Diagnosis of FC power generators

Invited Lecture

« Diagnosis of Fuel Cell Power Generators »

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- OUTLINE -

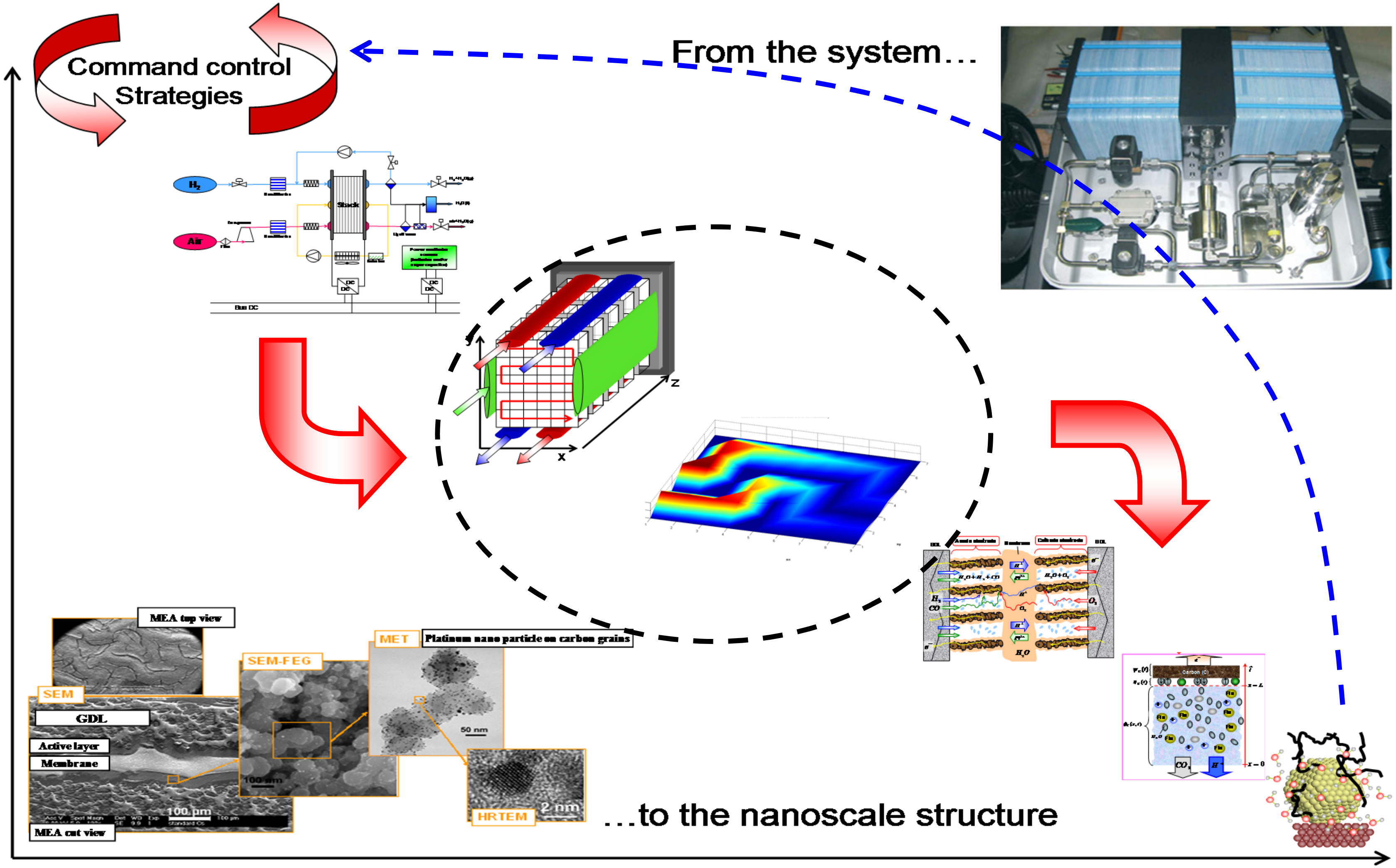
- Introduction – Durability

http://www.greencarcongress.com

- **Durability of the FC system**
  - 8000h required for light vehicles
  - 30000h required for trucks
  - 100000h required for rail and stationary power generators
  - … approx. 3000h obtained today for PEMFC systems, more for HT FC systems

- **Parameters reducing the FC lifetime**
  - Fuel impurities (sulfur, CO for PEMFC, …)
  - Oxidant impurities (oil from the compressor, salt from environment, …)
  - Fuel and oxidant stack starvation (linked to the dynamic and the control of the system)
  - Temperature supervision (linked to the system control)
  - Thermal cycling for SOFC (linked to the system control)
  - Hydration supervision for PEMFC (linked to the system control)
  - Pressure variations (linked to the system control)
  - Peak power demands and current ripples (linked to the control and to the power electronics)
  - Open circuit voltage operation for PEMFC (linked to the control)
  - …

- Introduction – Stack/System Interactions



Gérard, M., Poirot-Crouvezier, J.P., Hissel, D., Péra, M.C., "Oxygen starvation analysis during air feeding faults in PEMFC", Int. Journal of Hydrogen Energy, vol. 35, n°22, pp. 12295-12307, 2010.

- Introduction – Diagnosis objectives

- **Objectives**
  - Increase durability of the stack and of the system
  - Increase efficiency of the FC system
  - Increase reliability of the FC system
  - Increase dynamic performances of the FC systems

⇨ **FC STACK S.O.H. DIAGNOSIS METHODOLOGIES ARE A KEY ISSUE !!!**

- **Constraints**
  - Use of a minimal number of actual sensors
    - For complexity purpose
    - For cost purpose
    - For reliability purpose
    - For real-time control constraints

- PhD / Projects –

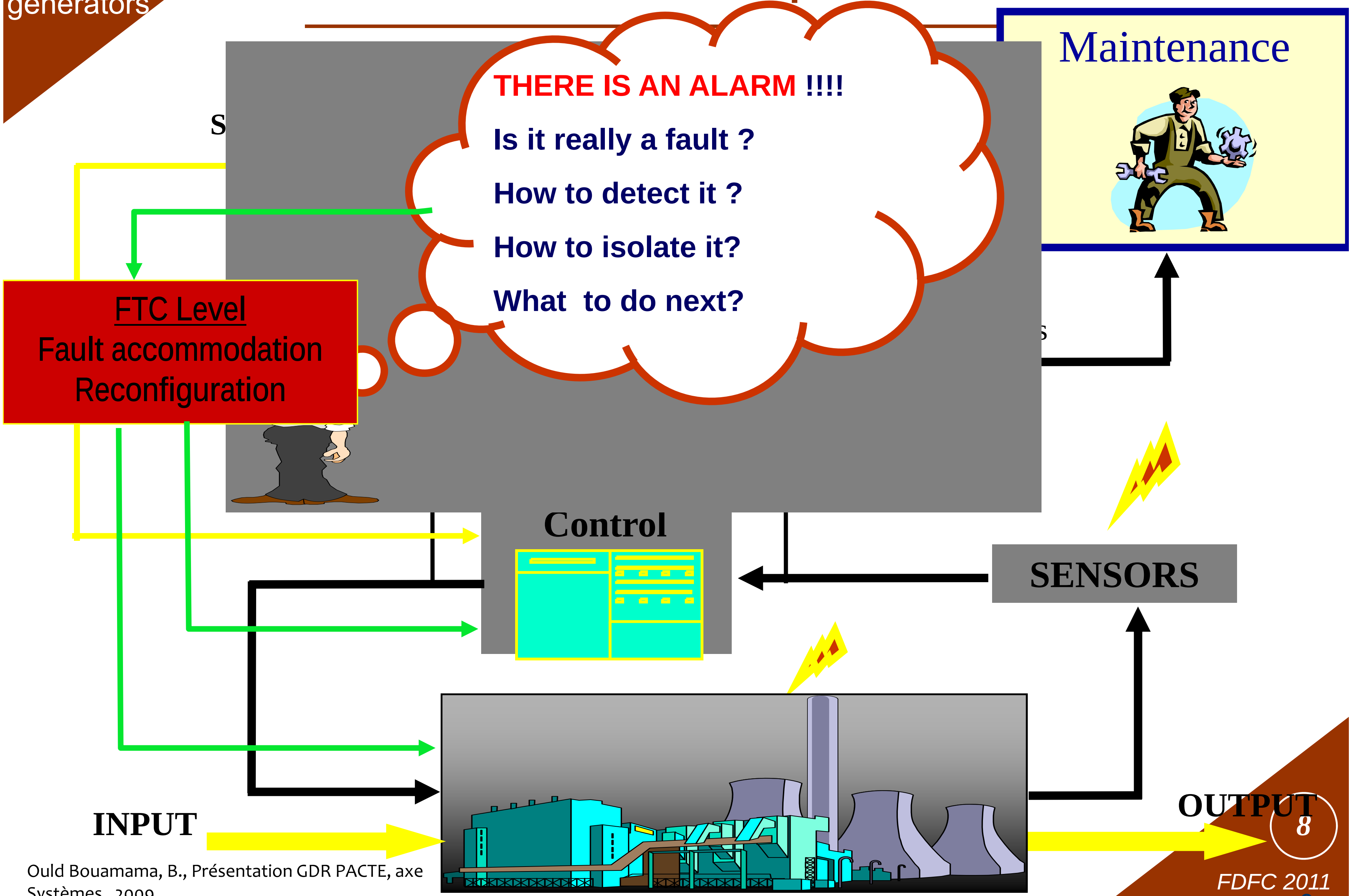
- **2 ongoing EU projects**
  - JTI H2-FC
  - D-CODE – Diagnostic of PEM Fuel Cell
  - GENIUS – Diagnostic of SO Fuel Cell

- **2 ANR Projects** (DIAPASON 1 & DIAPASON2) **+ 2 CNRS projects**

- **PhDs**
  - A. Hernandez (2006) : Diagnosis of PEM fuel cells (analytical approach)
  - A. Narjiss (2008) : On-line EIS of PEM fuel cells
  - E. Laffly (2008) : Durability modeling of PEM fuel cells
  - N. Steiner (2009) : Wavelet based approach for diagnosis of PEM fuel cells
  - S. Wasterlain (2010) : Bayesian network approach for PEM fuel cells
  - M. Gérard (2010) : Interactions between system and stack (PEMFC)
  - K. Wang (2012) : Diagnosis (wavelet, Bayesian) of SOFC
  - R. Onanena (2012) : Ageing diagnosis (Kohonen) of PEMFC
  - I. Rabaaoui (2014) : On line time diagnosis of PEMFC
  - Z. Zheng (2014) : DC-DC converter based diagnosis of PEMFC
  - X. Li (2014) : Statistical approach for the diagnosis of PEMFC
  - R. Silva (2014) : Prognostic of PEMFC
  - XXX (2015) : ….

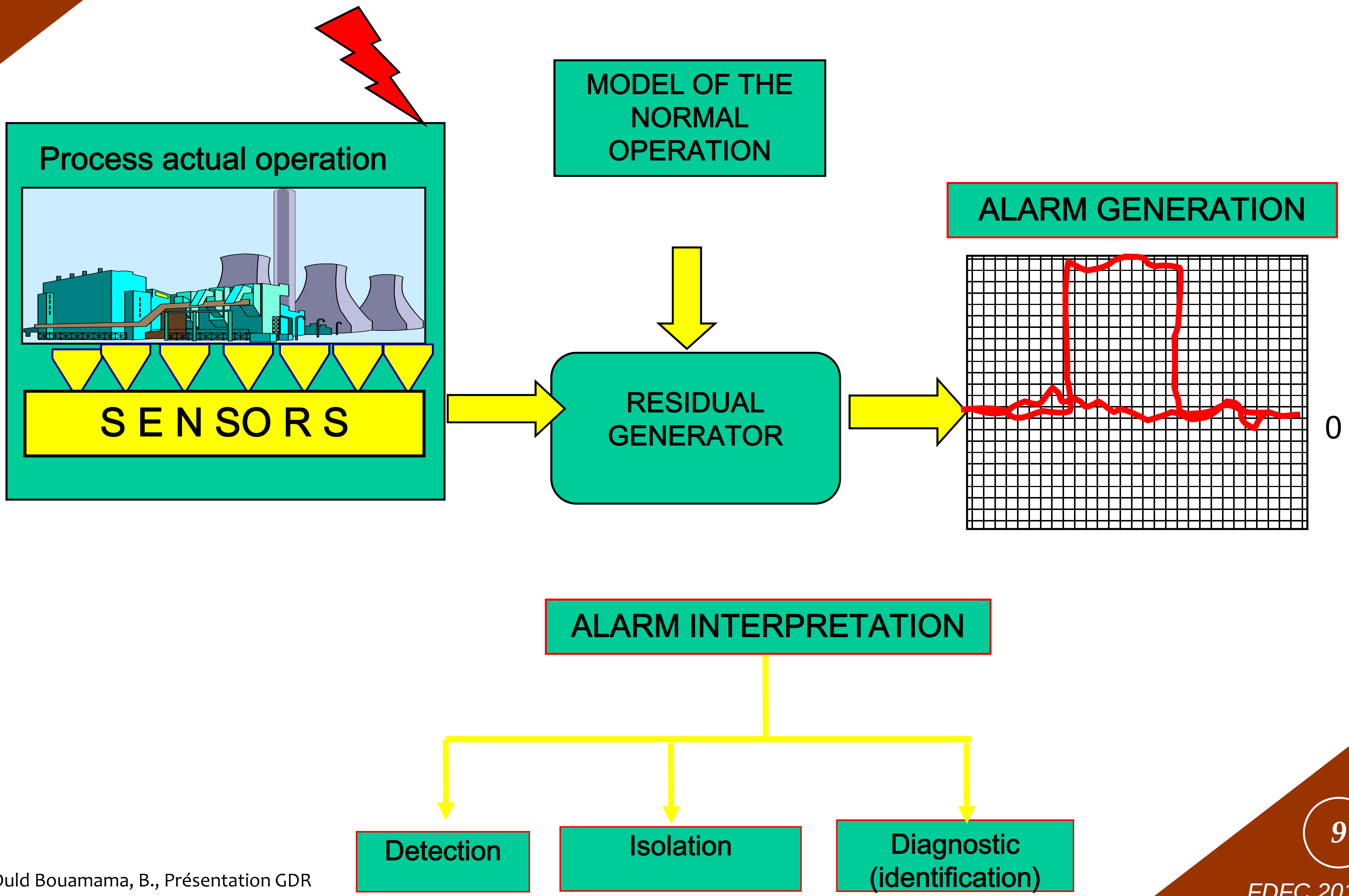
- OUTLINE -

- Diagnosis – Supervision & Maintenance



Ould Bouamama, B., Présentation GDR PACTE, axe Systèmes, 2009.

- Diagnosis – Model-based FDI



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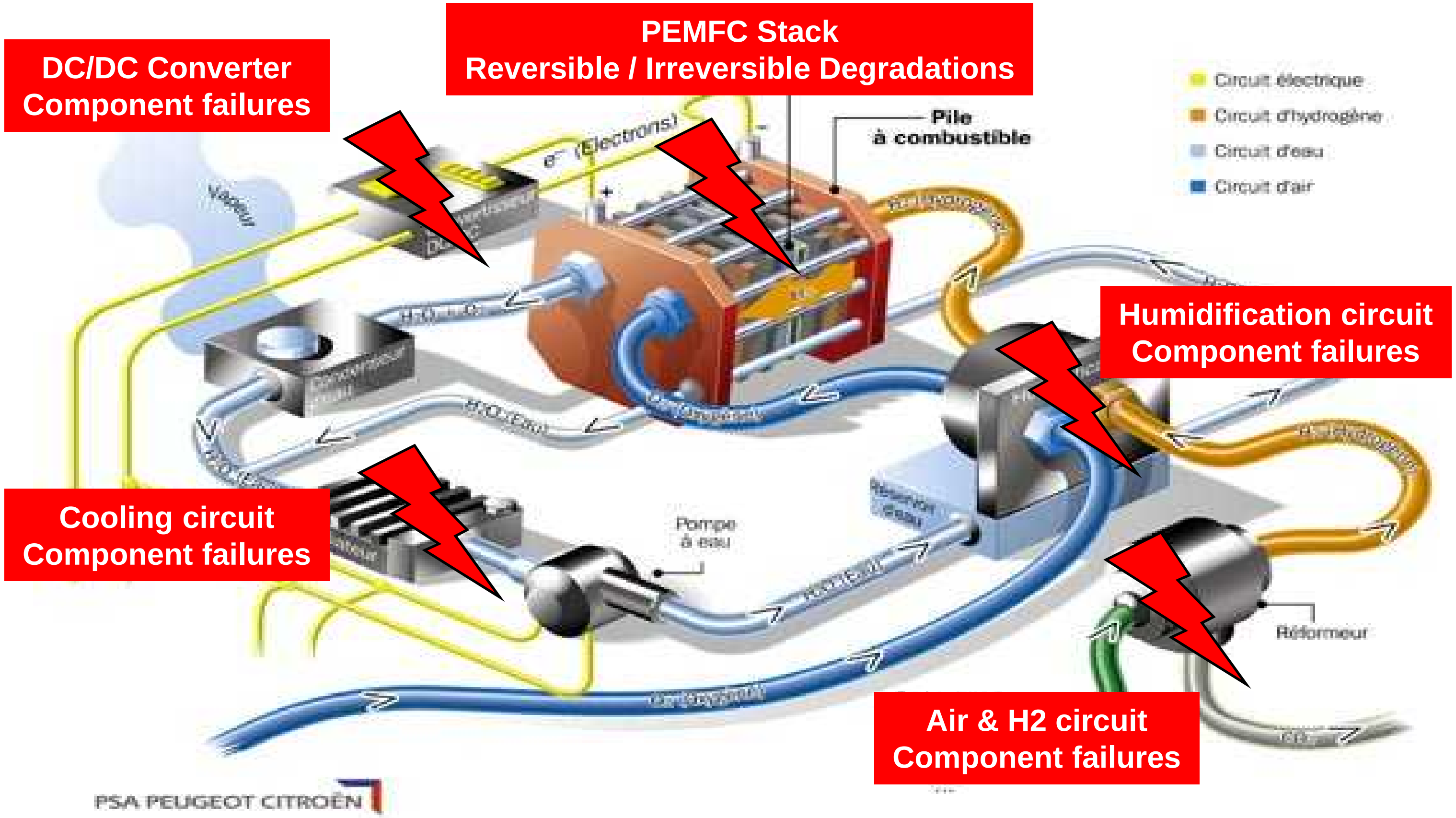
- OUTLINE -

- Occurring faults –

Case of an embedded PEM fuel cell system



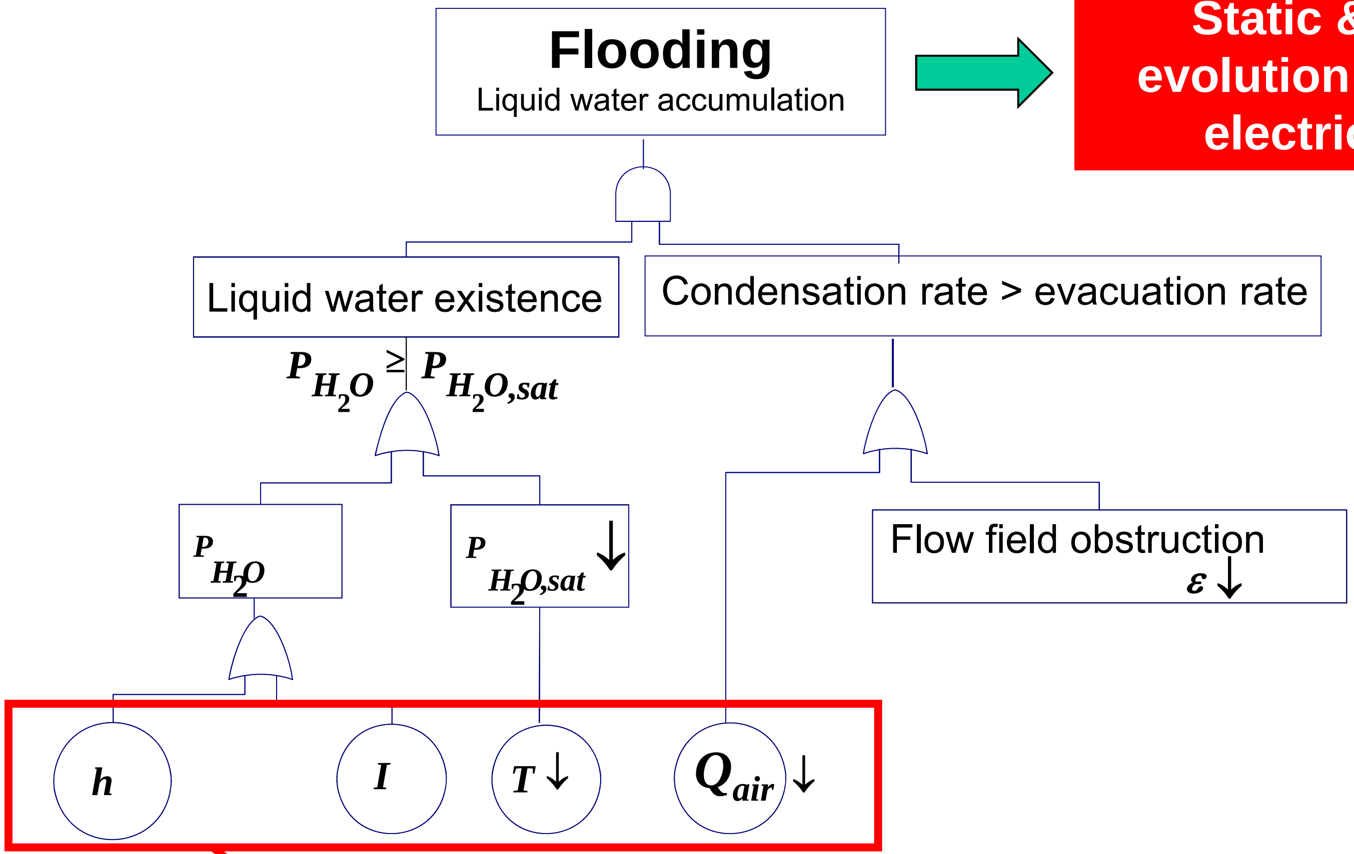
Sensor failures

Control failures

- Fault tree analysis –

Link between operating parameters and faults

→ **Fault tree analysis : intuitive approach of diagnosis**



Static & dynamic evolution of delivered electrical power

Multiphysics parameters

Yousfi-Steiner, N., Candusso, D., Moçoteguy, Ph., Hissel, D., Hernandez, A., Aslanides, A., "A review of PEM voltage degradation associated with water management: impacts, influent factors and characterization", Journal of Power Sources, vol. 183, n°1, pp. 260-274, 2008.

- Requirements and Constraints -

Use of a minimum number of actual sensors (linked to feasibility, cost, reliability, dynamic, …)

Measurements technically or economically possible	Measurements technically or economically not really possible	Measurements technically or economically obviously not possible
• Stack current • Stack voltage • Cooling water temperature • Air / H2 temperatures (inlet / outlet) • Air compressor speed	• Single-cell voltages • Air / H2 pressures (inlet / outlet) • Stack internal temperatures	• Air flow • H2 flow • Channels (air, H2, water) flows • Current density • Air/ H2 hygrometry • Electrolyte membrane water content • Stack impedance using a specific impedancemeter • Inlet gases composition • Outgoing effluents composition

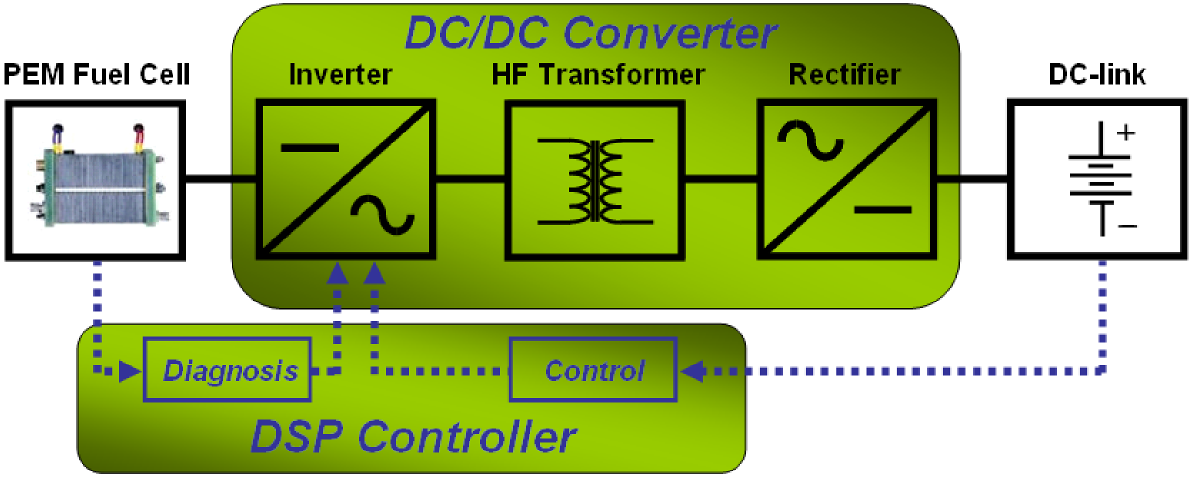
➡ Need of a « minimum » diagnosis device

- OUTLINE -

1. INTRODUCTION
2. WHAT IS "DIAGNOSIS" ?
3. BACK TO THE FC SYSTEM
4. A FOCUS ON SOME SOLUTIONS
5. CONCLUSION

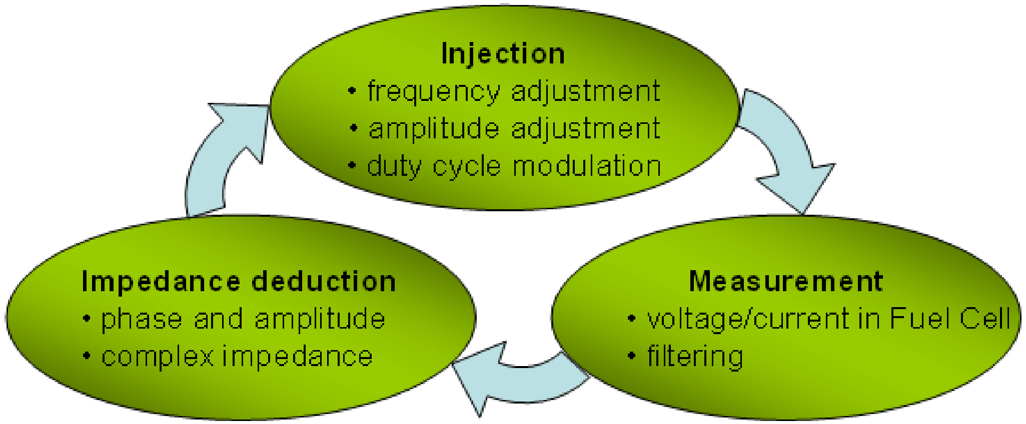
- Solutions -

1. On-line impedance spectrometry



General description of the energy conversion scheme
-
Here DC/AC/DC power converter

FC impedance spectroscopy principle



- **Semi-conductors : Mosfets + Diodes**
- **F_{PWM}=50kHz**
- **Planar technology transformer**

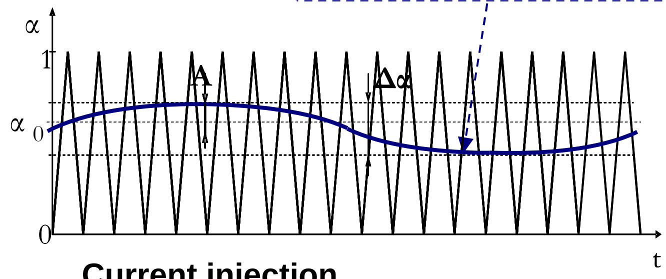
Narjiss, A., Depernet, D., Gustin, F., Hissel, D., Berthon, A., “Design of a high efficiency fuel cell DC/DC converter dedicated to transportation applications”, ASME Fuel Cell Science and Technology, vol. 5, n°4, 11p., 2008.

- Solutions -

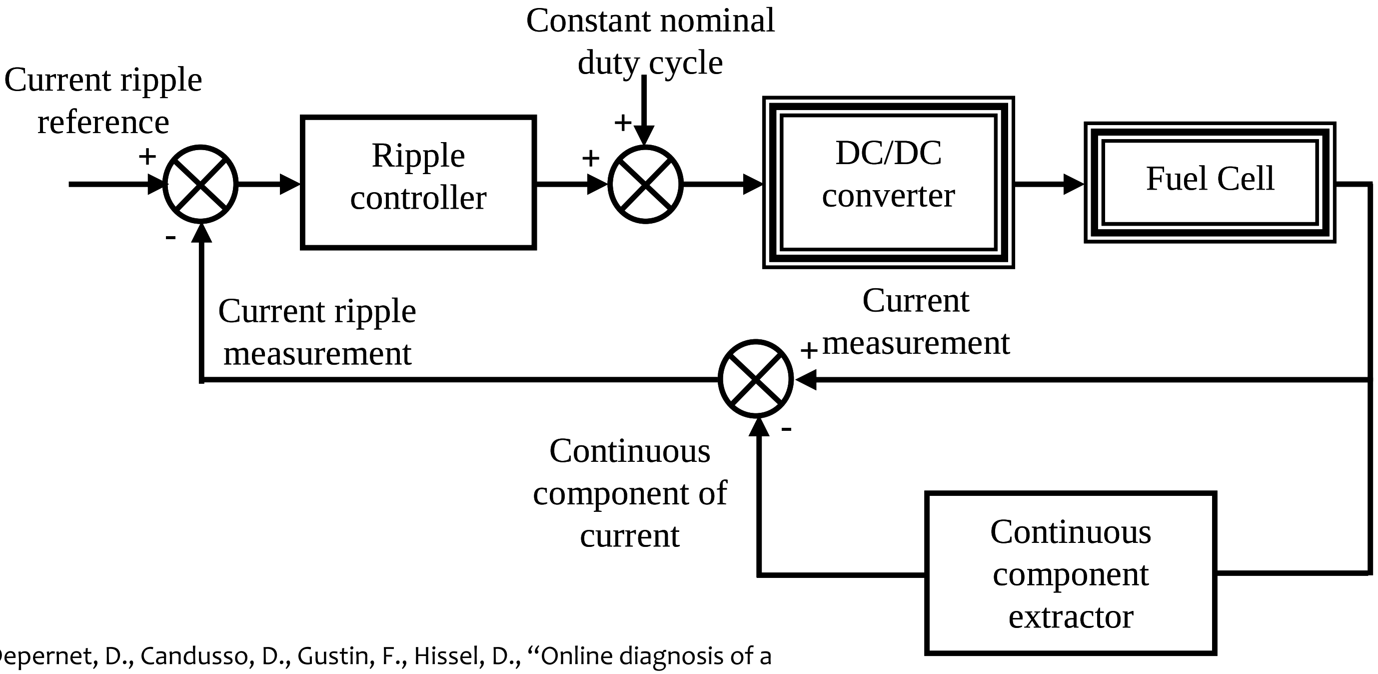
1. On-line impedance spectrometry

Injection strategy of fuel cell stimulus
- duty cycle sinusoidal modulation
- control of the current ripple amplitude

$\alpha = \alpha_0 + A.\sin(\omega t)$



Current injection
α_0 : duty cycle => normal behavior
A : sinusoïdal modulation amplitude



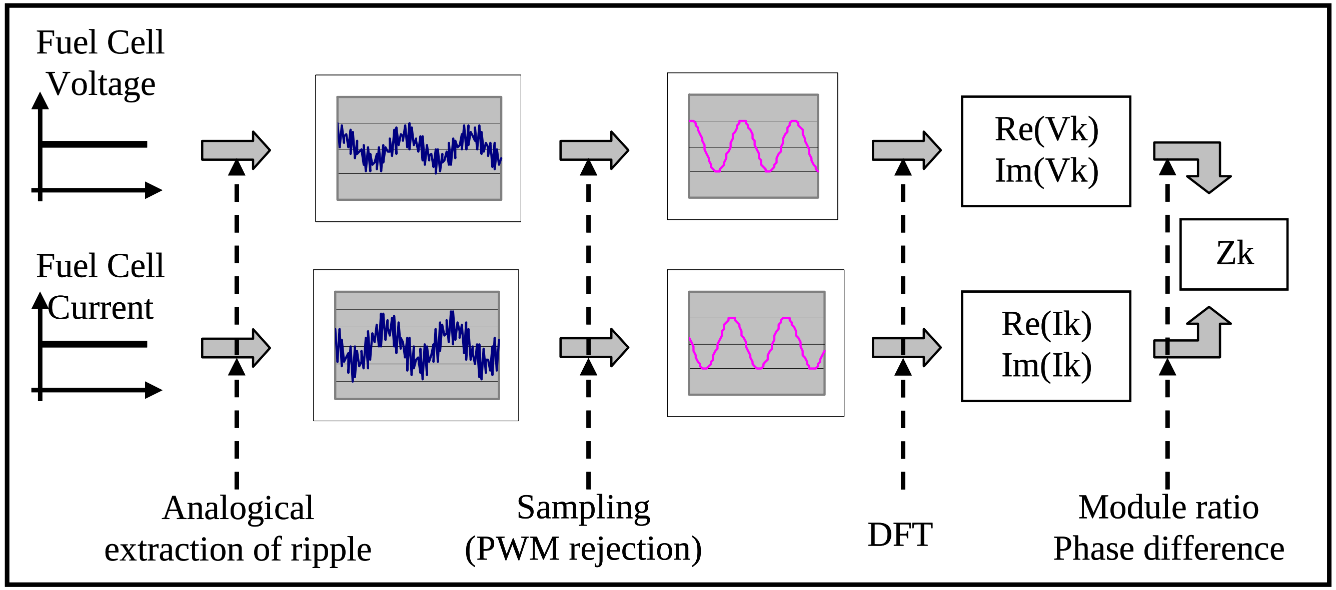
Narjiss, A., Depernet, D., Candusso, D., Gustin, F., Hissel, D., “Online diagnosis of a PEM fuel cell”, EPE PEMC Conference, CD-ROM, pp. 749-754, Poznan, Poland, 2008.

- Solutions -

1. On-line impedance spectrometry

Impedance measurement principle

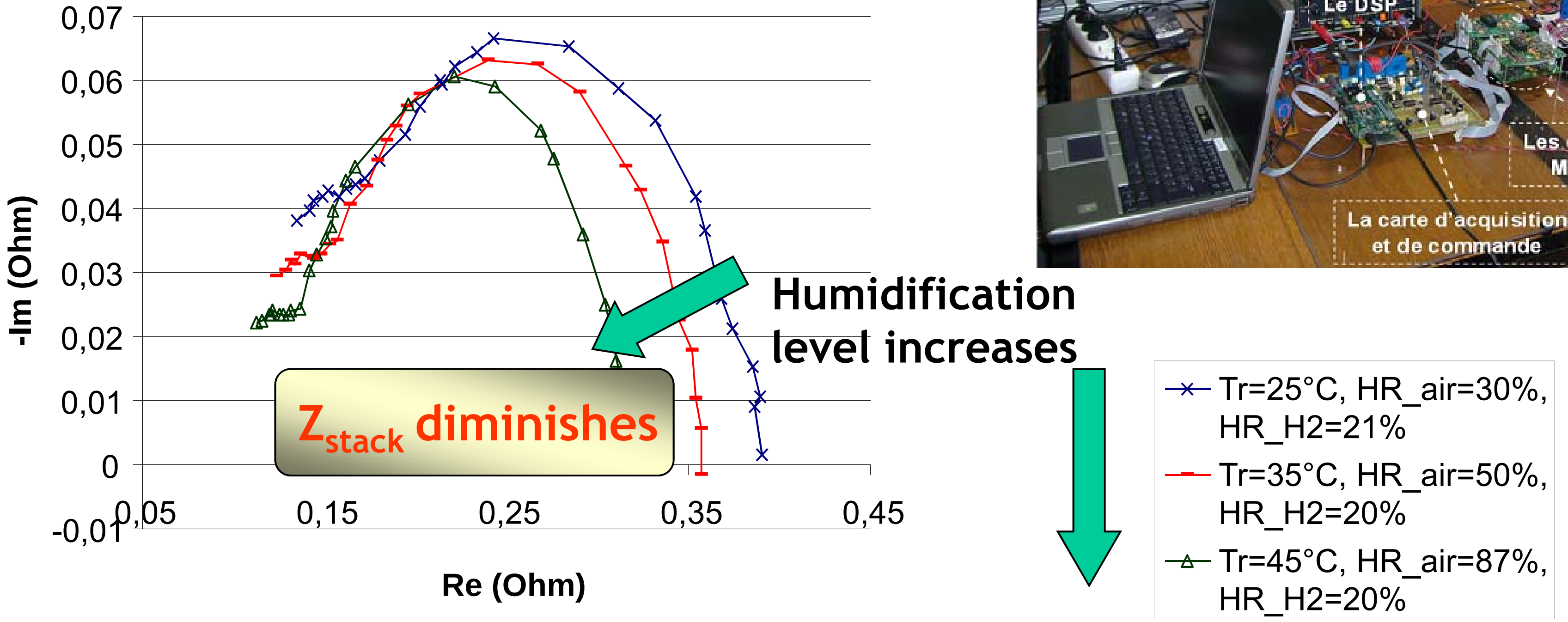
- extraction of ripple
- PWM rejection
- filtering and phase referencing of desired ripple with DFT (Discrete Fourier Transform)
- harmonic impedance

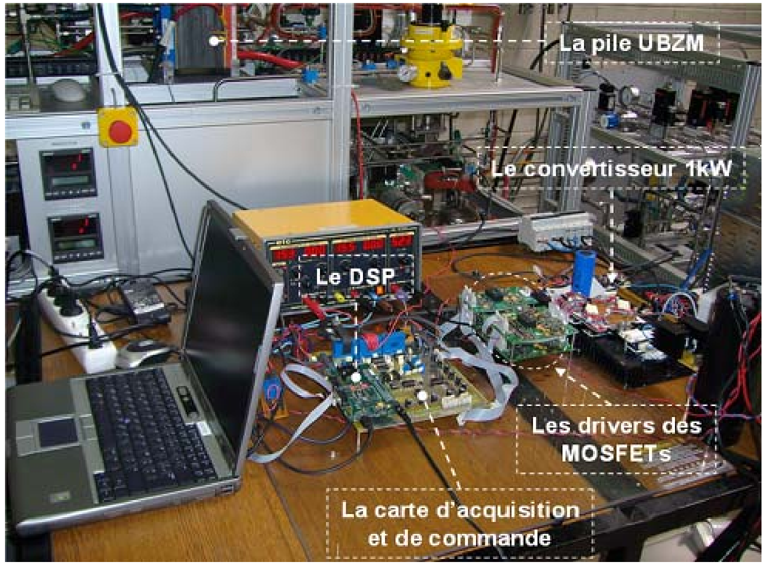


- Solutions -

1. On-line impedance spectrometry

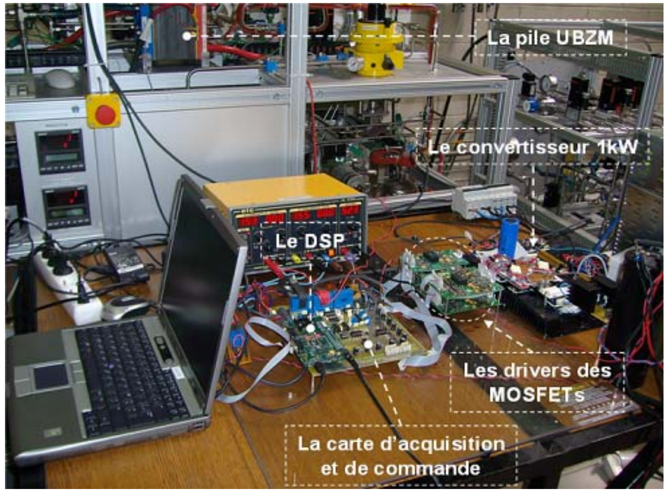
Experimental results : effect of the air hydration level



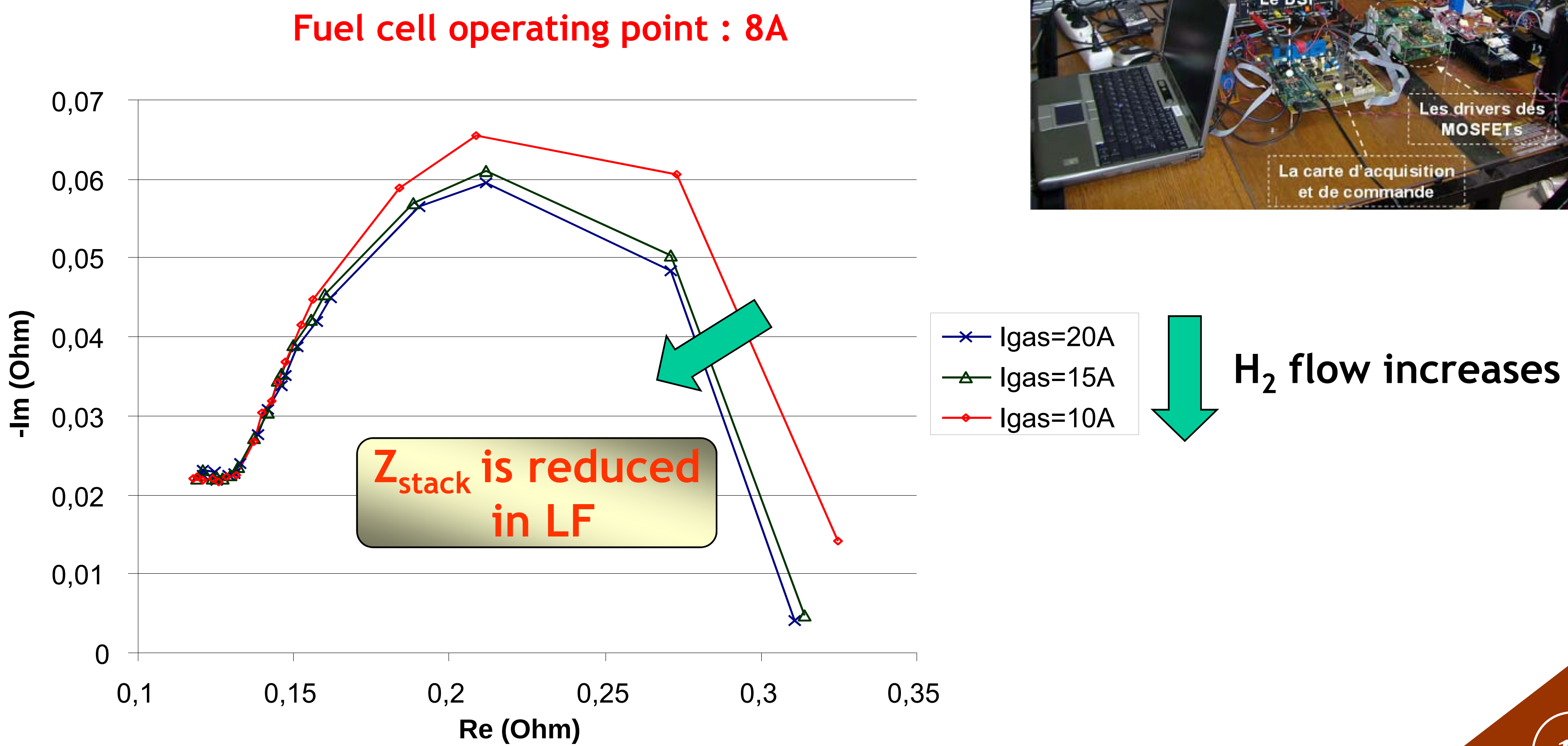


- Solutions -

1. On-line impedance spectrometry



Experimental results : effect of H_2 gas flow



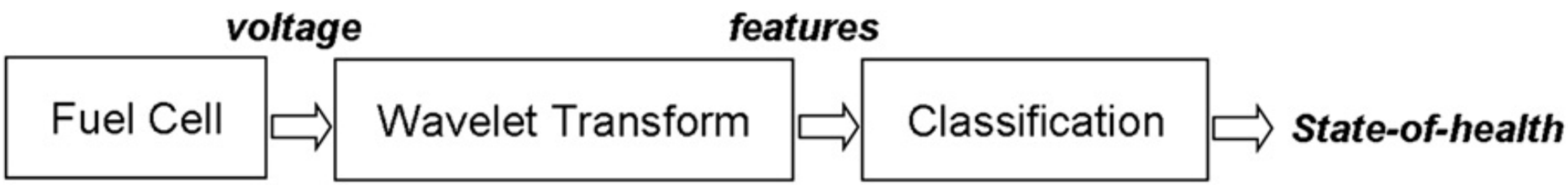
- Solutions -

2. Non-intrusive diagnosis by wavelet packets

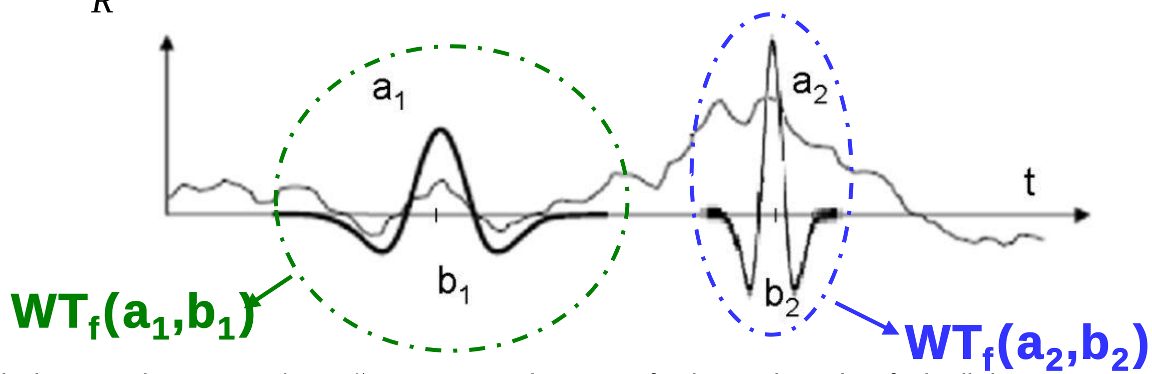
Idea : use directly the output voltage signal to perform the diagnosis of the fuel cell SOH's

Methodology :

- Use time-scale signal treatment methods
- Here Wavelet Transformation is considered
- Principle : the time-varying signal is projected on a wavelet basis



$$WT_f(a,b) = \int_R f(t)(\psi_{a,b}(t))^* dt \quad \text{with} \quad \psi_{a,b}(t) = \frac{1}{\sqrt{2^j}}\psi\left(\frac{t-2^j k}{2^j}\right), \quad (j,k) \in Z^2$$



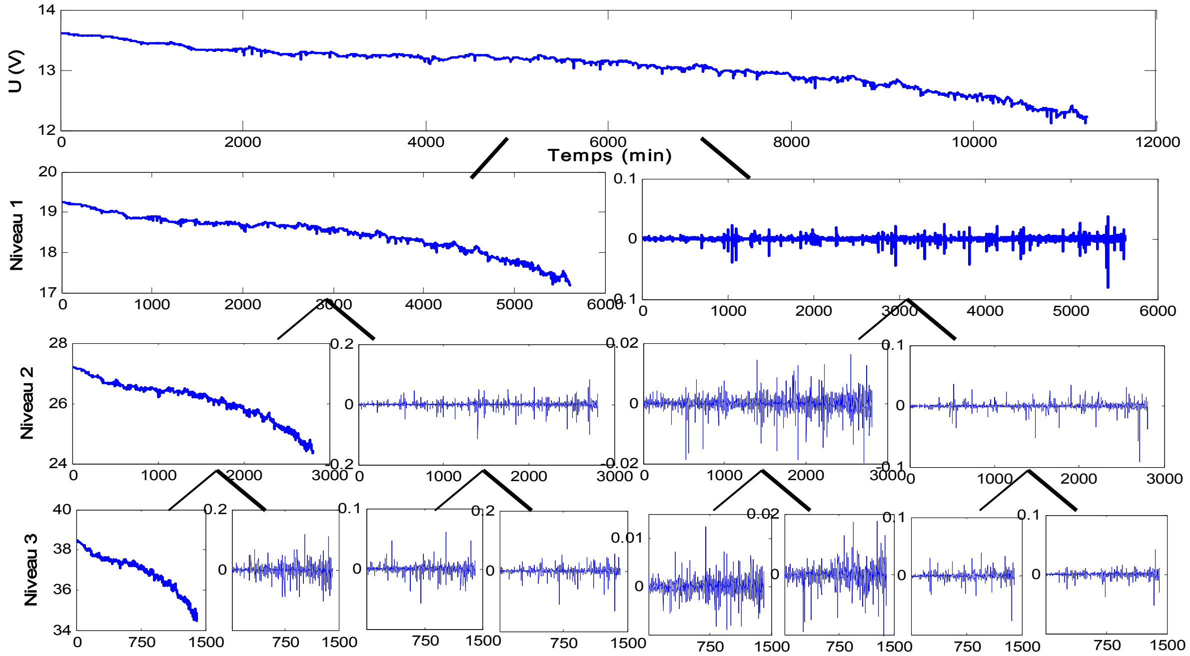
N. Yousfi Steiner, D. Hissel, Ph. Moçotéguy, D. Candusso. "Non intrusive diagnosis of polymer electrolyte fuel cells by wavelet packet transform", Int. Journal of Hydrogen Energy, In Press, Corrected Proof, Available online 18 November 2010.

- Solutions -

2. Non-intrusive diagnosis by wavelet packets

Wavelet packets transform :

- The aim is to obtain a redundant representation of the signal
- Example : experimental results on a PEMFC stack during cathode flooding



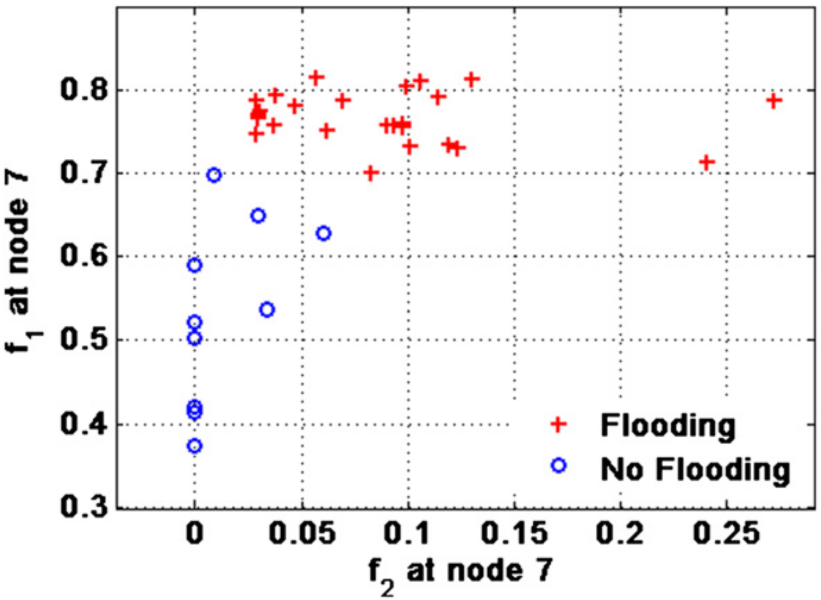
- Here 7 levels are considered, i.e. 254 packets / measured signal

- Solutions -

2. Non-intrusive diagnosis by wavelet packets

Then :

- For each wavelet packet, select specific parameters able to characterize a specific fault class
- Optimization of the representation space (i.e. selecting the most suitable parameters among the total list of parameters)
- Classification : here experimental results for flooding / non flooding operating mode in a PEMFC stack



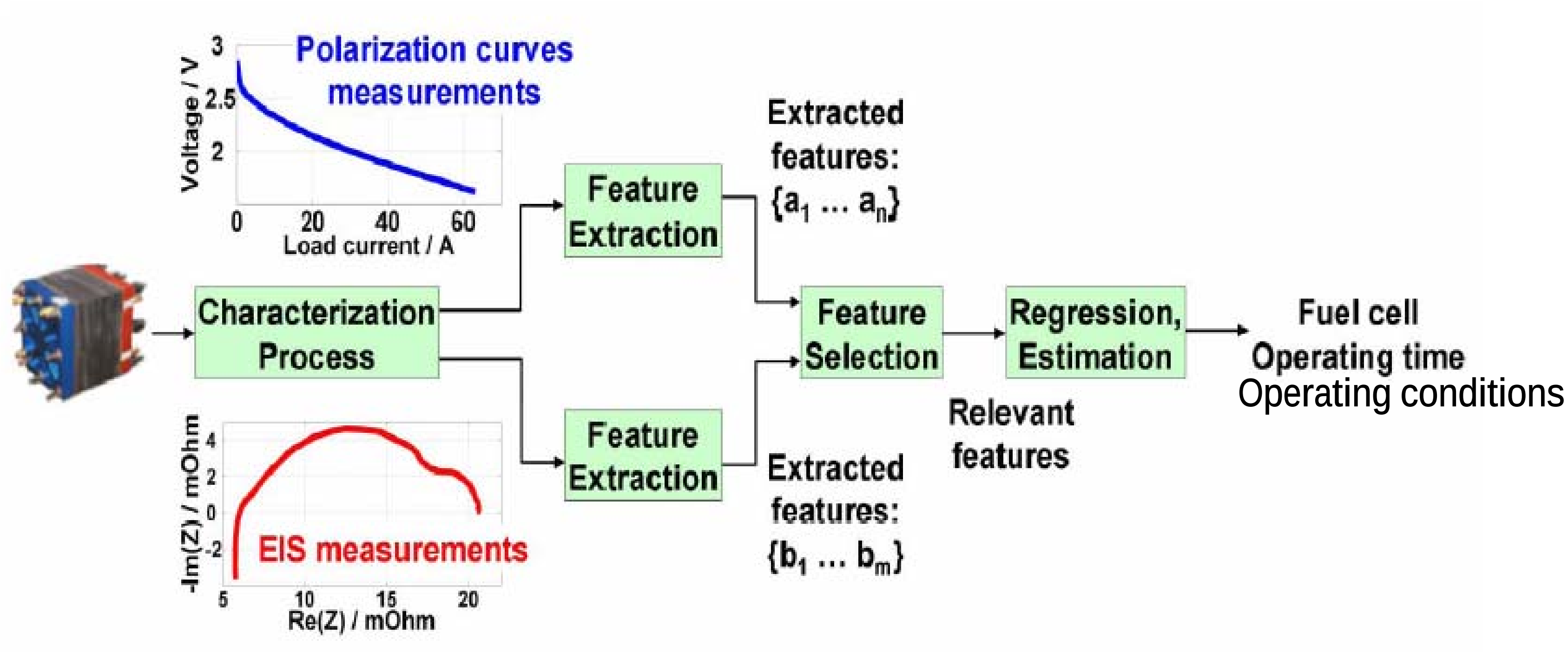
- Solutions -

Objective **: answering the following questions by carrying out low-cost experimental characterization on an unknown stack**

What is the age of the stack ?
What is the remaining lifetime ?
On which conditions it was operated ?
When should I do predictive maintenance ?

- Solutions -

3. Ageing diagnosis



- **No analytical model is required**
- **Relies on classification technique**
- **Inputs (symptoms) must be typical for the studied degradation**

- Solutions -

3. Ageing diagnosis

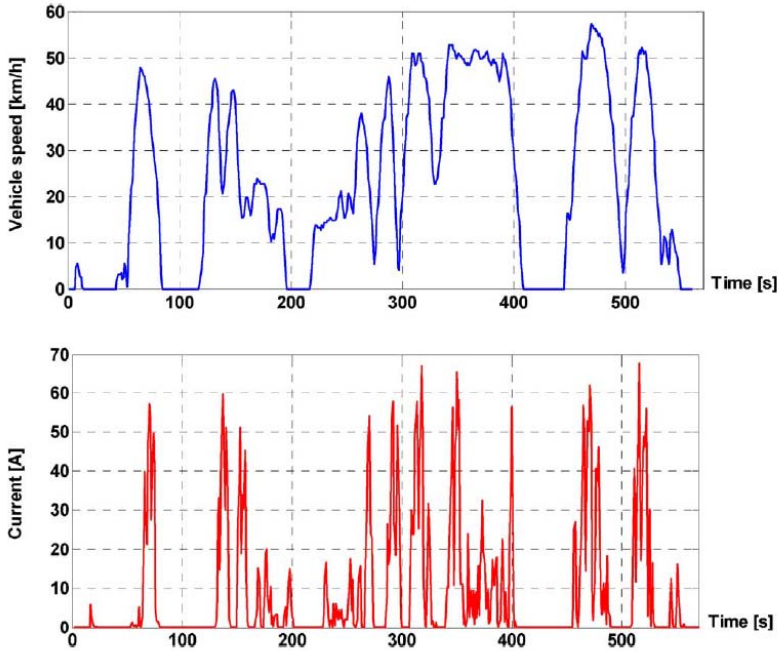
Experimental example

2 load conditions (1000h duration test)

Stack 1 : constant current 50 A

Stack 2 : dynamic current profile (from real car solicitation)

Normalized mean current : 12.5 A



TECHNICAL SPECIFICATIONS OF THE CONSIDERED PEFC STACKS

Number of cells	3
Nominal current	50A
Maximal power	100W
Cell area	100cm^2
Operating temperature	20°C to 65°C
Nominal operating temperature	55°C
Nominal air dew point	45°C
Operating pressure	Max 1.5 bar (abs)
Maximal differential pressure (anode/cathode)	0.6 bar
Media inlet	
Anode	Pure, dry hydrogen
Cathode	Humidified air
Coolant circuit	De-ionized water

- Solutions -

Experimental example

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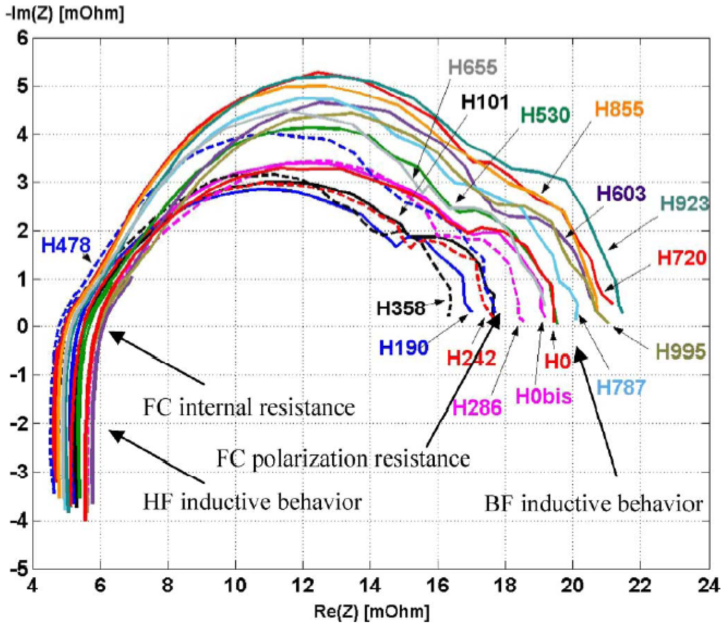
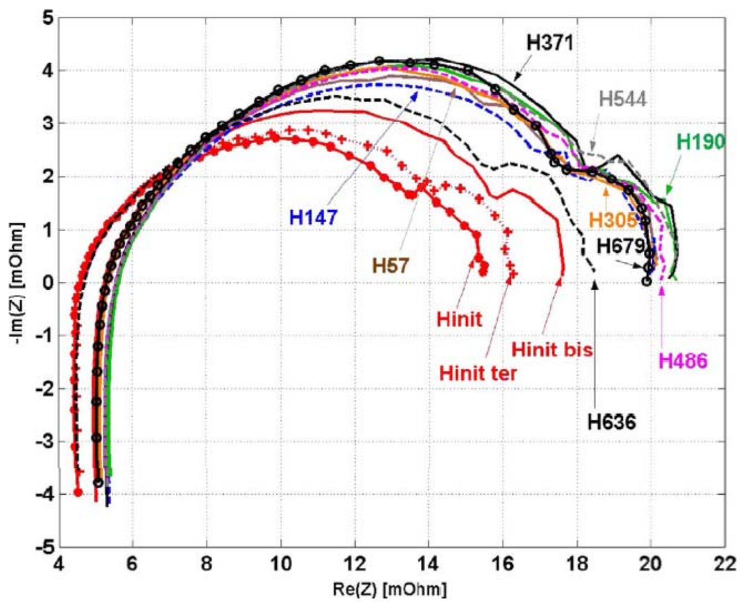




- Solutions -

Fuzzy clustering approach : identifying past operating conditions

Data points collection (ex) :

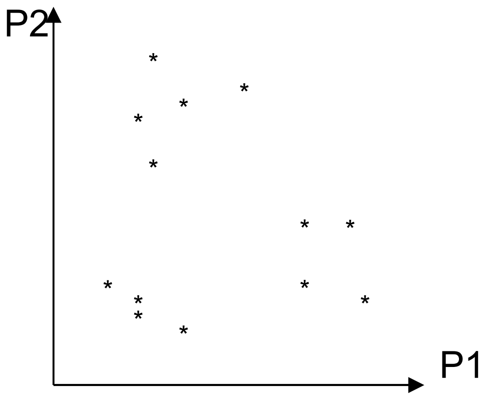
Inputs: 2 relevant parameters (P1 & P2)

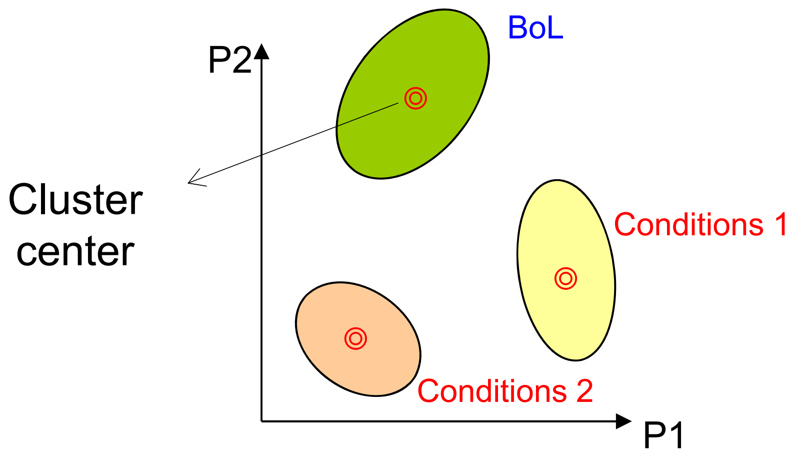
Output: degradation type

(BoL / conditions 1 / conditions 2 / undefined)

k -means algorithm:

- Find the cluster center that best represents each class (here 3 classes)
- Link each class to a particular degradation type





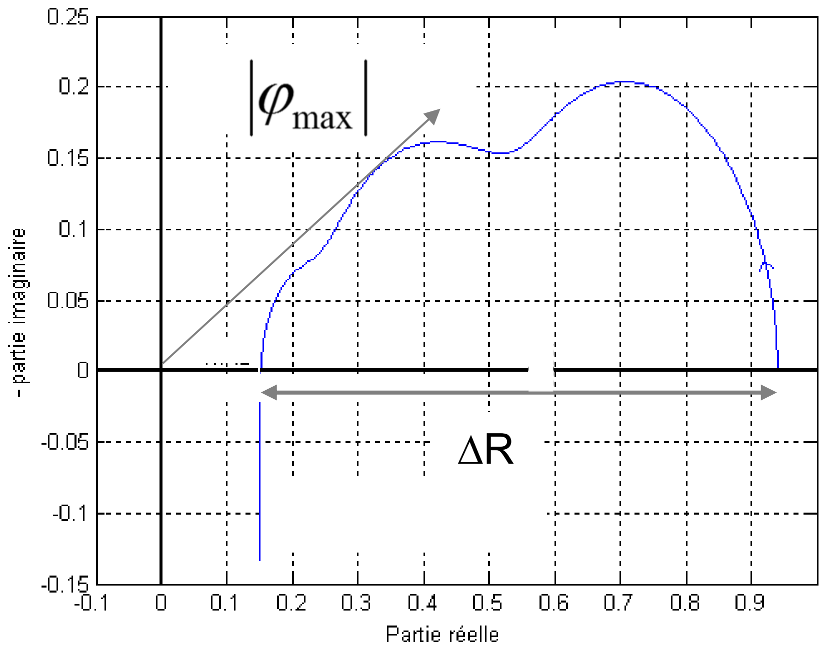
- Each data point belongs to all classes with a certain degree of membership
- This degree depends upon the (Euclidian) distance to all cluster centers

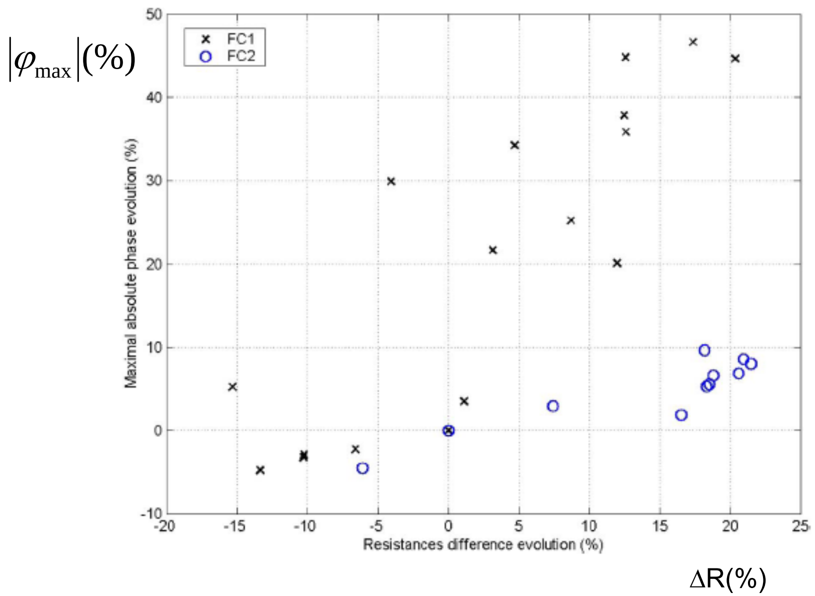
Hissel, D., Candusso, D., Harel, F., "Fuzzy-clustering durability diagnosis of polymer electrolyte fuel cells dedicated to transportation applications", IEEE Transactions on Vehicular Technology, vol. 56, n°5, pp. 2414-2420, 2007.

- Solutions -

Fuzzy clustering approach : identifying past operating conditions

- ***Data collection*** : 2 relevant hyper-parameters for each EI spectrum



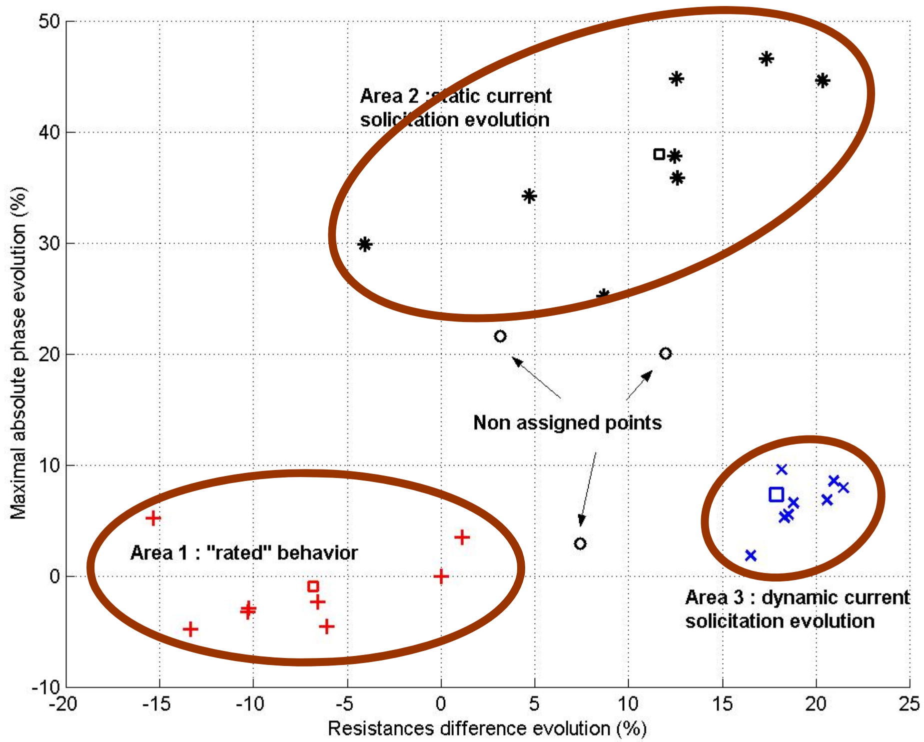


- Solutions -

Fuzzy clustering approach : identifying past operating conditions

Data collection

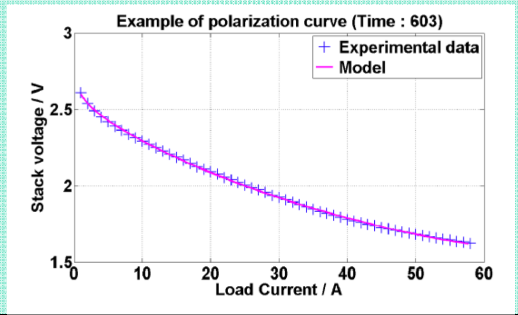
1. BoL
2. Typical degradation under static current solicitations
3. Typical degradation under dynamical current solicitations
4. Some “transient” operating points (non-assigned points)



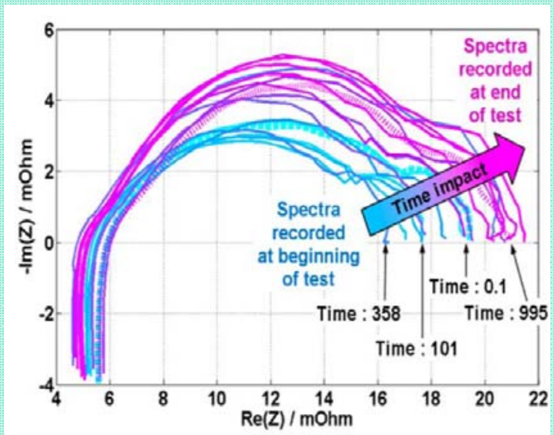
- Solutions -

Latent process approach : identifying actual operating time

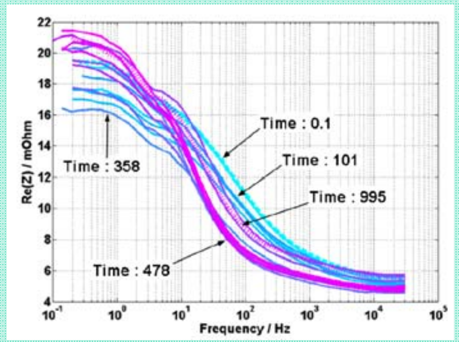
Static characteristics



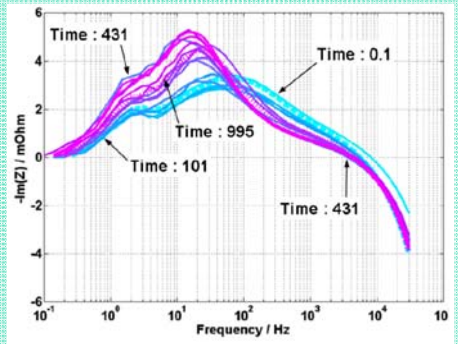
Dynamic characteristics



Real Part



Imaginary Part



R. Onanena, L. Oukhellou, D. Candusso, A. Same, D. Hissel, P. Aknin, "Estimation of fuel cell operating time for predictive maintenance strategies", Int. Journal of Hydrogen Energy, Volume 35, Issue 15, pp. 8022-8029, 2010.

- Solutions -

Latent process approach : identifying actual operating time

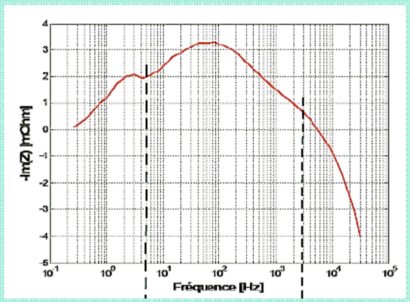
Static behavior is described by a empirical model : $U = \alpha + \beta I + \gamma I^2 + \delta \log(I)$

→ 4 parameters

Real Part is described by a parametric model : $\mathrm{Re}(\log f) = \dfrac{a_1}{1 + \exp(-a_2.\log f - a_3)} + a_4$

→ 4 parameters

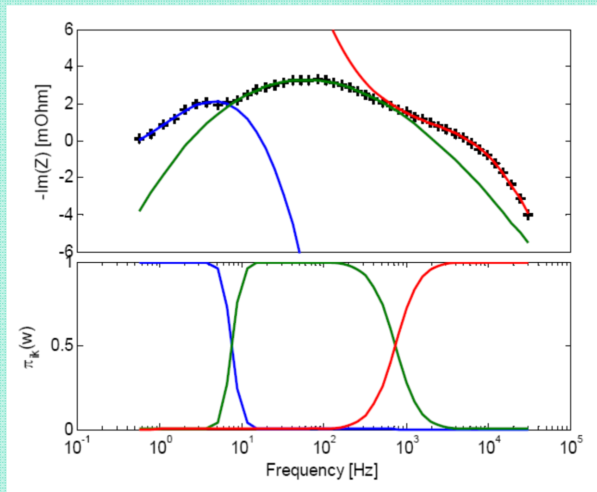
Imaginary Part is described by a latent regression model :



→ 3 physical areas
(diffusion, charge transfer,
inductive behavior of connections)

→ Regression model with
hidden logistic functions

→ 21 parameters



- Solutions -

Latent process approach : identifying actual operating time

- Adaptative Brench & Bound optimization algorithm (ABB)

- Experimental results :

	Optimization method : ABB	
	Remaining error (in hours) : learning base	Remaining error (in hours) : test base
Learning on static characteristics only	131.5	144.1
Learning on impedance spectra only	68.8	103.8
Learning on static characteristics & impedance spectra	eps	2.4

➡ Ability to identify the age of a fuel cell stack at 0,2%
Predictive maintenance is on the way…

- OUTLINE -

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3. BACK TO THE FC SYSTEM
4. A FOCUS ON SOME SOLUTIONS
5. CONCLUSION

- Conclusions –

- **FC stack and system diagnosis is a key issue in the development**
  - In order to increase durability
  - In order to increase performances
  - In order to enable predictive maintenance
  - In order to increase reliability

- **FC stack and system diagnosis**
  - should use as few sensors as possible
  - should allow real-time operation
  - should be as robust as possible vs. operating point, faults, models, …

- **Many programs are underway**
  - among JTI-H2FC
  - among ANR in France
  - in the industry

It's only the beginning of the story…

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Invited Lecture

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