguistic variables defined by trapezoid, triangular and Interval membership functions:
NH, NM, NL, Z, PL, PM, PH

N - Negative	H - High	Z - Zero
P - Positive	M - Medium	L - Low



IF $e^*_{SOC_{batt}}$ is NH

AND dP is NH

THEN dP_{ICE} is NH

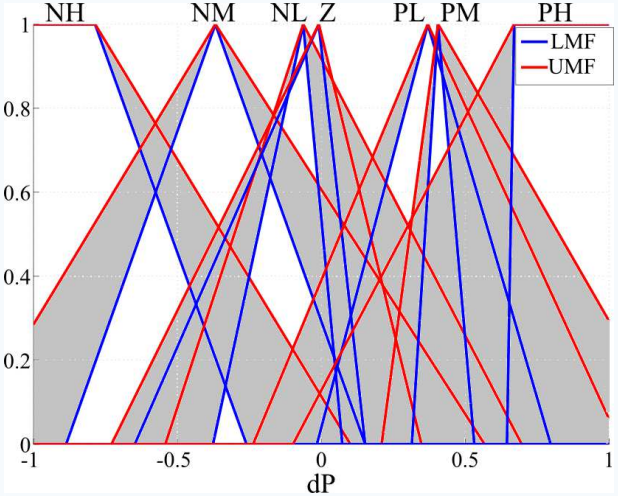
If power delivered by the ICE is > than the power required by the mission AND if the batteries must be discharged THEN the power delivered by the ICE is reduced.

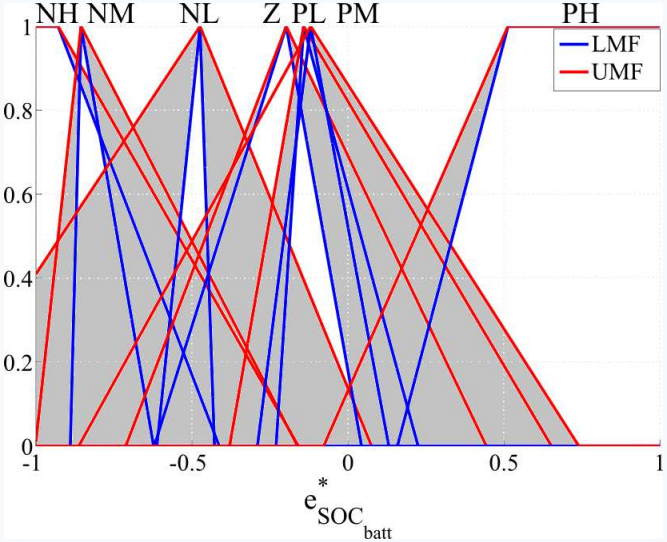
=> 2 inputs × 7 linguistic variables + output × 7 linguistic variables = 21 membership functions

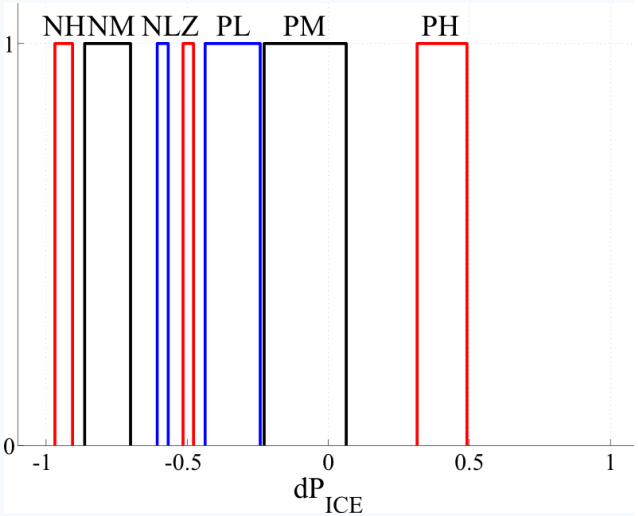
Hybrid Electric Locomotive (EMS – FL)

Fuzzy Logic Controller design

Fuzzy Logic Controller of the implemented EMS







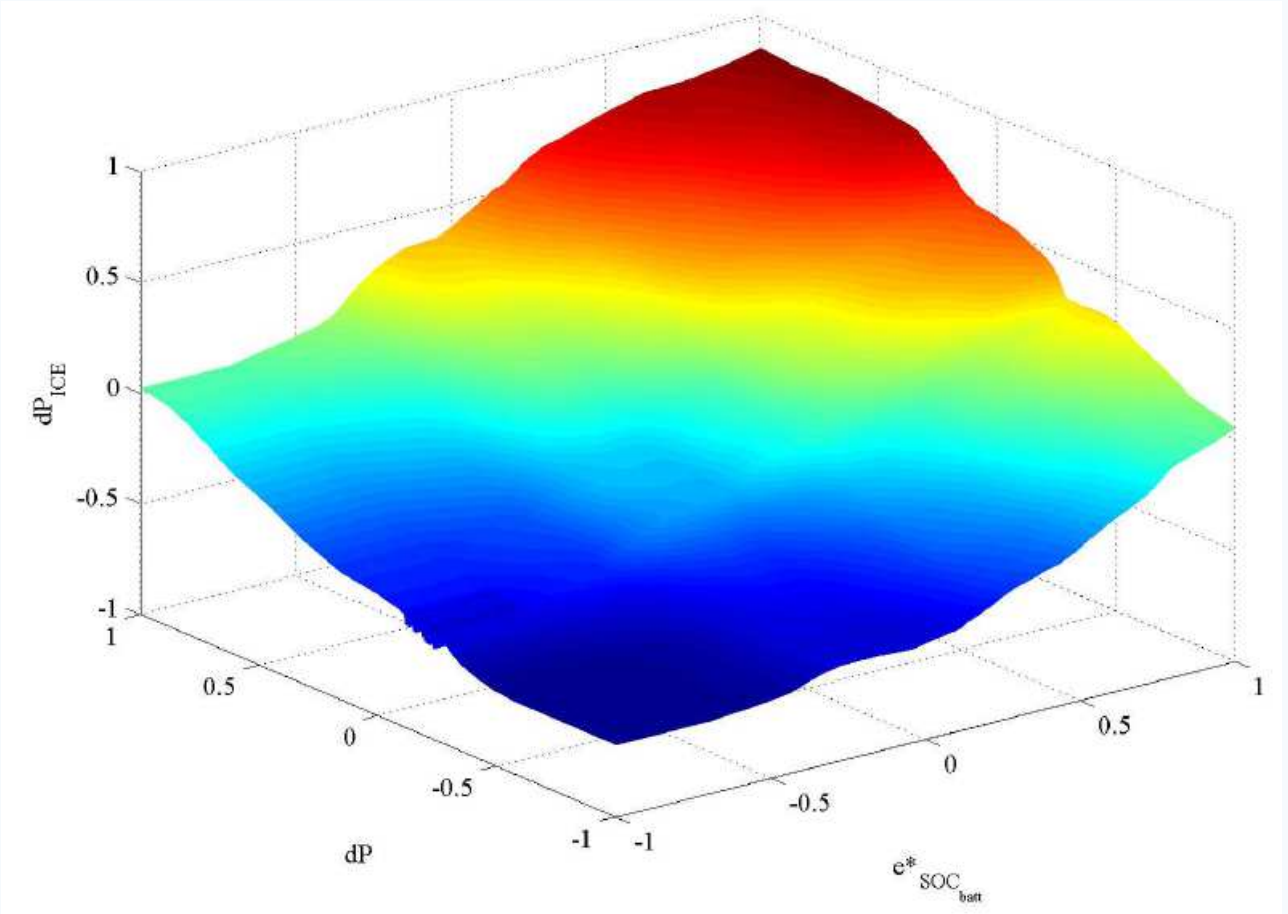
$e^*_{SOC_{batt}}$ dP dP_{ICE}

- Optimization of the parameters of the controller using a genetic algorithm in order to minimize the fuel consumption of the diesel driven generator set.

Hybrid Electric Locomotive (EMS – FL)

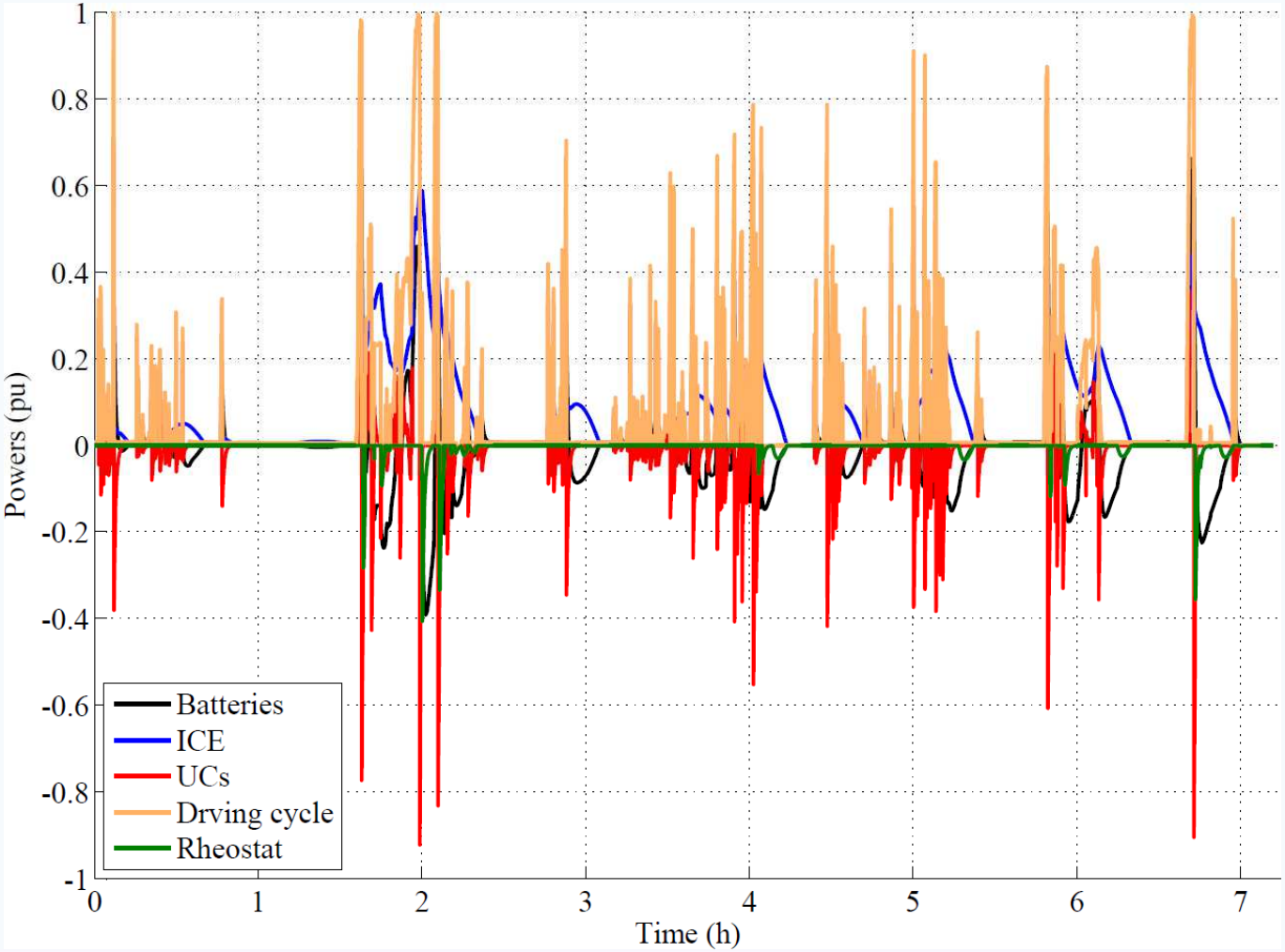
Fuzzy Logic Controller design

Optimized IT2 FLC ➔ Map



Hybrid Electric Locomotive (Results)

Results – Power distribution

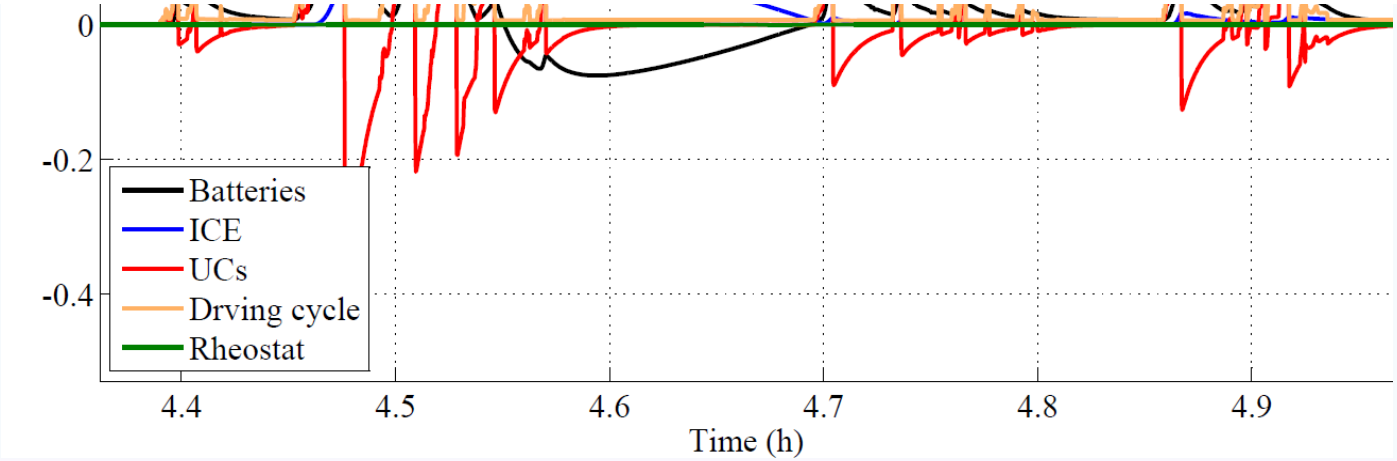


Hybrid Electric Locomotive (Results)

Results – Power distribution (zoom)

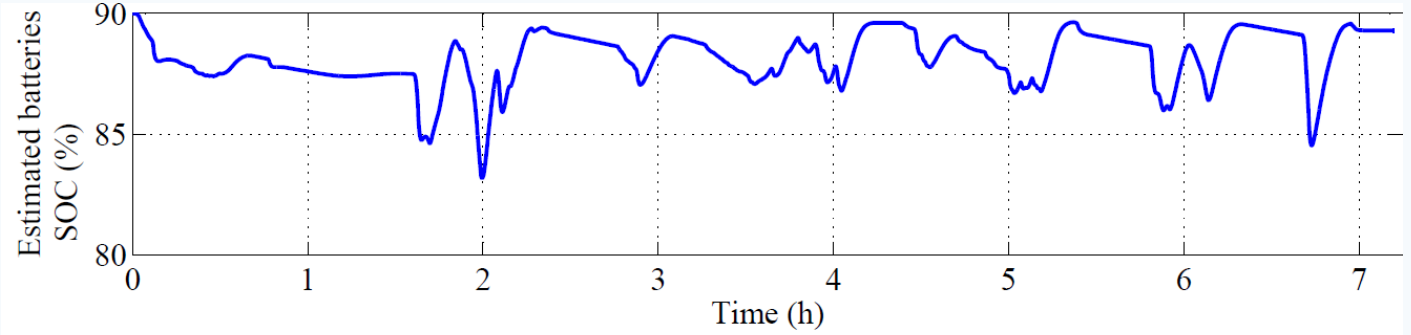
High frequencies of the power are dedicated to the UCs

Low frequencies of the power are dedicated to the batteries



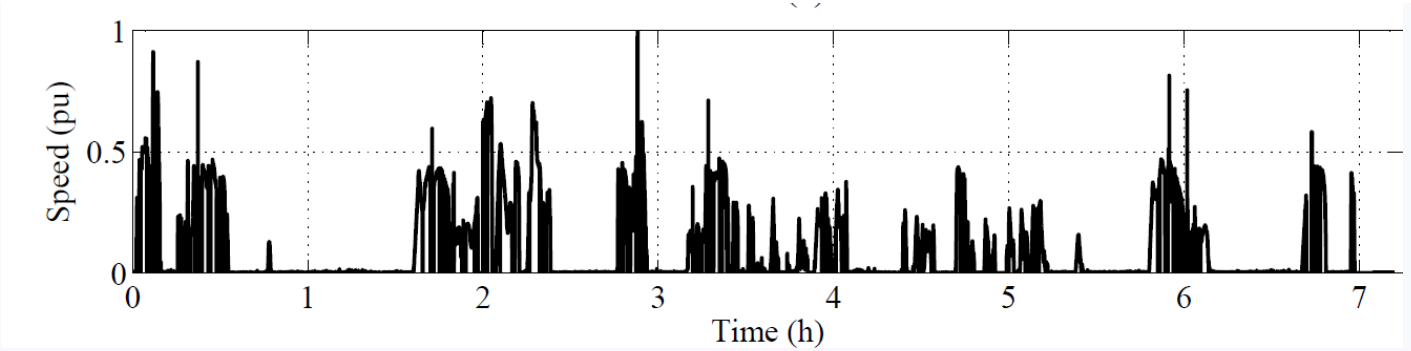
Hybrid Electric Locomotive (Results)

Results – State of Charge and speed



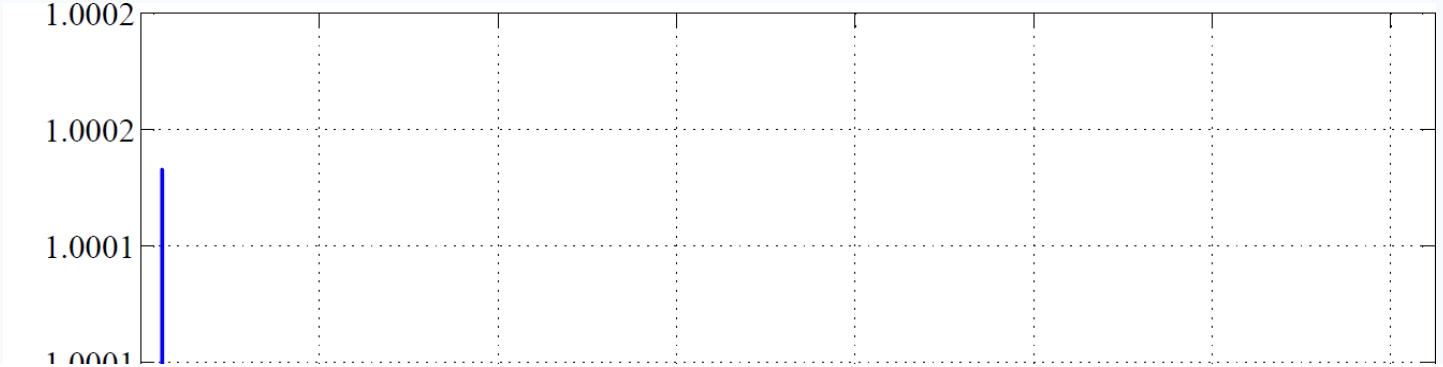
UCs' SOC is controlled using the speed of the locomotive and is limited between 50% and 100%

Batteries' SOC is controlled using the acceleration of the locomotive and is limited between 70% and 90%

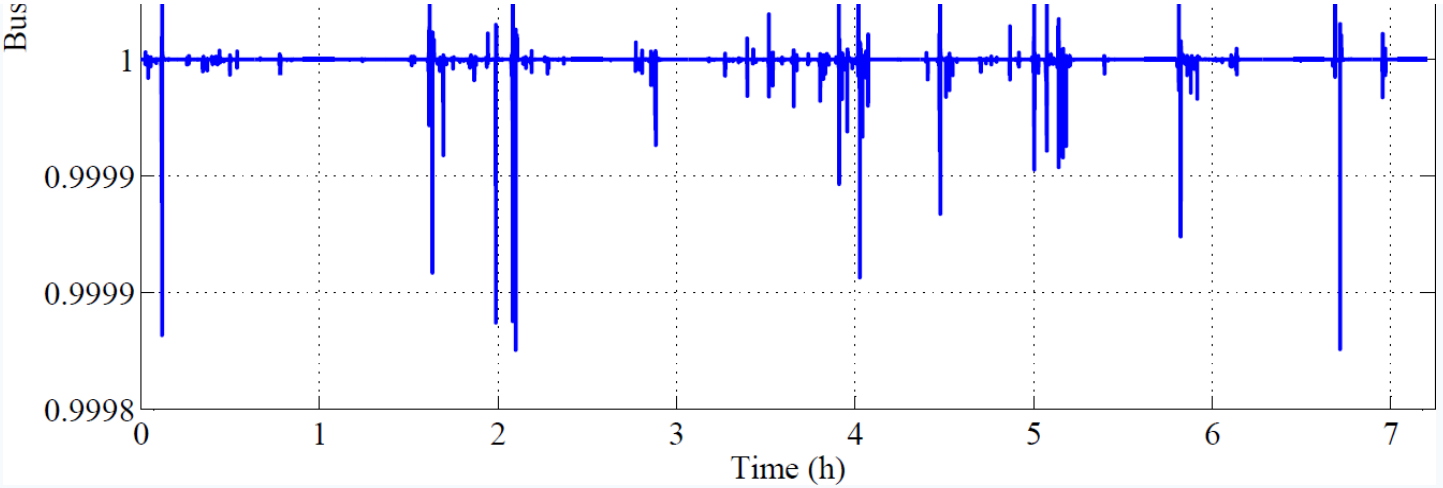


Hybrid Electric Locomotive (Results)

Results – Bus voltage control



The implemented fuzzy EMS ensures the stability of the bus voltage



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Hybrid Electric ECCE

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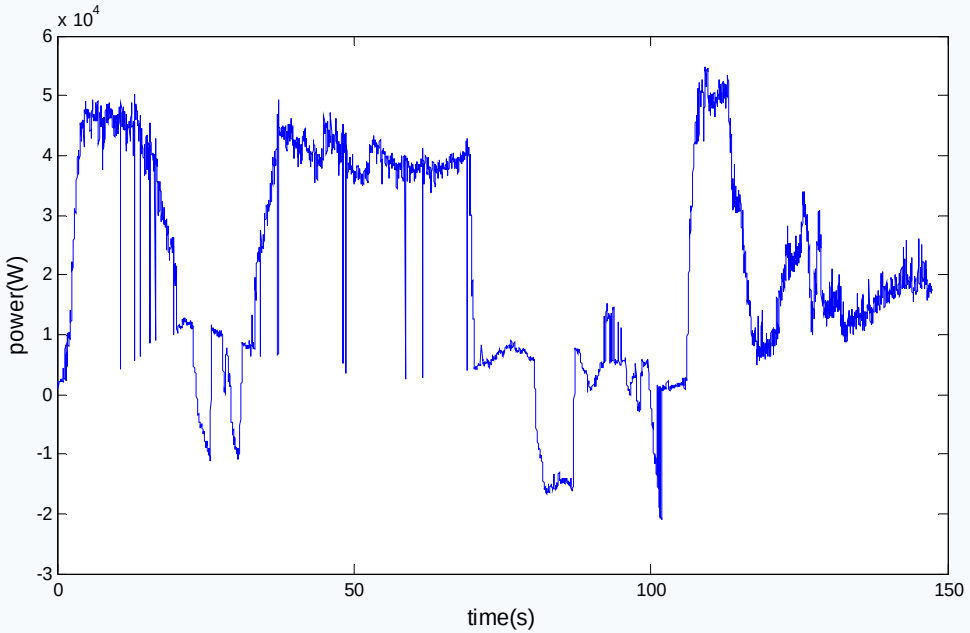
- ECCE Mobile Test bench ➔ 16 tons
- HEV based on batteries, UC, 80 kW PEMFC, diesel/alternators, in wheel motors.
- Partners : DGA, Hélion, Panhard.

Hybrid Electric ECCE

- Power demand

The power demand represents the actual demand, at each instant, in power of a HEV's driver, added to the value of the power demand coming from auxiliaries of the vehicle (lights, radio, air conditioner, etc …)



Power demand signal

The power demand signal has rapid variations, different frequencies components, and transients

Hybrid Electric ECCE

- Steps for energy management strategy

Wavelet transform for separating high and low frequencies components from the demand signal

→

High frequency signal for ultracapacitor

Low frequency signal to be shared by battery and fuel cell

→

Prediction for online part by Nonlinear Autoregressive Neural Network

→

Simulation over a part of the obtained signals

Hybrid Electric ECCE (DWT)

- Wavelet Transform is a method which can extract characteristics of sharp variations in a given signal, non stationary and transient parts

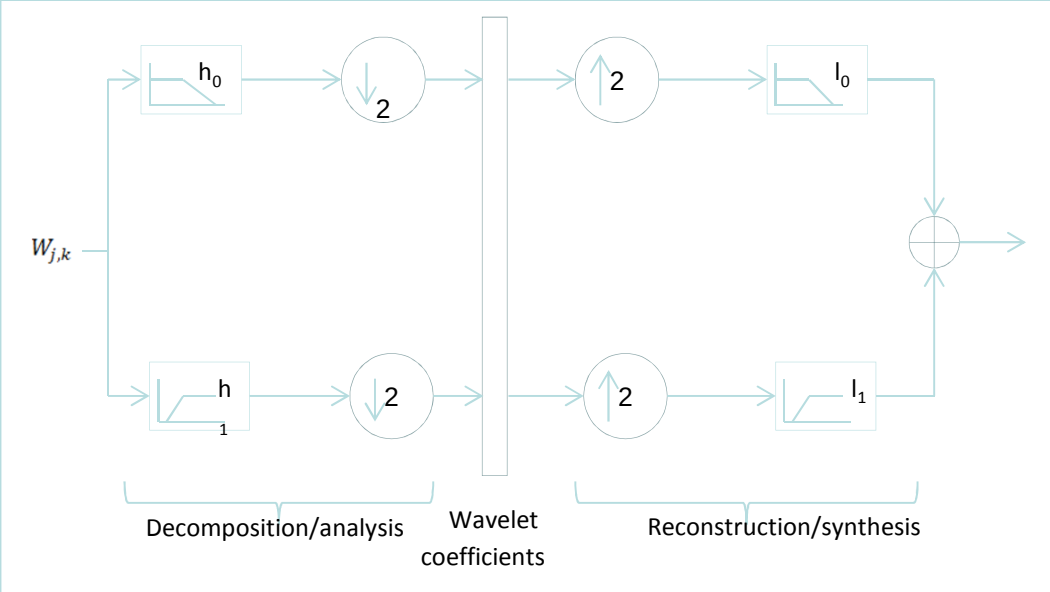
$$W_{j,k}(t) = \int_{-\infty}^{+\infty} x(t)\varphi_{j,k}^{*}(t)dt$$

- x (t) is the signal to be transformed is the complex conjugate
- *a* and *b* are respectively the scale and position parameters;
- φ is is the wavelet basis

$$\varphi_{i,j}(t) = 2^{-\frac{j}{2}}\varphi(2^{-j}t - k)$$

The Discrete Wavelet Transform (DWT) is equivalent to a filtering operation.
The signal x (t) is decomposed into two signals:

- High frequency signal (approximation signal)
- Low frequency signal (detail signal)



Hybrid Electric ECCE (off-line)

- Discrete Wavelett Transform

$$x(t) = \underbrace{A_j(t)}_{\text{Approximation signal}} + \underbrace{D_j(t) + \cdots + D_1(t)}_{\text{Detailed signal}}$$

Hybrid Electric ECCE (off-line)

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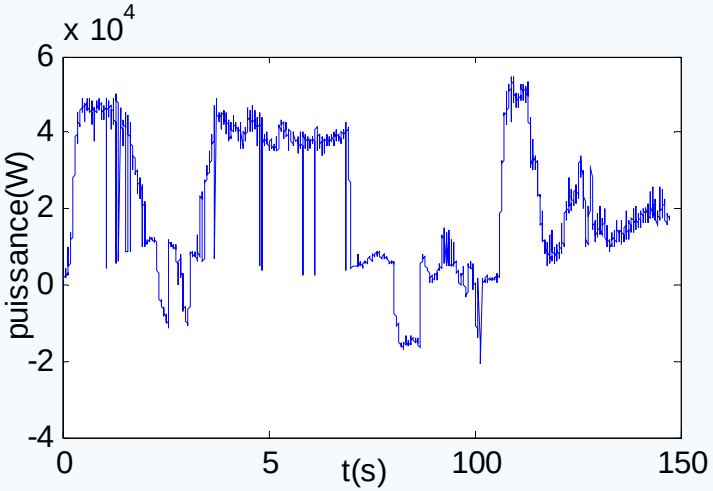
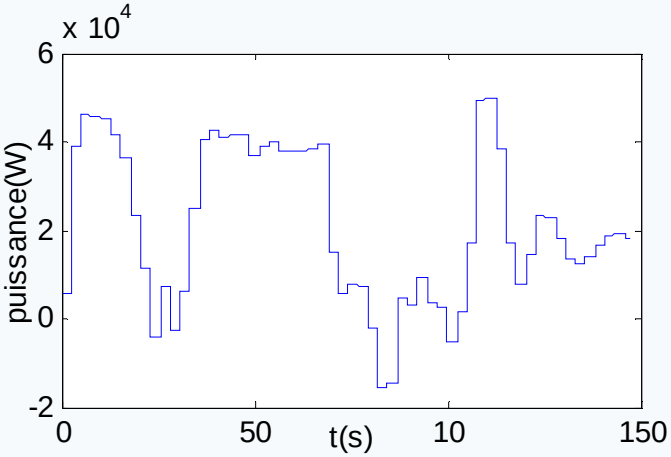
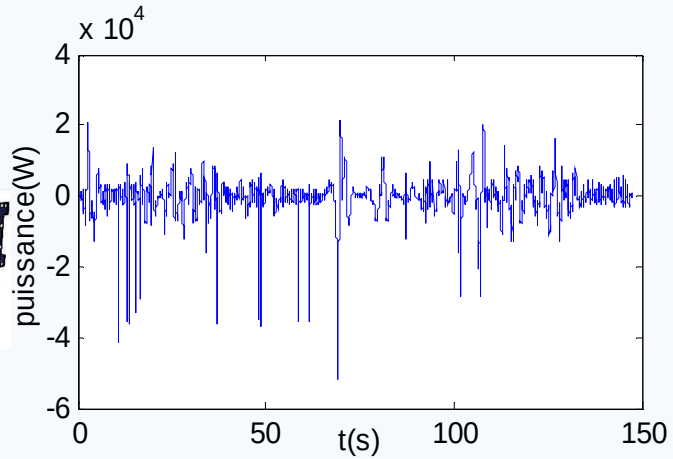
- Off-line EMS

  Batteries & UC topology



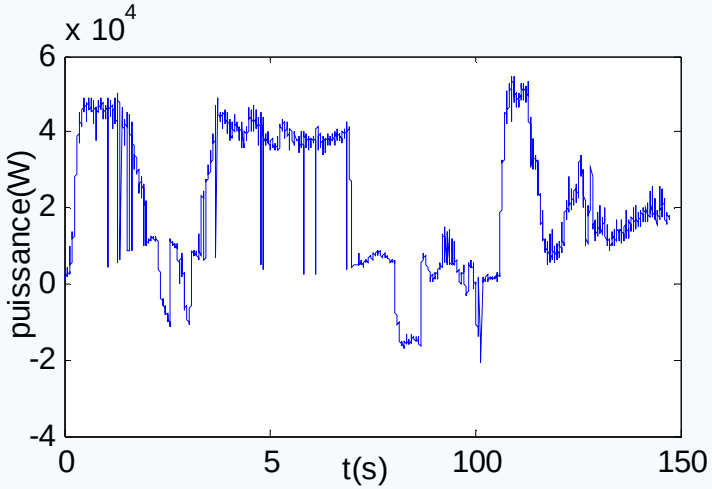


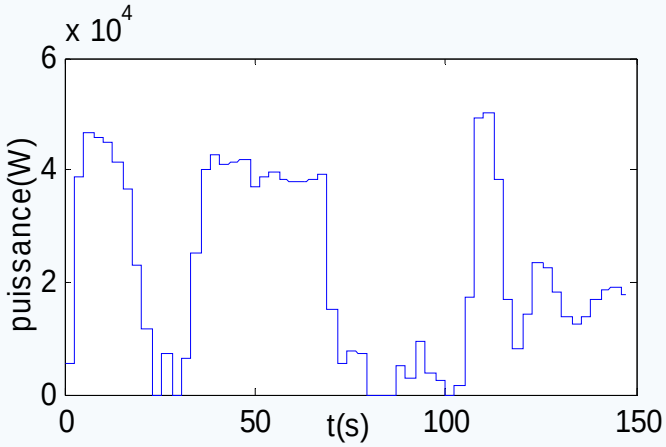


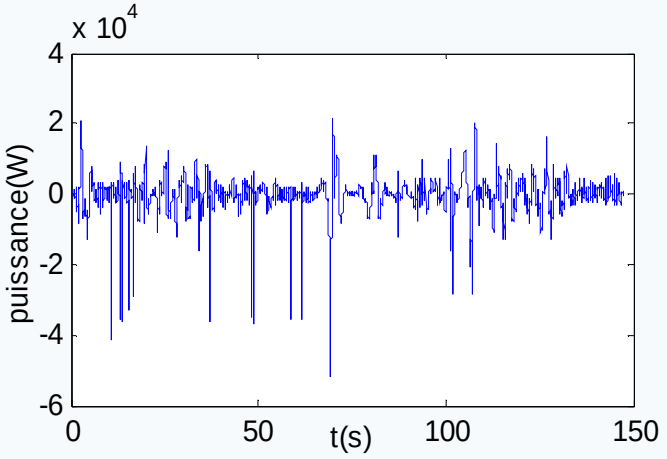
Hybrid Electric ECCE (off-line)

- Off-line EMS

FC & UC topology



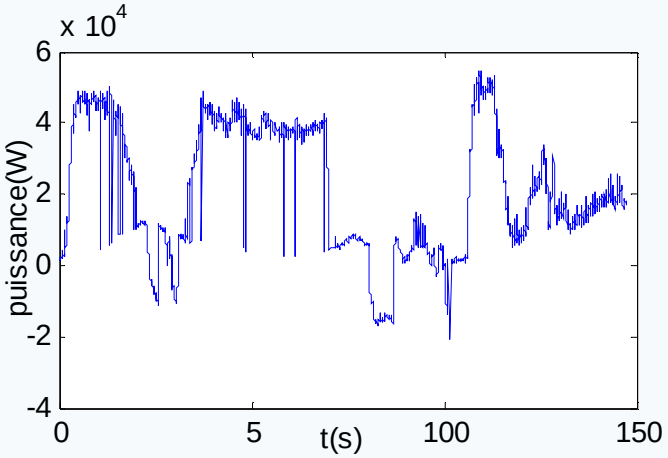


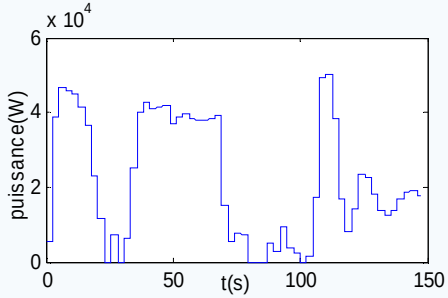


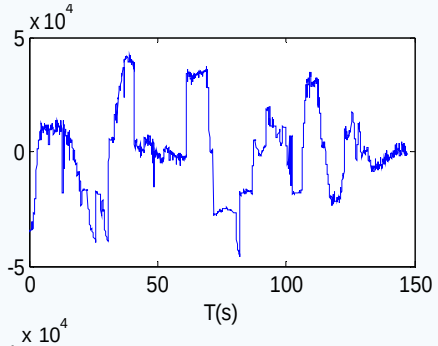
Hybrid Electric ECCE (off-line)

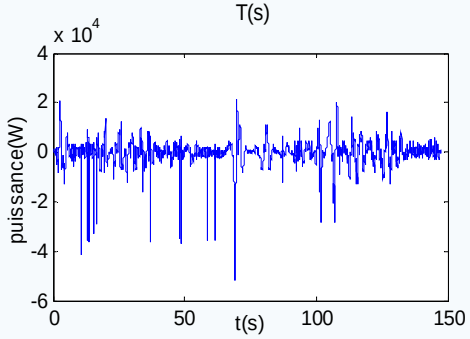
- Off-line EMS

FC, Batteries & UC topology









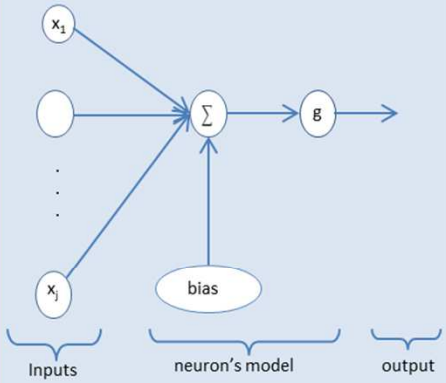
Hybrid Electric ECCE (on-line)

- Nonlinear AutoRegressive Neural Network (NARNN) for Time Series Prediction

Formal Neuron

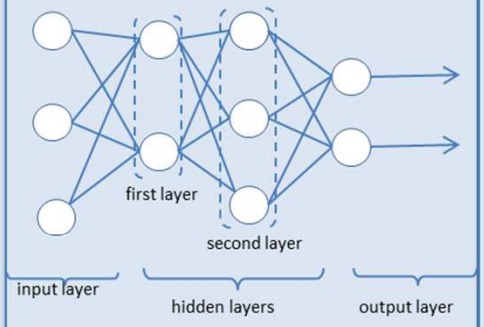
A formal neuron is an algebraic, parametric, bounded and real function, having the mathematic formulation :

$$y_i = g\left(\sum_{j=1}^{n} x_j\, w'_{ij} + b'_i\right)$$



Multi-Layer Perceptron (MLP)

The MLP is composed by multiple layers of formal neurons. The information moves from the input layer to the output one. Each layer is composed by several neurons, and the output layer's neurons correspond to the output of the system

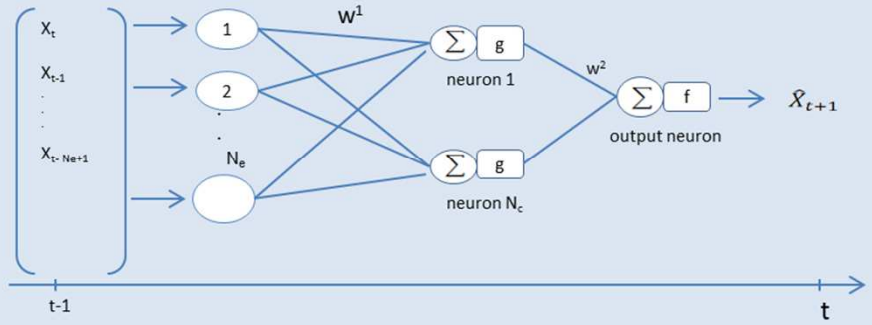


MLP for Time Series Prediction

In the specific MLP used for time series prediction, the output of the system corresponds to the prediction of the time series at time $t(\hat{x}_t)$, mathematic formulation:

$$\hat{X}_{t+1} = \sum_{i=1}^{N_c} g\left(\sum_{j=1}^{N_e} X_{t-j+1}\, w'_{ij} + b'_i\right) w_i^2 + b^2$$

N_e is the number of input neurons
N_c is the number of hidden neurons
g is the activation function

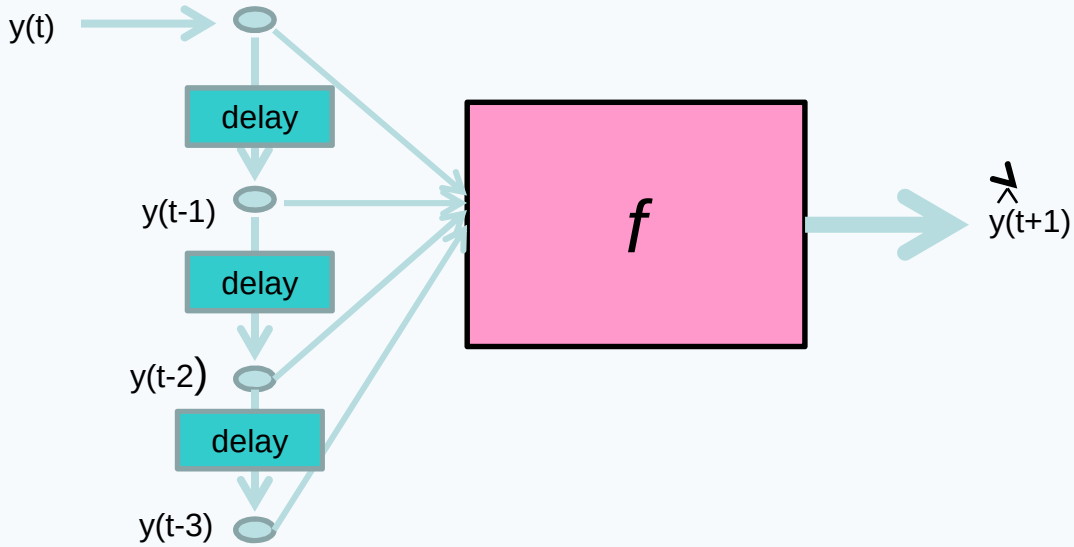


Hybrid Electric ECCE (on-line)

- Parameters definition

  Number of delay ?

  Number of neurons ?



- 10 neurons & 4 delays

Hybrid Electric ECCE (on-line)

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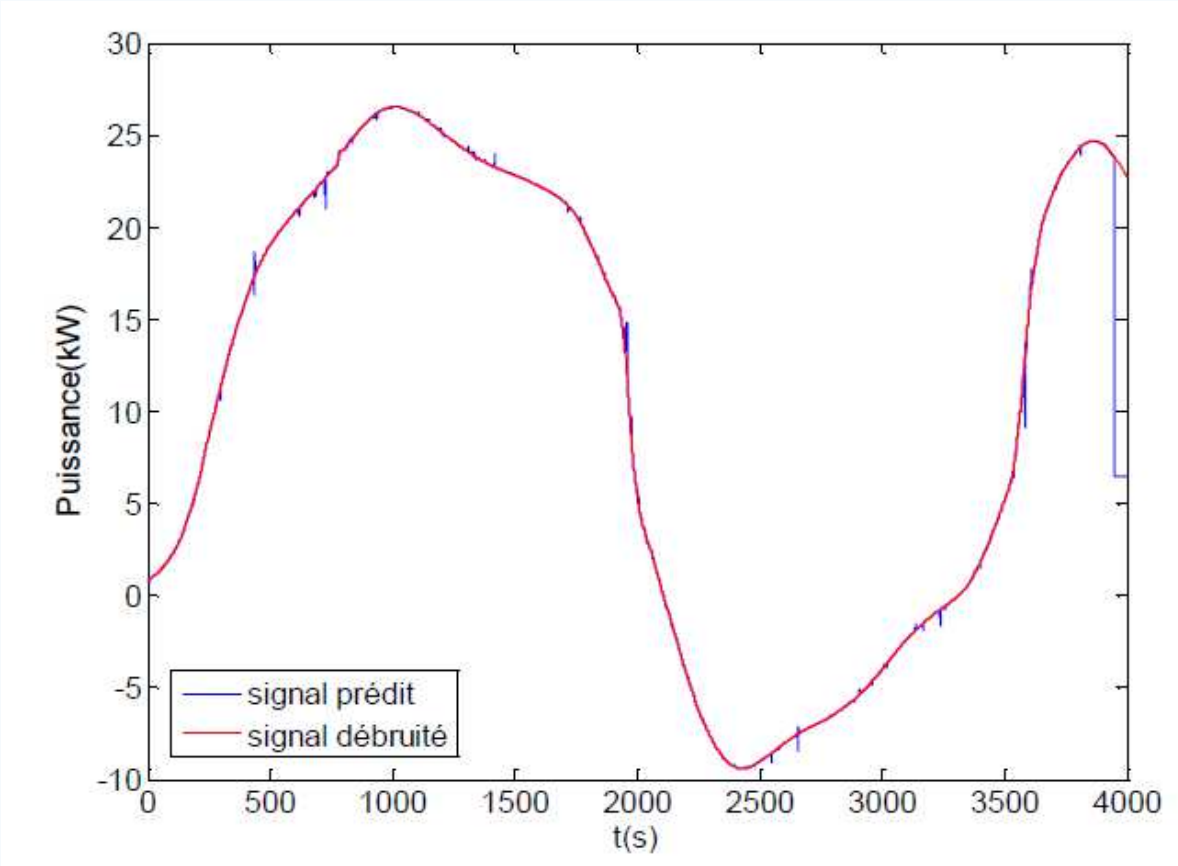
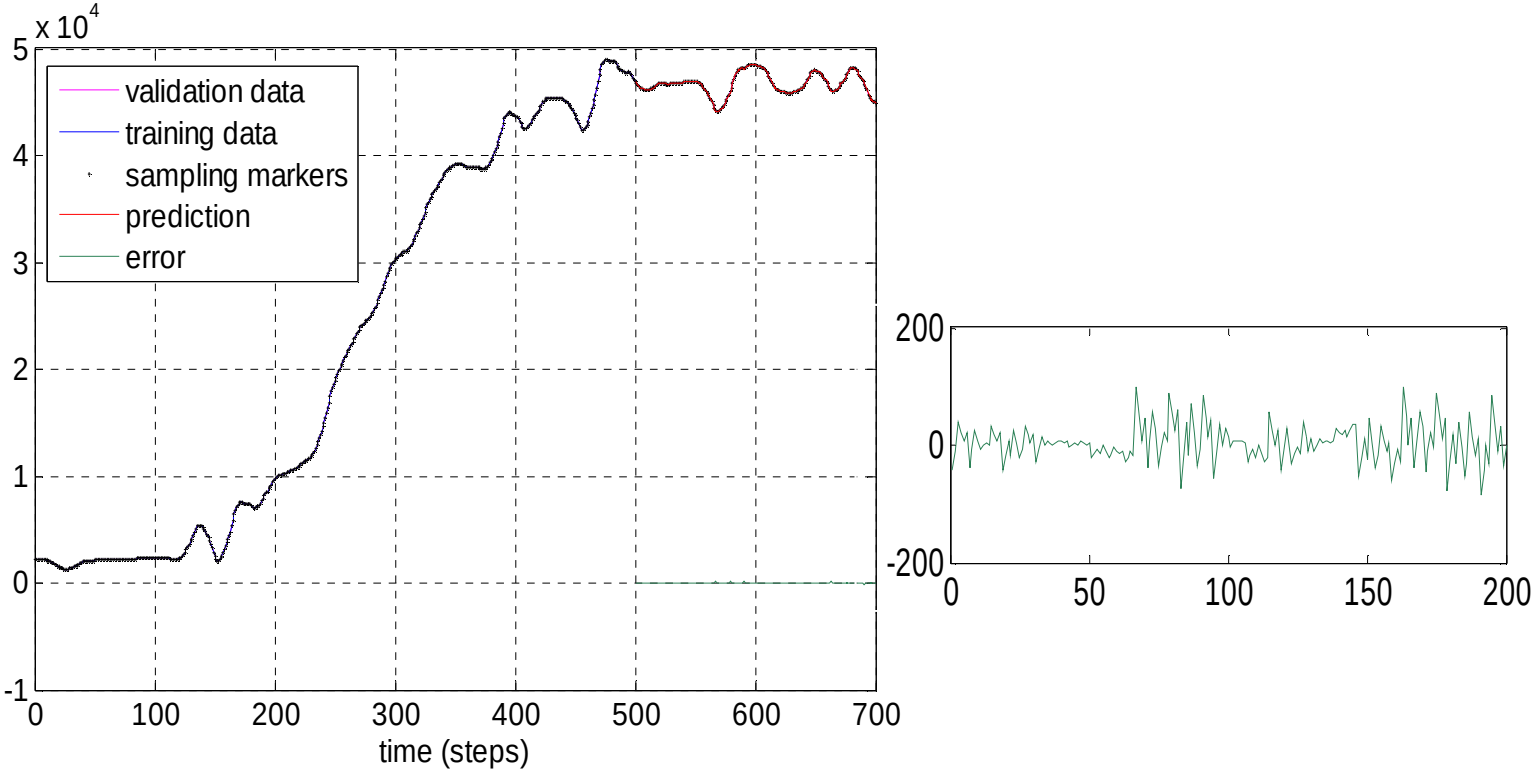
- Results

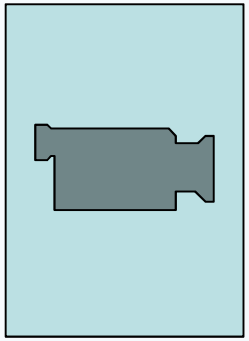


Hybrid Electric ECCE (on-line)

- Results



Hybrid Electric ECCE



Outline

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1. Introduction
   - FR FCLAB, goals and objectives
2. Hybrid Electric Locomotive
   - Modeling of the HEL
   - Otimal Fuzzy Logic Energy Management Strategy
3. Hybrid Electric Heavy Duty Truck
   - Wavelet Transform
   - Energy Management Strategy
5. **Conclusions.**

Conclusions (1/2)

- **Development of the on-board sources dynamical models with their control**

- **Experimental characterization of the NiCd battery cells**
  - Test of the capacity
  - Internal resistance evaluation according to the temperature and the SOC

- **Development of an intelligent Energy Management Strategy:**
  - No prior knowledge of the driving cycle
  - Fuzzy Logic management of the diesel driven generator set
  - Minimization of the use of the internal combustion engine
  - Comparison of the Survey based Interval Type-2 and optimized Type-1, Interval Type-2 and General Type-2 FLCs' efficiencies

Conclusions (2/2)

- **Development of an off-line Energy Management Strategy**
  - Based on DWT
  - Different energy sources : FC, UC and batteries
  - Set up of the DWT parameters

- **Development of an on-line Energy Management Strategy (1/2)**
  - Based on Neural Networks
  - Time prediction acceptable
  - Fast execution time

- **Development of an on-line Energy Management Strategy (2/2) NOT PRESENTED HERE**
  - Based on Auto Regressive Integrated Moving Average (ARIMA)
  - Time prediction linked to the decomposition level
  - Execution time > NARNN

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Research

Energy Management Strategies for Hybrid Electric Vehicle

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