Prognostic, Diagnostic & Health Management of Fuel Cells – A state of the art

Rafael Gouriveau, Daniel Hissel

FEMTO-ST Institute, UMR CNRS 6174
FCLAB Research Federation, FR CNRS 3539

rafael.gouriveau@femto-st.fr
daniel.hissel@univ-fcomte.fr

Authors

Professor **Daniel Hissel**

- Director of the FCLAB (Fuel Cell Lab) Research Federation
- Head of “Hybrid & Fuel Cell Systems" research team, FEMTO-ST Institute
- Head of “Fuel Cell Systems” research axis, French CNRS research grouping on Hydrogen & Fuel Cells

daniel.hissel@univ-fcomte.fr

Associate Professor **Rafael Gouriveau**

- Head of "PHM" research team, FEMTO-ST Institute
- Scientific coordinator of "PHM axe", FCLAB Research Federation

rafael.gouriveau@femto-st.fr

PHM of a Fuel Cell System

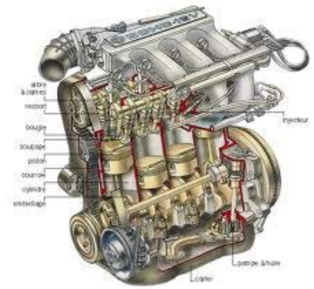
Prognostic, Diagnostic & Health Management of Fuel Cells – A state of the art

Motivations

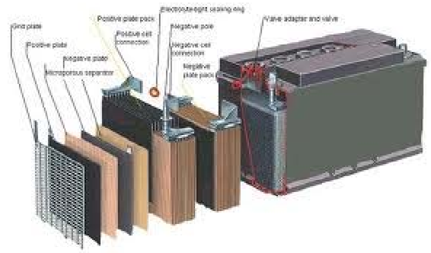
Towards FC systems

– **Switching to fuel cell ? – Transportation applications**

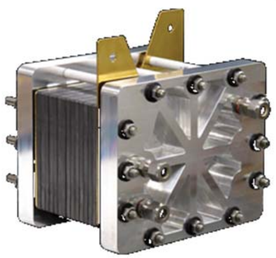
- **The age of utilizing exclusively fossil fuels comes to an end**
  - Resource reduction
  - Pollution issues



- **First alternative: rechargeable batteries**
  - Significant progress has been made BUT
    – Long duration recharging operation
    – Limited autonomy of the electrical vehicle
    ⇨ Mostly “hybrid” vehicles : reduce rather than eliminate the dependency on fossil fuels…



- **Second alternative: fuel cell systems**
  - When combined with oxygen, hydrogen produces electricity
  - Residues: water and heat
  - (*Theoretical & in-situ*) pollutant emissions is zero
  - ⇨ **Attractive alternative**
  - ⇨ **High energy density (but linked to H2 storage)**



Towards FC systems

– **Switching to fuel cell ? – Stationary applications**

- **Increasing interest for the storage of electricity**
  - Wide introduction of renewables
  - Intermittency of renewables

- **First alternative: “classical” solutions**
  - Electrochemical batteries, flywheels
    - – High cost, limited durability, limited energy density
    - ➔ moreover, limited ability to store electricity for long time
  - Pumped storage
    - – Large scale only at specific places

- **Second alternative: hydrogen**
  - Exploit the duality between electricity & hydrogen
  - Ability for long duration storage
  - Can be considered at a microgrid level and at a grid level
  - ⇨ **Attractive alternative**

Where are development headings?

– **Towards enhanced durability**
  - **Scientific and technological bolts**
    - Fuel cell system **efficiency**
      – Increase it from about 30-40% to about 40-50%
    - Public **acceptance**
      – Socio-economic aspect: hydrogen-based energy is unknown
      – Strong link with public policies

    - **Cost** (whole life cycle)
      – Linked to industrial deployment
    - Fuel cell system **durability** (need to increase the lifespan)
      – Ex. for PEMFC systems
        - Common life duration of around 1500 – 3000 hours
        - Where 5000 hours are required for transportation applications
        - And up to 100000 hours for stationary applications & railways

PHM technology for FCS ?

femto-st SCIENCES & TECHNOLOGIES

Prognostic, Diagnostic & Health Management of Fuel Cells – A state of the art

Part 1 – Fuel Cell technology and PEMFC Systems

UFC Université de Franche-Comté · CNRS · ENSMM · UTBM université de technologie Belfort-Montbéliard

FC LAB Research

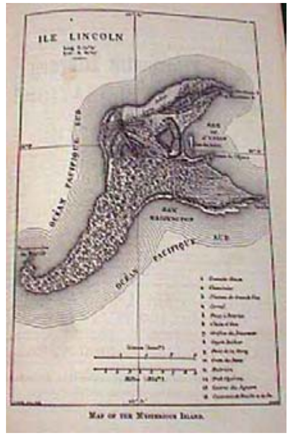
Fuel Cell technology

– Is Science Fiction becoming Reality ?

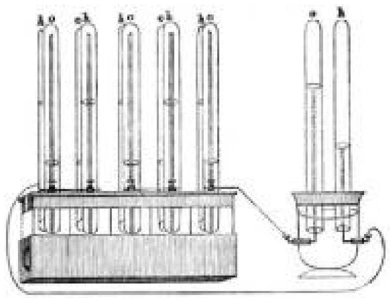
- **Jules Verne, 1875: "*The Mysterious Island*"**

  « … but after the European mines, […] , the American and Australian mines will for a long time yet provide for the consumption in trade. For how long a time? […] For at least two hundred and fifty or three hundred years.

  That is reassuring for us, but a bad look-out for our great-grandchildren! […] And what will they burn instead of coal? […] water decomposed into its primitive elements... "



- **Basic principle discovered and demonstrated in 1839**
  - British physicist William Grove
  - For more than a century, the priority given to the development of thermal machines and electrical batteries overshadowed this invention.



Fuel Cell technology

– Brief history

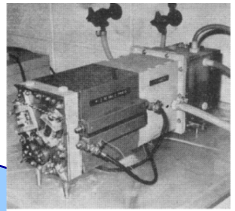
Grove (**1839**)

Verne (**1875**)

Allis-Chalmers (**1959**)
first fuel-cell-powered
vehicle (tractor)

NASA – Space conquest
FCS to power the rockets of
the Gemini (**1963**) and
Apollo (**1968**) programs

Alsthom (**1968**)



Oil shock
- Increasing research in USA / Japan
- Research wilderness in Europe

DC Necar 2
(**1996**)

DC Necar 5
(**2000**)

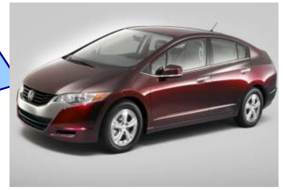
The come-back

FC Submarine
(**2005**)

GM Sequel
(**2005**)

PSA Epure
(**2006**)

Honda FCX
(**2008**)



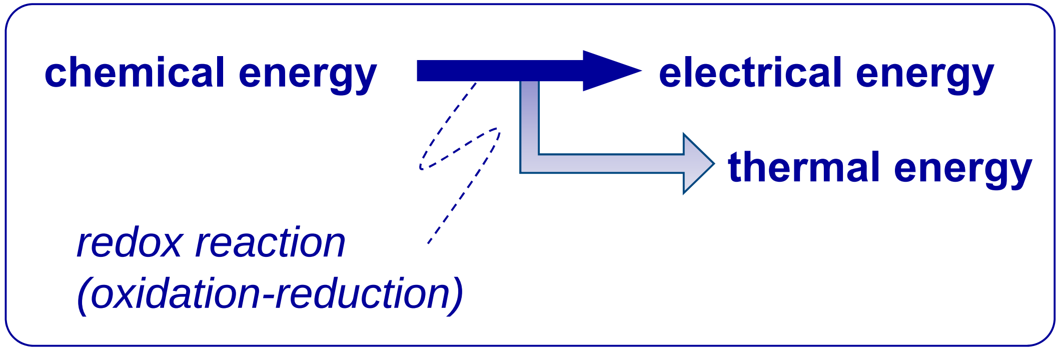
Toyota (**2015**)

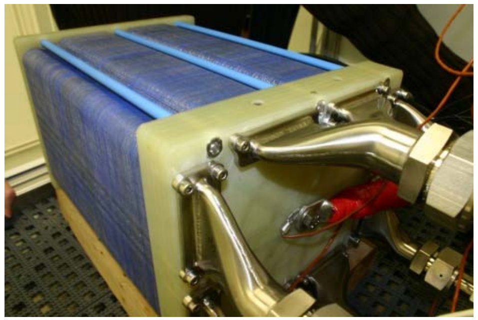
Fuel Cell technology

– Principle of a fuel cell

▪ What is a Fuel Cell?

- US Fuel Cell Council definition, modified by FC Testing and STandardisation NETwork
  - An **electrochemical device** that continuously converts the chemical energy of a fuel and an oxidant to electrical energy (DC power), heat and other reaction products. The fuel and oxidant are typically **stored outside** of the cell and transferred into the cell as the reactants are consumed.
- Main difference with "traditional" battery
  - Fuel is **supplied continuously** & **stored outside**





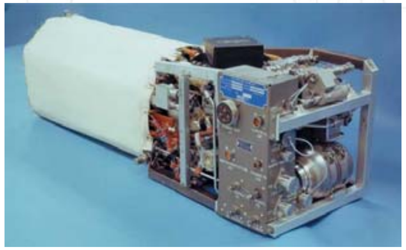
PEMFC -CEA

Fuel Cell technology

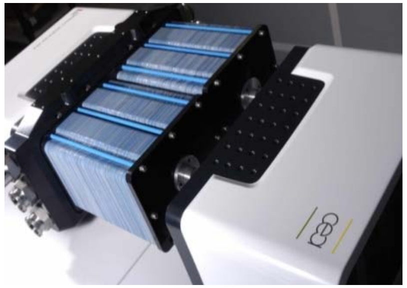
– Taxonomy of Fuel Cell

	Oper. Temp. (°C)	Power range (W)	Main application area
DMFC	20 – 90	1 – 100	Low-power portable applications (mobile phones, computers)
PEMFC	30 – 100	1 – 100k	**Automobile / Transport** Low-power stationary appl. (residential sector)
AFC	50 – 200	500 – 10k	Spaceships
PAFC	~220	10k – 1M	Domestic heat & electricity co-generation (CHP)
MCFC	~650	100k – 10M+	High-power units for CHP, maritime applications
SOFC	500 – 1000	1k – 10M+	Same as MCFC + **Transport**

AFC – Apollo (NASA)



PEMFC – Car Appl. (CEA)

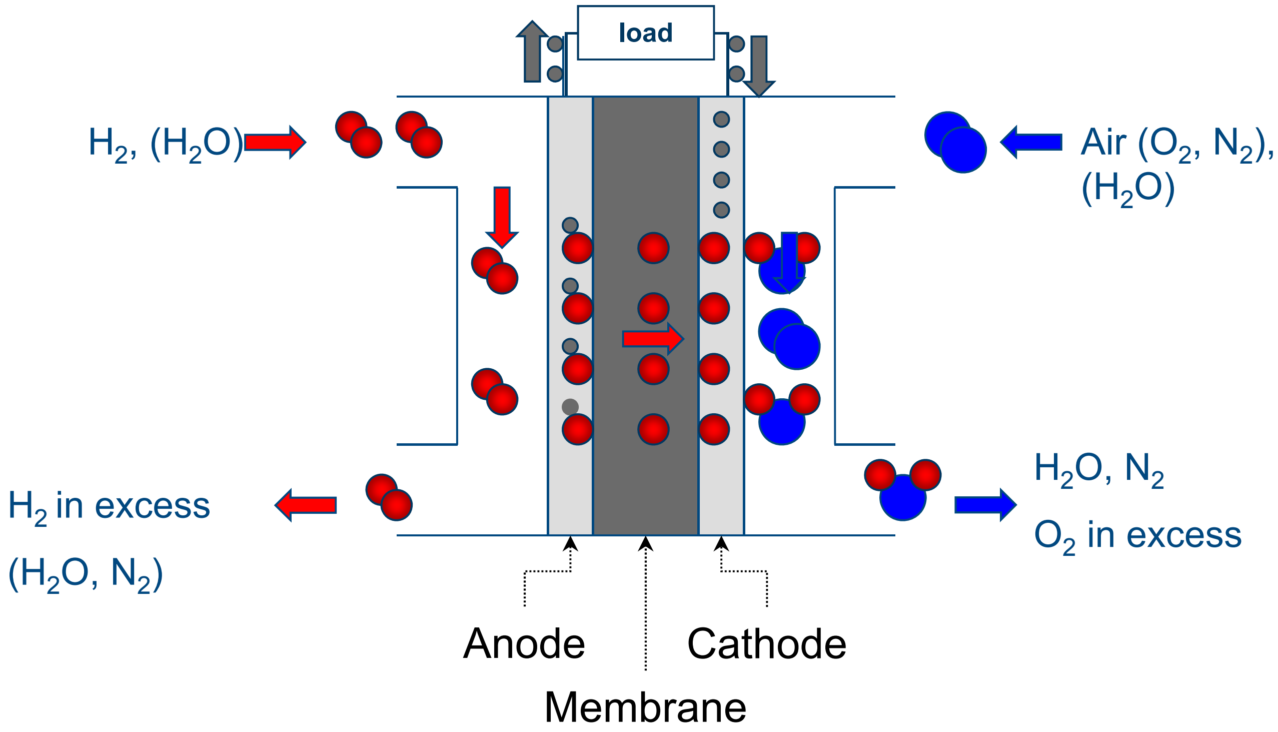


SOFC – Stat. Appl. (MSRI)

PEMFC Systems

– PEMFC – operating principle

- **Fuel / Fuel Oxidizer: H_2 (pure or reformed) / Air**



GENERAL CASE

Anode : Fuel Oxidization (Ra)

$Ra \rightarrow Oa + n.e^-$

Cathode : Reduction of fuel oxidizer Oc

$Oc + n.e^- \rightarrow Rc$

PEMFC

Anode: $H_2 \rightarrow 2H^+ + 2e^-$

Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_20$

Global reaction

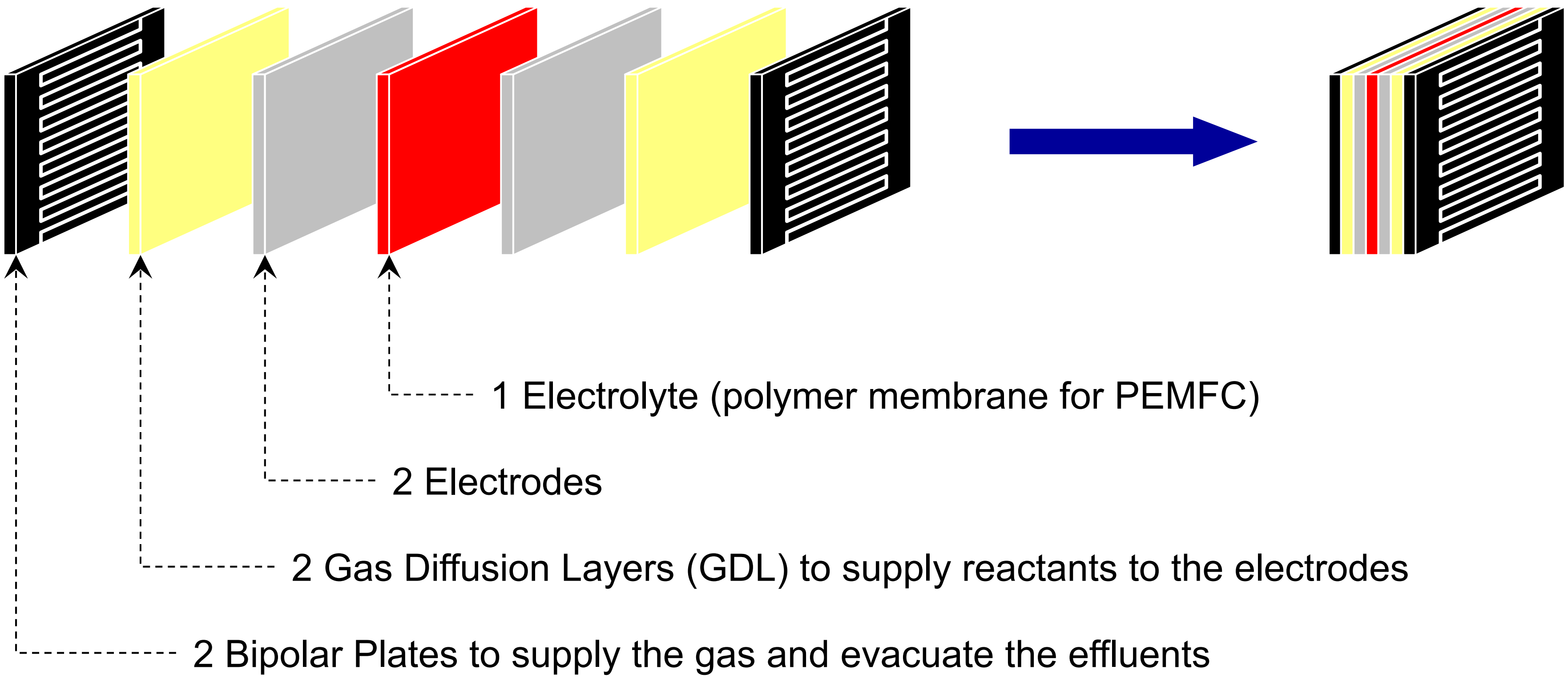
$2H_2 + O_2 \rightarrow 2H_2O$ + electricity + heat

PEMFC Systems

– Structure

▪ Structure of a single cell

- PEMFC = **Polymer** Exchange **Membrane** Fuel Cell

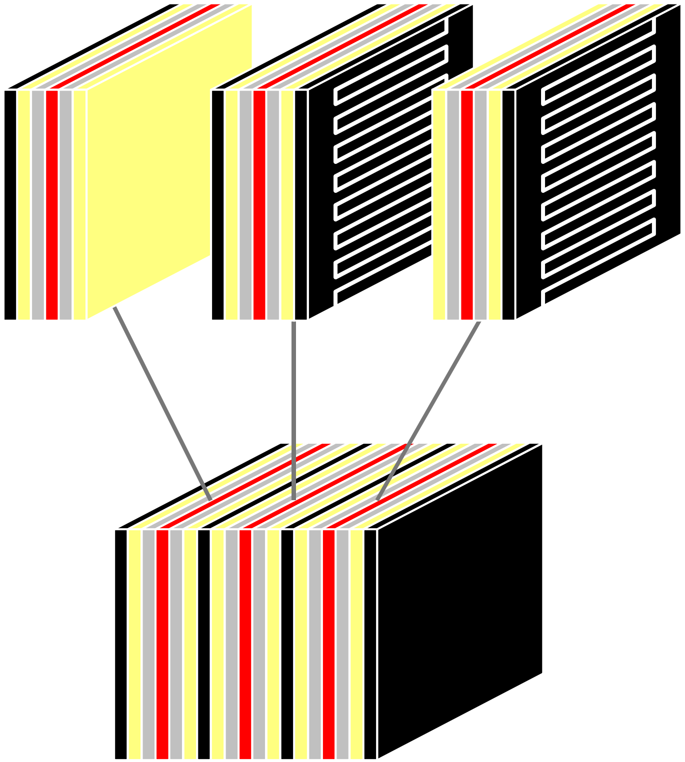


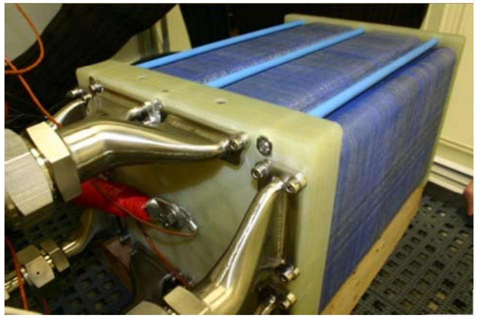
PEMFC Systems

– Structure

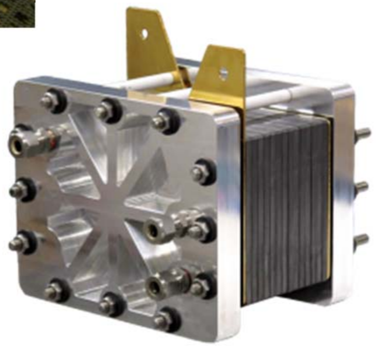
▪ Structure of a stack

- Assembly of several cells in series ⇨ to increase the operation voltage





CEA



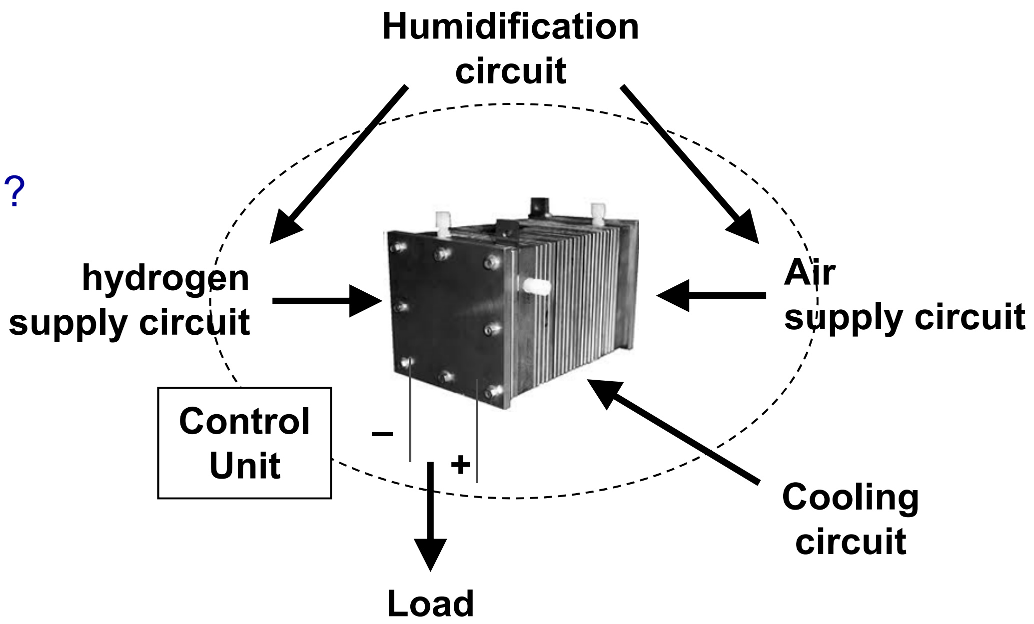
Pragma Ind.

PEMFC Systems

– Whole PEMFC System

- **The stack within a whole system**
  - Stack "only" converts energy…
  - Prior to the electrochemical reaction
    - – How to supply "produce", store, and supply the hydrogen and oxygen?
  - Posterior to the electrochemical reaction
    - – How to manage the electricity generated?
    - – How to manage the heat generated?
    - – How to manage the water generated?
  - During the electrochemical reaction
    - – How to control the process?
    - – How to ensure safety of the whole system?

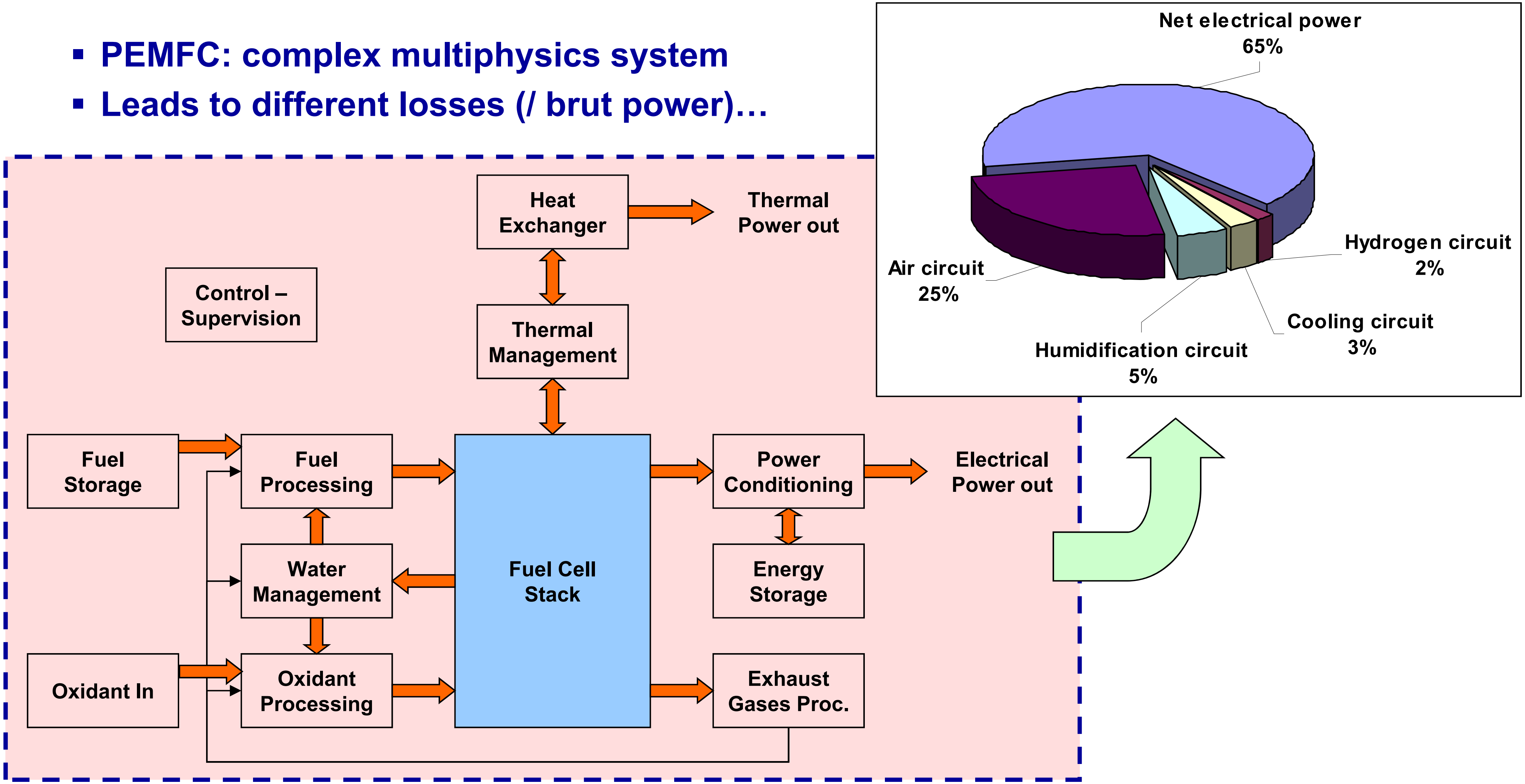
⇨ **FC System = Stack + Ancillaries**



PEMFC Systems

– Drawback from FC system's ancillaries

- PEMFC: complex multiphysics system
- Leads to different losses (/ brut power)…

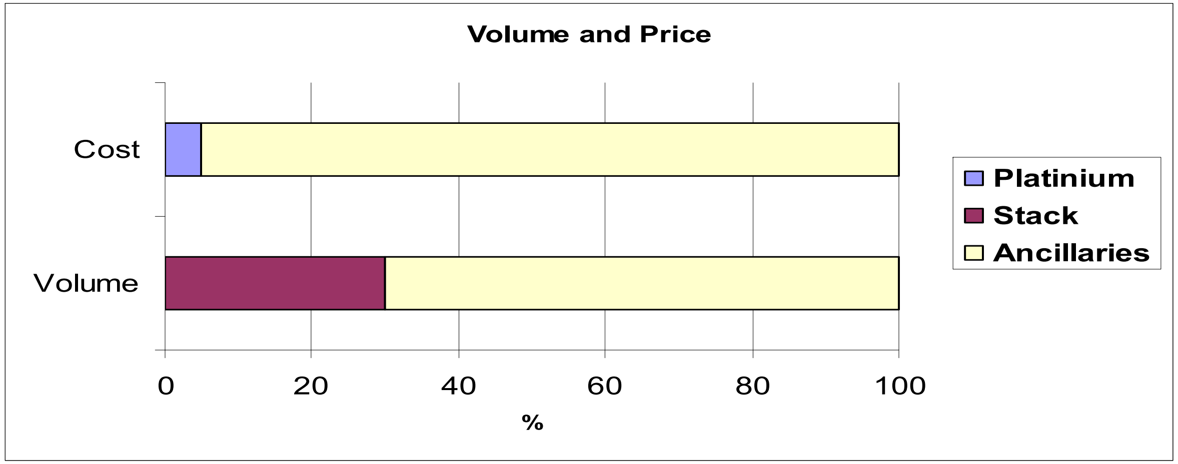


PEMFC Systems

– Some ideas about numerical values… (1)

- **Efficiency**
  - Maximal (elec.) efficiency of a FC stack ≈ 55%
  - In fuel cell power generators, up to 40% of the produced energy is consumed by all their ancillaries

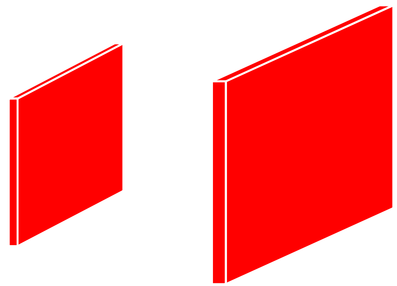
- **Volume and prize**
  - Fuel cell stack volume ≈ 30% of the fuel cell system volume (70% is linked to ancillaries)
  - Fuel cell stack price ≈ ancillaries' price
  - Platinum price (within catalyst) ≈ only about 5% of the price of a whole PEMFC power generator



PEMFC Systems

– **Some ideas about numerical values… (2)**

- **Current**
  - Current density (A/cm2)
    - Directly linked to performances of FC stack materials (membrane, electrode quality, gas diffusion…)
    - Typically between 0.5 et 1 A/cm^2 (PEMFC)
  - Active area
    - For a given cell type, increasing current implies increasing electrode area



- **Voltage**
  - Per cell
    - Thermodynamic limitation: 1,18V at atmospheric pressure and at 80°C
    - Open circuit voltage per cell (I=0A): typically 0.9V
    - Nominal voltage per cell: 700mV
    - Minimum voltage per cell: typically about 400mV
  - Stack: linked to the number of cells associated in serial arrangement

Prognostic, Diagnostic & Health Management of Fuel Cells – A state of the art

Part 2 – Behavior and losses of PEMFC

Behavior and losses of PEMFC

– PEMFC as a complex system

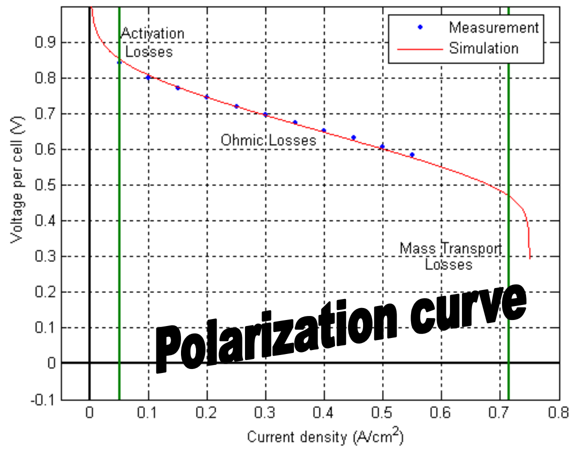
- **Building behaviors models would be of prime importance for design, control, diagnostics, optimization… BUT**
- **FC = highly multiphysics and multiscale systems**
  - Multiphysics = electrical, mechanical, thermal engineering, electrochemistry…
  - Multiscale = from the µm to the m
  - Multiscale = different time constants are involved
    - Electrochemistry ≈ instantaneous
    - Electrical power converter ≈ 10^{-4}s
    - Membrane water hydration content ≈ 10^{0}s
    - Temperature ≈ 10^{2}s
    - Durability ≈ 10^{5}s
- **High difficulty to access internal parameters**
  - Specific know-how of the manufacturers
  - No sensor available

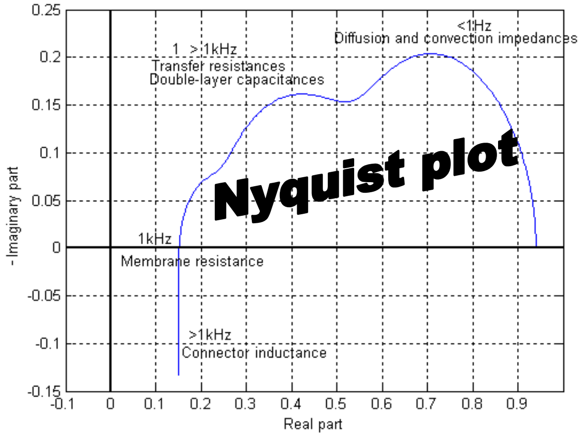
PEMFC behavior is hard to catch. Even if research increases in this area, a "complete" FC system model is still not available. Some developments at the "stack level".

Behavior and losses of PEMFC

– Characterization of a stack

- **Two useful "tools"**
  - Polarization curve
    - – Enables to estimate losses
    - – Enables to estimate efficiency
  - Electrochemical Impedance Spectroscopy
    - – Enables to build impedance spectra (Nyquist plots)
    - – Nyquist plot
      - Enables to estimate internal resistances / impedances of a fuel cell
      - Enables to depict and analyze failure / ageing mechanisms (~ feature for PHM community)

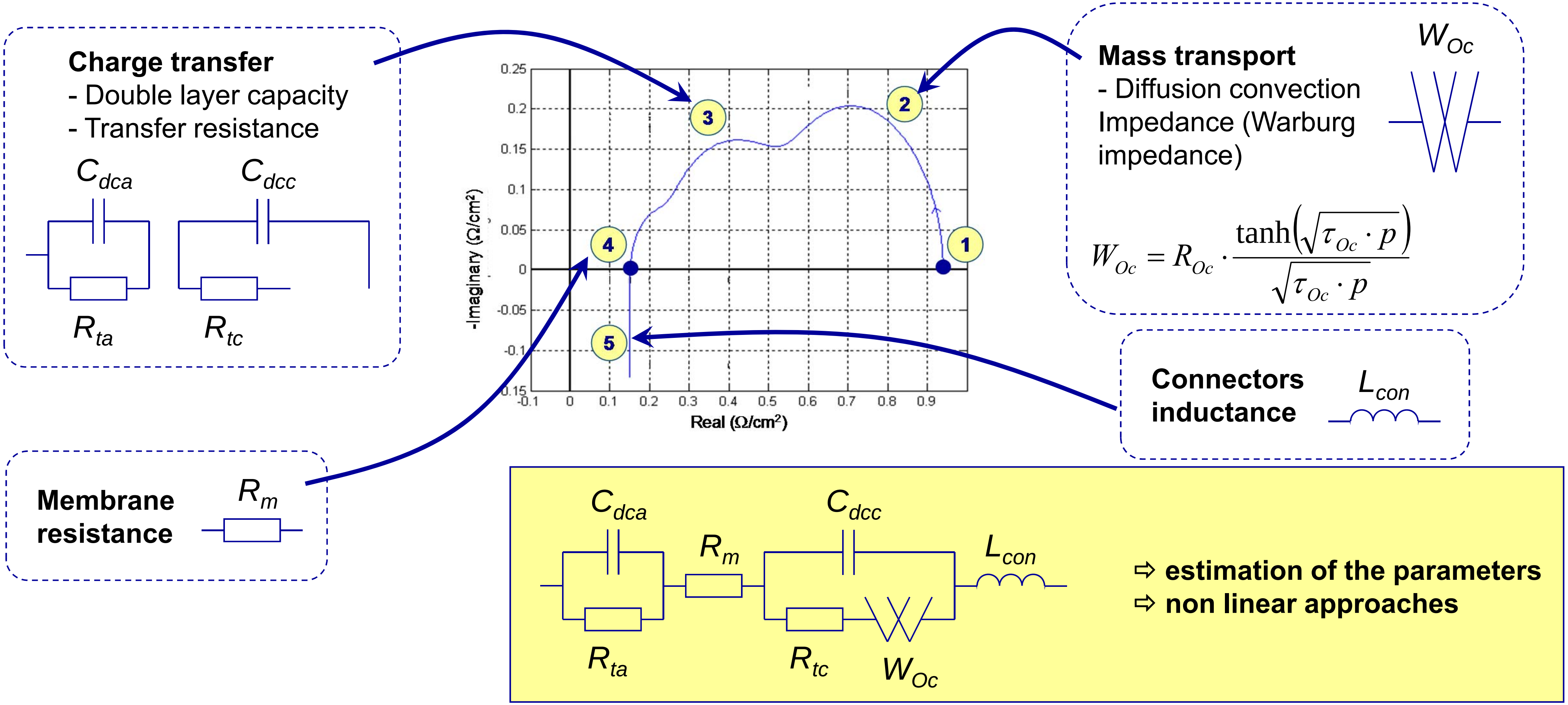




Behavior and losses of PEMFC

– Towards modeling

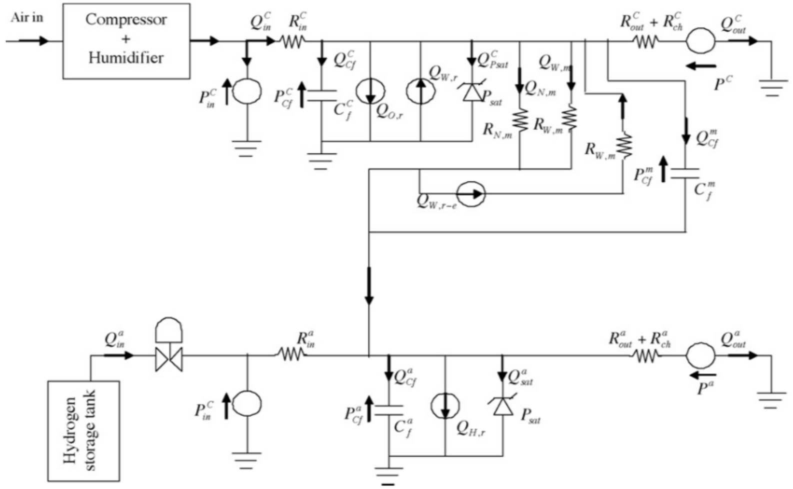
- **Electrical behavior - however insufficient / all normal-faulty possible modes…**



Behavior and losses of PEMFC

– Other modeling approaches

Electrical equivalence



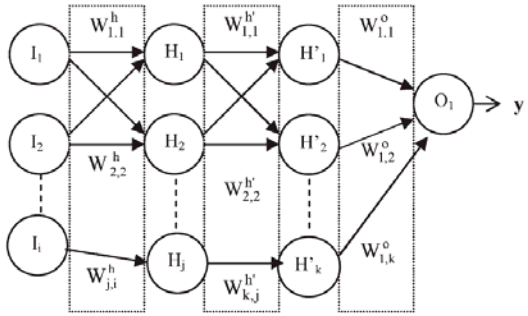
M.Becherif et al., Journal of Power Sources, 2010.

State space model

$$\begin{cases} \frac{dP}{dt} = RTV\left(2UP + \begin{pmatrix}\bar{P}^c - \frac{m^c_{in}}{\sigma^c_{in}} \\ \bar{P}^a - \frac{m^a_{in}}{\sigma^a_{in}}\end{pmatrix}^T UX + IB + DP + CP + P_{sat}\begin{bmatrix}C_{ev}\\ C_{ev}\end{bmatrix}\right) \\ \frac{dV_{H_2O,l}}{dt} = 1.8\times 10^{-5}\left(c_{ev}\left(C_1P - P_{sat}\right) - \frac{V_{H_2O,l}}{Vc}\sigma^c_{out}\frac{m^c_{in}}{\sigma^c_{in}}\left(\bar{P}^c - P_{atm}\right)\right)\end{cases}$$

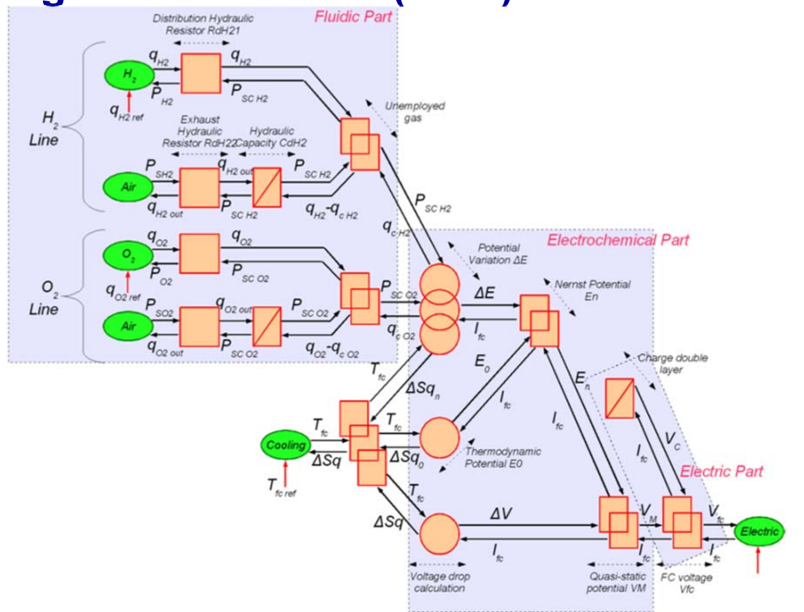
A.Hernandez et al., Fuel Cells, 2006.

Neural networks



S.Jemeï et al., IEEE Trans. on Ind. Elec., 2008.

Energetic formalisms (EMR)



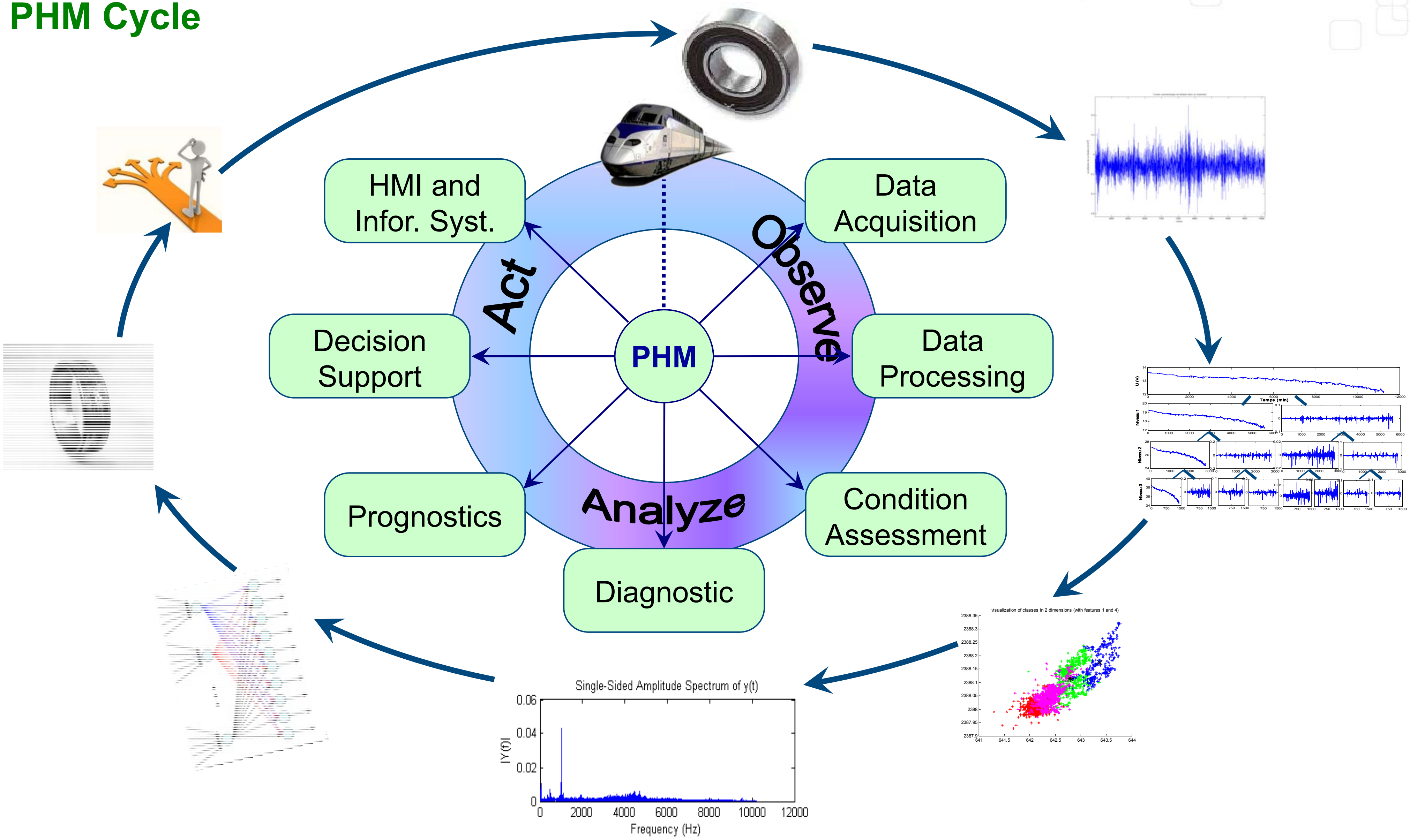
D.Hissel et al., Int. Rev. of Elec. Eng., 2008.

Prognostic, Diagnostic & Health Management of Fuel Cells – A state of the art

Part 3 – Prognostics & Health Management

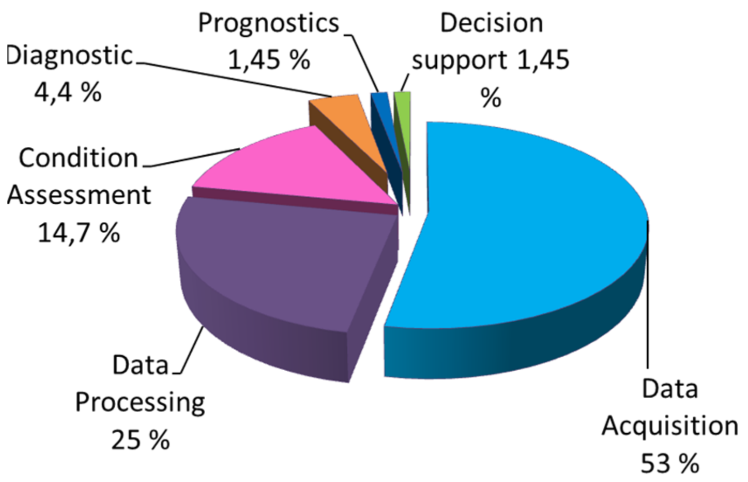
Implementing PHM

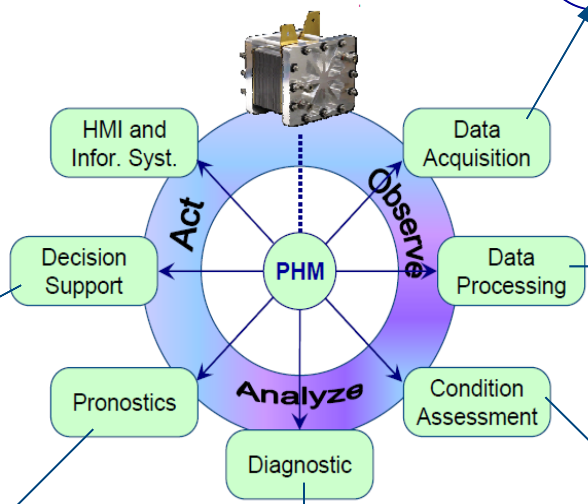
– **PHM Cycle**



State-of-the-art

– **Works repartition on PHM layers (M.Jouin & al, 2013)**
  - **Study limited to the stack - 68 references used**





- EIS
- Gas chromatography
- Neutron Imaging
- Current interrupt
- Cyclic voltammetry
- Etc.

(36 works)

- Fourier transform
- Wavelet transform
- Hyperparameters extraction
- Fuzzy model
- Nyquist diag. / polariz. curve
- Etc.

(17 works)

- Automatic corrective actions

(1 work)

- Kalman filter based approach

(1 work)

- Bayesian Networks
- PCA + Square pred. error
- Residues signatures

(3 works)

- Residues (data - model)
- ANN, Fuzzy logic (clust.)
- Pattern recognition algorithm
- Parameters representation

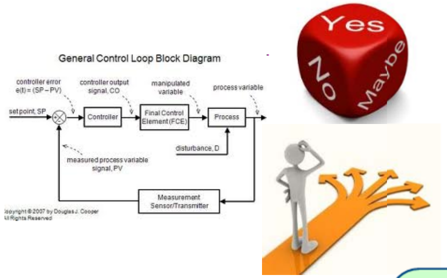
(10 works)

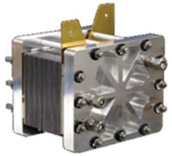
State-of-the-art

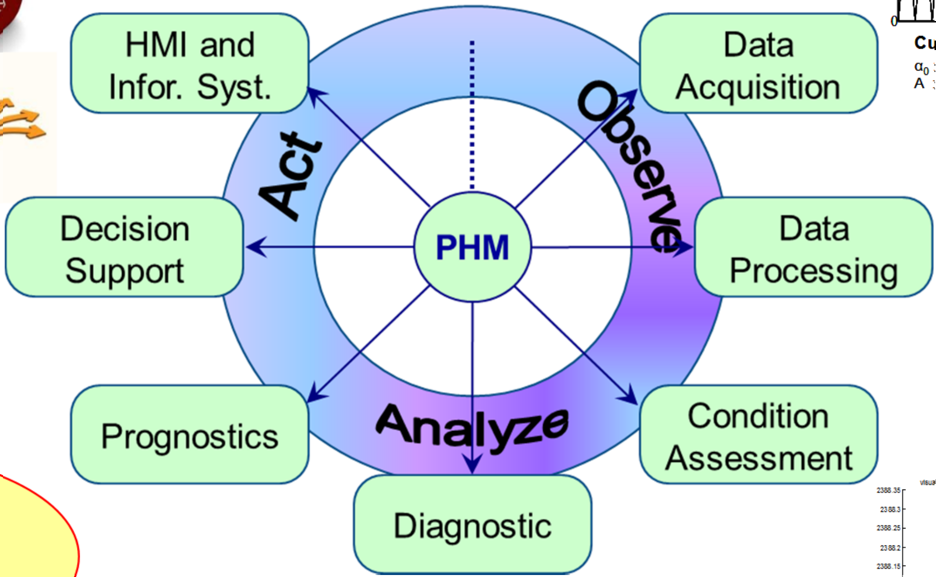
– **Already on-going works**

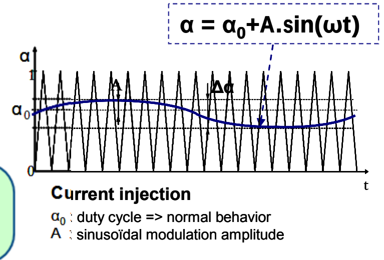
- taxonomy of failures
- wearing mechanism analysis…

- residual-based control…

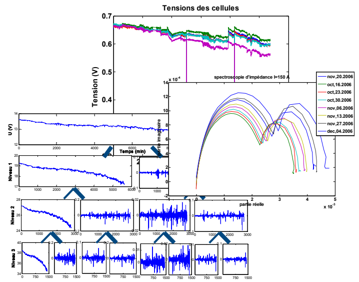




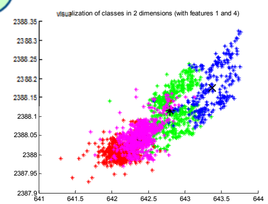




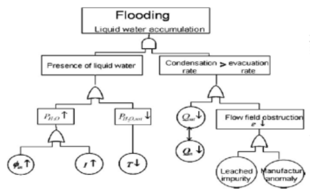
- T°, I, V
- EIS…

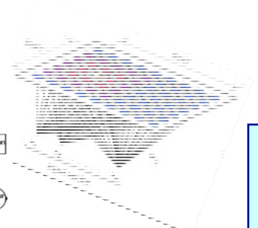


- polarization curves
- Nyquist diagrams…



Not well addressed





- fault tree analysis
- ANN models, wavelet analysis…

femto-st SCIENCES & TECHNOLOGIES

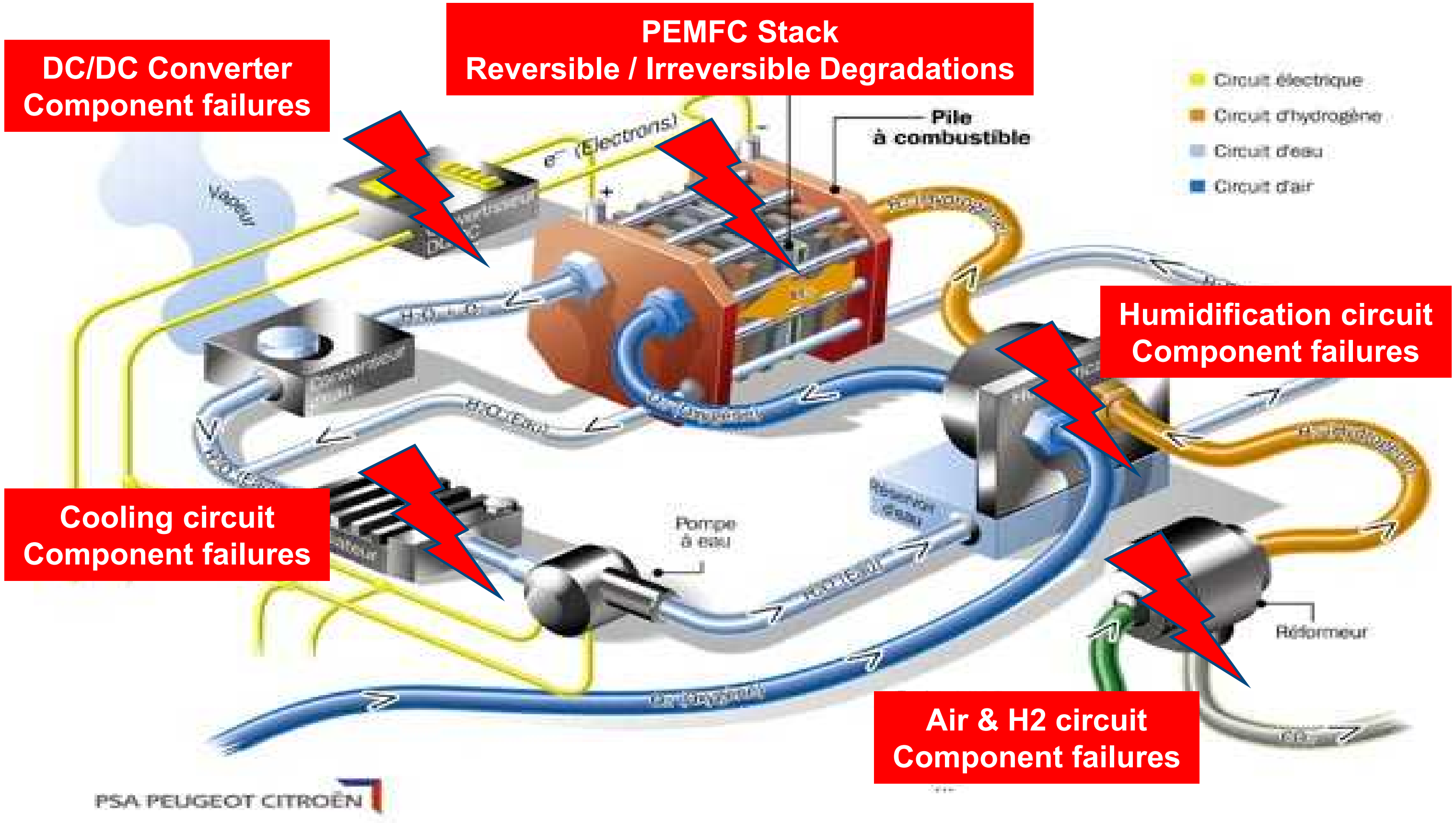
Prognostic, Diagnostic & Health Management of Fuel Cells – A state of the art

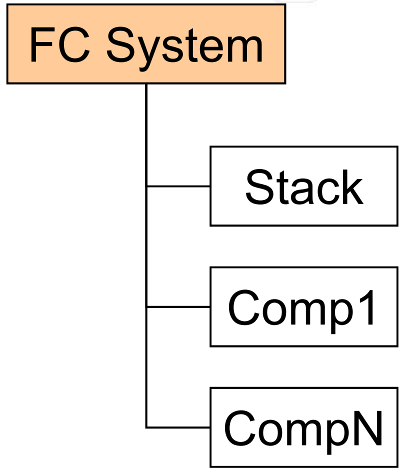
Part 4 – Ongoing works : diagnostic and health management of FC

FC LAB Research

Failure mechanisms

– **Degradations/failures at system's level**





Sensor failures

Control failures

Failure mechanisms

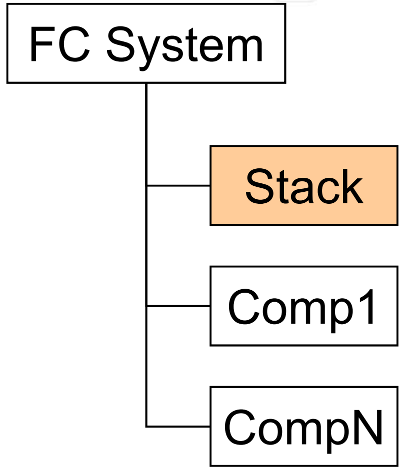
– Data to be gathered?

- **Real data are required to assess the health state of the system**
  - 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

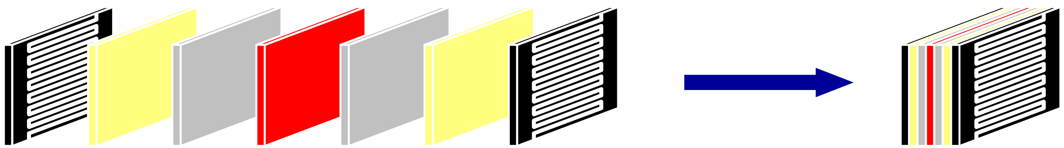
Failure mechanisms

– Degradations of the stack



- **Taxonomy / nature of the degradation**
  - Mechanical degradation
    - – Mainly due to improper manufacturing processes (crack…)
    - ⇨ Often the cause of early failure
  - Thermal degradation
    - – Use of the cell outside the its optimal operating range (T°…)
    - ⇨ Involves changes at micro/nano levels – changes in physical properties
  - Chemical and electrochemical degradation
    - – Presence of contaminants like fuel impurities, air pollutants
    - ⇨ Affects electrode kinetics, conductivity and mass transfer – affects FC performance

- **Taxonomy / localization of the degradation**
  - Membrane
  - Catalyst layers (electrodes)
  - Gas diffusion layers
  - Bipolar plates



Failure mechanisms

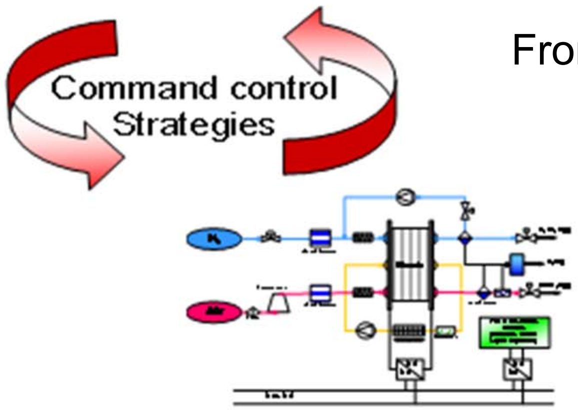
– Degradation modeling?

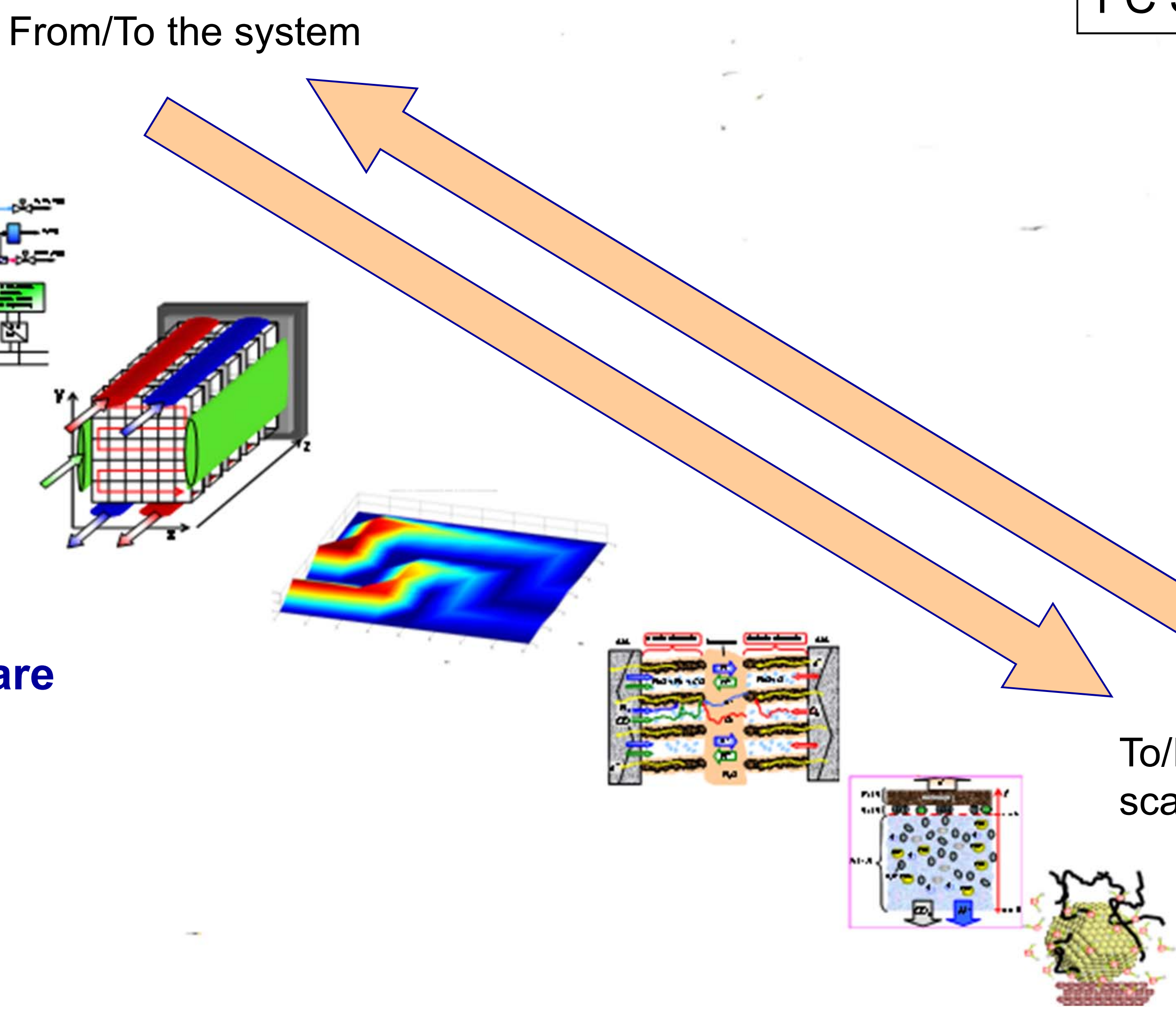
- **Parameters reducing the FC lifetime**
  - Fuel impurities (sulfur, CO for PEMFC, …)
  - Oxidant impurities (oil from the compressor, salt from environment, …)
  - Fuel and oxidant stack starvation (linked to the dynamic and the control of the system)
  - Temperature supervision (linked to the system control)
  - 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)…
  - ⇨ **Gives an overview of potential causes…**

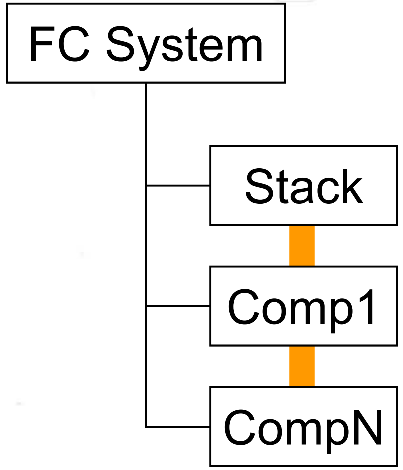
- **Whatever the degradation is…**
  - It results in a voltage drop
  - ⇨ **Gives an idea of potential effect…**

Failure mechanisms

– Influence of the environment on the stack





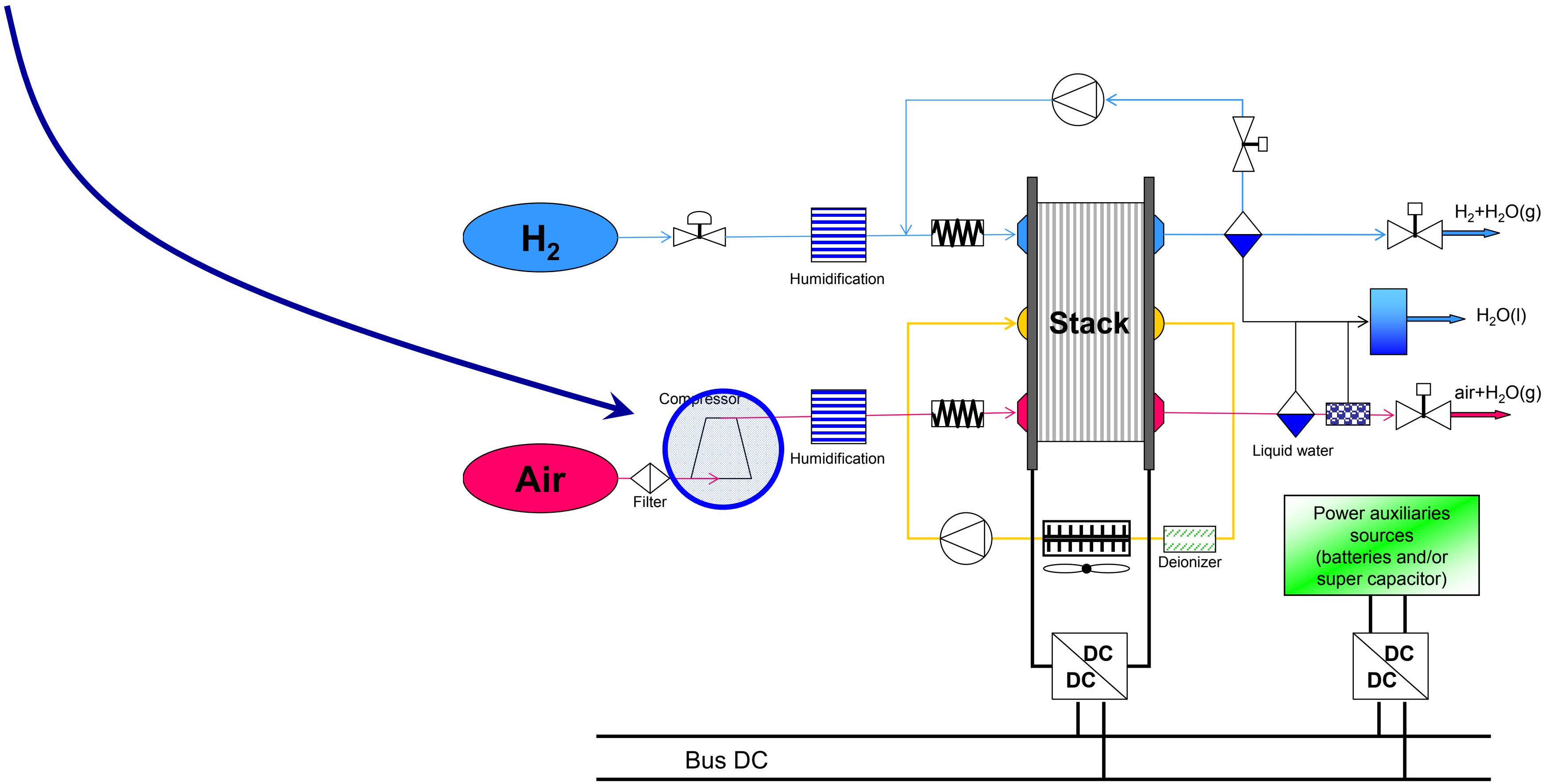


Failure Mechanisms are complex and multi-dimensional…

Examples of interactions system / stack

– **Impact of compressor failure – oxidant circuit**

- **Compressor failures**
  - Oxygen starvation ⇨ consequences on performance and durability

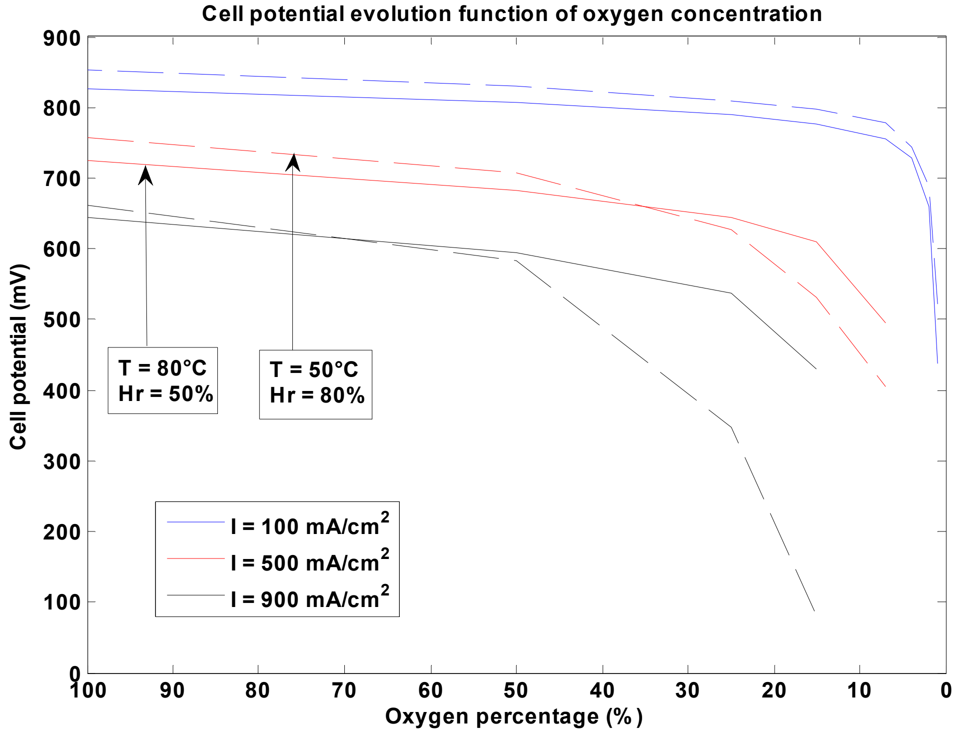


Examples of interactions system / stack

– Impact of compressor failure – oxidant circuit

- **Experiment conditions (Gérard et al. 2010a)**
  - 5 cm² single cell area ; High oxidant flow (to perform the water evacuation)
  - 3 current concentrations ; 2 sets of operating conditions

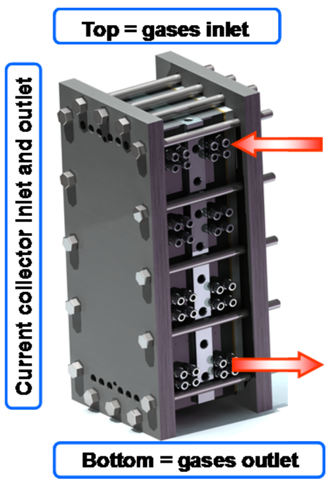
- **Performance Evaluation**
  - Whatever the operating conditions :
    - Potential collapse when oxygen concentration is very poor
    - This collapse is linked to current density
    - Air hygrometry can increase or decrease the phenomena…

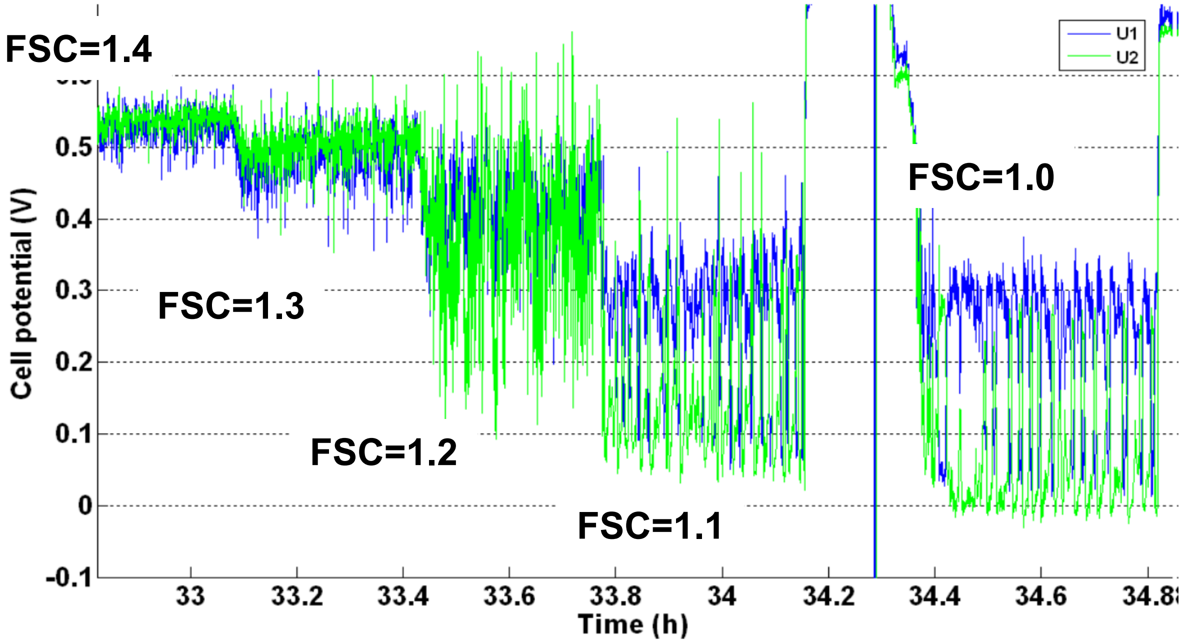


Examples of interactions system / stack

– **Impact of compressor failure – oxidant circuit**

- **Experiments at constant gas flow and low stoichiometry (Kulikovsky et al. 2004, Liu et al. 2006, Gérard et al. 2010)**
  - Potential oscillations
  - Potential can reach near zero (or even negative) values

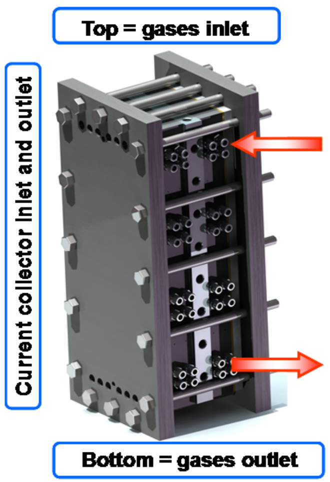


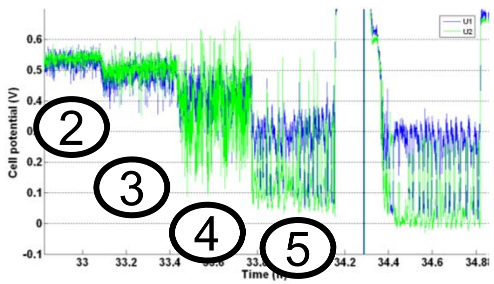


Examples of interactions system / stack

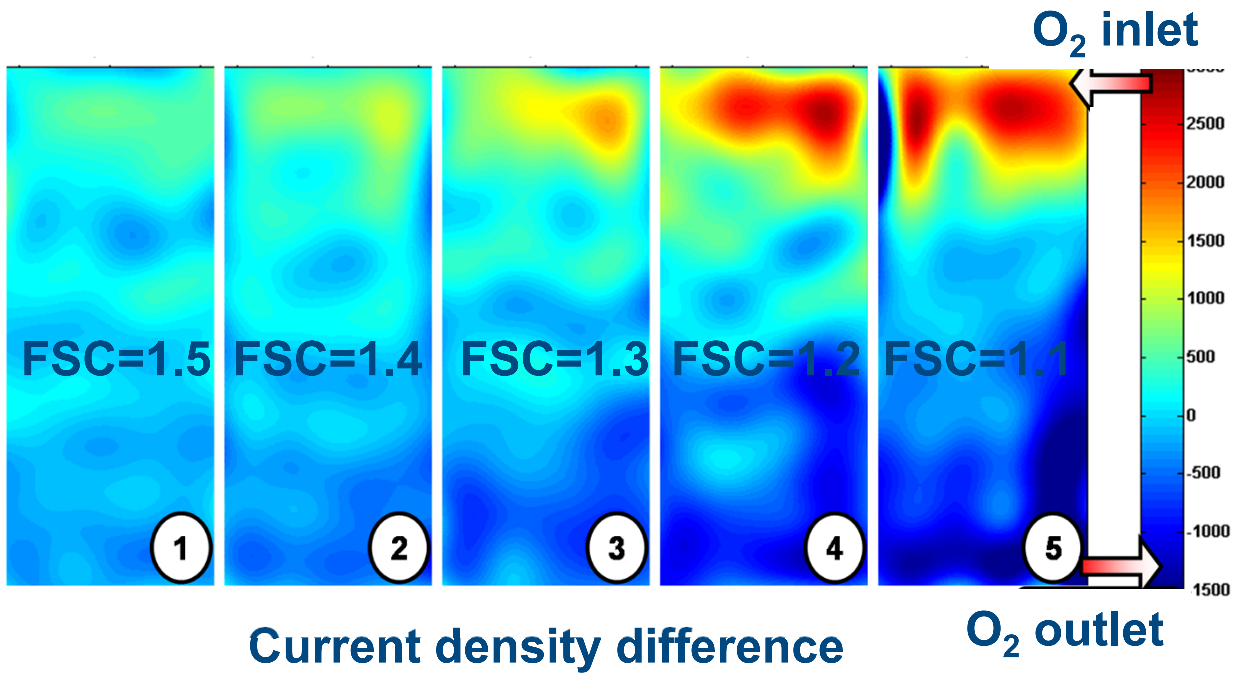
– **Impact of compressor failure – oxidant circuit**

- **Experiments at constant gas flow and low stoichiometry (2)**





Nominal conditions
I=0.5 A.cm^{-2}



If O2 flow is poor, displacement of the current at the inlet

Examples of interactions system / stack

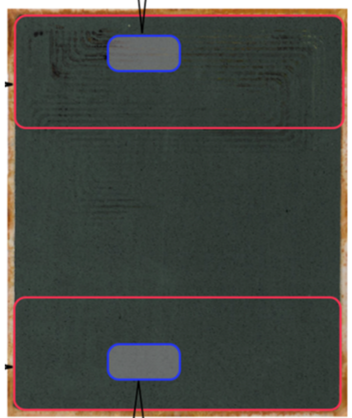
– Impact of compressor failure – oxidant circuit

▪ Consequences on ageing (3) – Post Mortem analysis

- Visual analysis
- TEM-FEG analysis

Sample 1

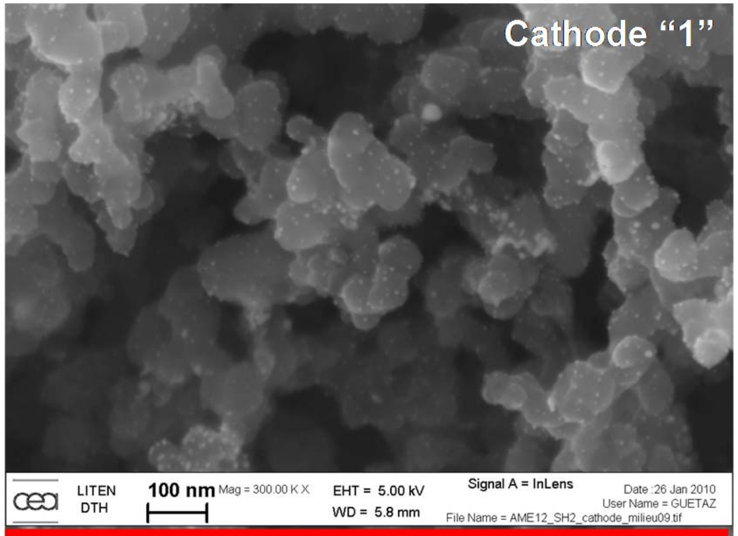
- Air Inlet
- High current density in starvation operation

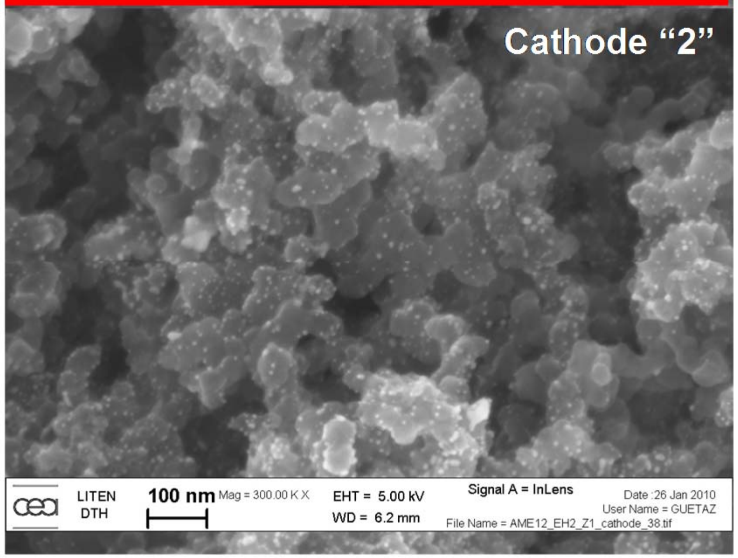


Sample 2

- Air Outlet
- No current density in starvation operation

- Metallic bipolar plate corrosion
- Marks of seals caused by hot temperature
- Platinum particles in the membrane at sample “1” (air inlet, high current density in starvation operation)
- Active layer structure difference between sample “1” and sample “2”

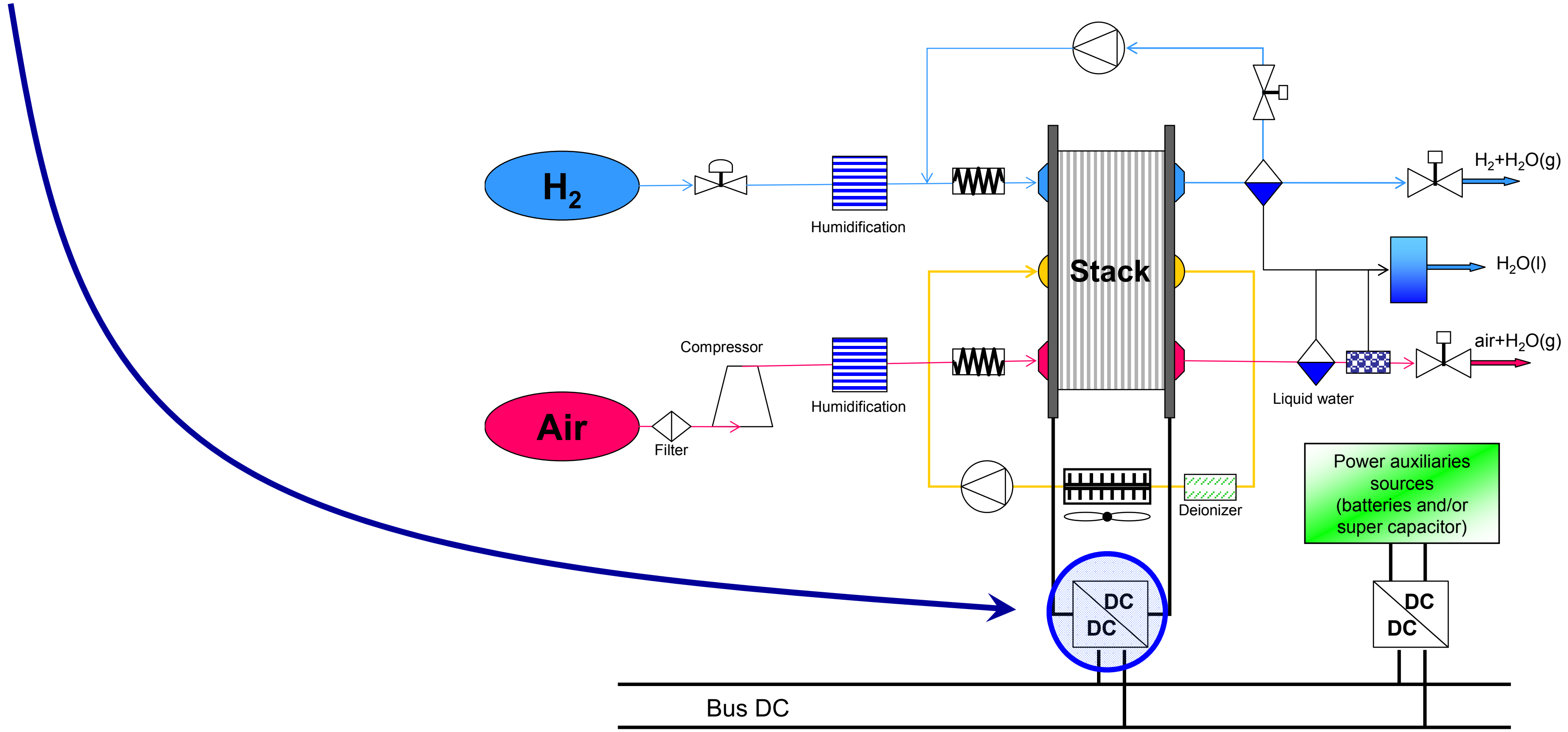




Examples of interactions system / stack

– **Impact of the converter – current ripple**

- **DC/DC converter**
  - The output fuel cell current is submitted to the high frequency switching leading to a current ripple
  - ⇨ Impact on durability



Examples of interactions system / stack

– Impact of the converter – current ripple

▪ Ageing tests

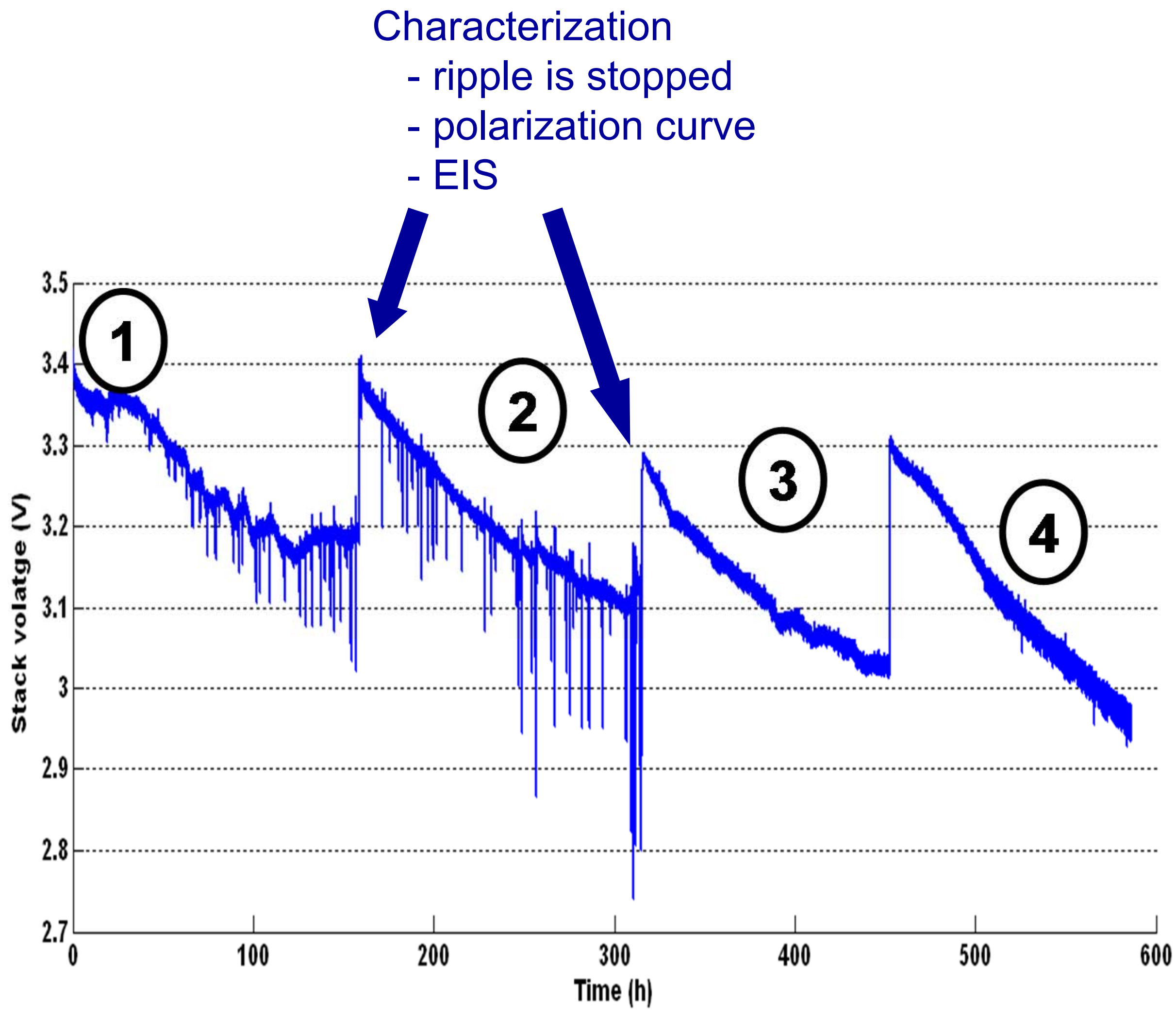
- 2 durability tests, same new stacks
  - with ripple (5kHz)
  - without ripple
- 5 cell stack, 220 cm²
- Characterizations every week
  - 4 polarization curves
  - 3 EIS (at 3 different current)

Ageing test nominal conditions	
Cooling temperature	348 K
Relative humidity	50%
Gas pressure	1.5 bars
Hydrogen stoichiometry	1.5
Oxygen stoichiometry	2
Nominal current density	110 A (0.5 $A.cm^{-2}$)
Ripple current frequency	5 kHz
Ripple current amplitude	20%

Examples of interactions system / stack

– Impact of the converter – current ripple

- **Stack potential comparison**
  - zone 1: 264 µV.h^{-1}
  - zone 2: 387 µV.h^{-1}
  - zone 3: 382 µV.h^{-1}
  - zone 4: 507 µV.h^{-1}



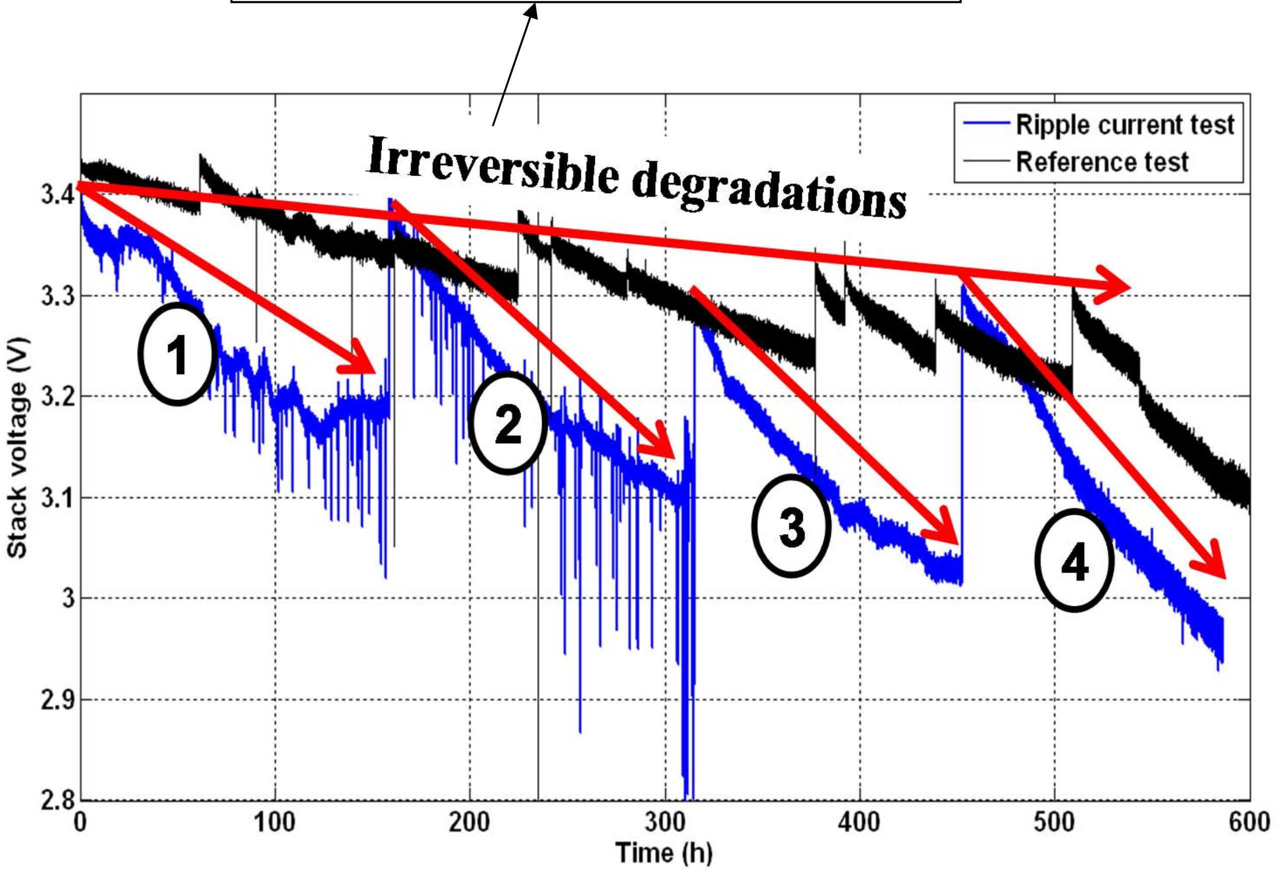
Examples of interactions system / stack

– **Impact of the converter – current ripple (Gérard et al. 2010)**

- **Stack potential comparison**
  - zone 1: 264 µV.h^{-1}
  - zone 2: 387 µV.h^{-1}
  - zone 3: 382 µV.h^{-1}
  - zone 4: 507 µV.h^{-1}

Much higher reversible degradation with ripple current

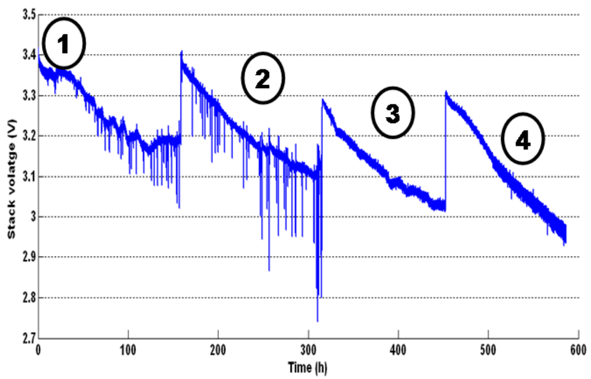
Irreversible degradation: 44 µV.h^{-1}

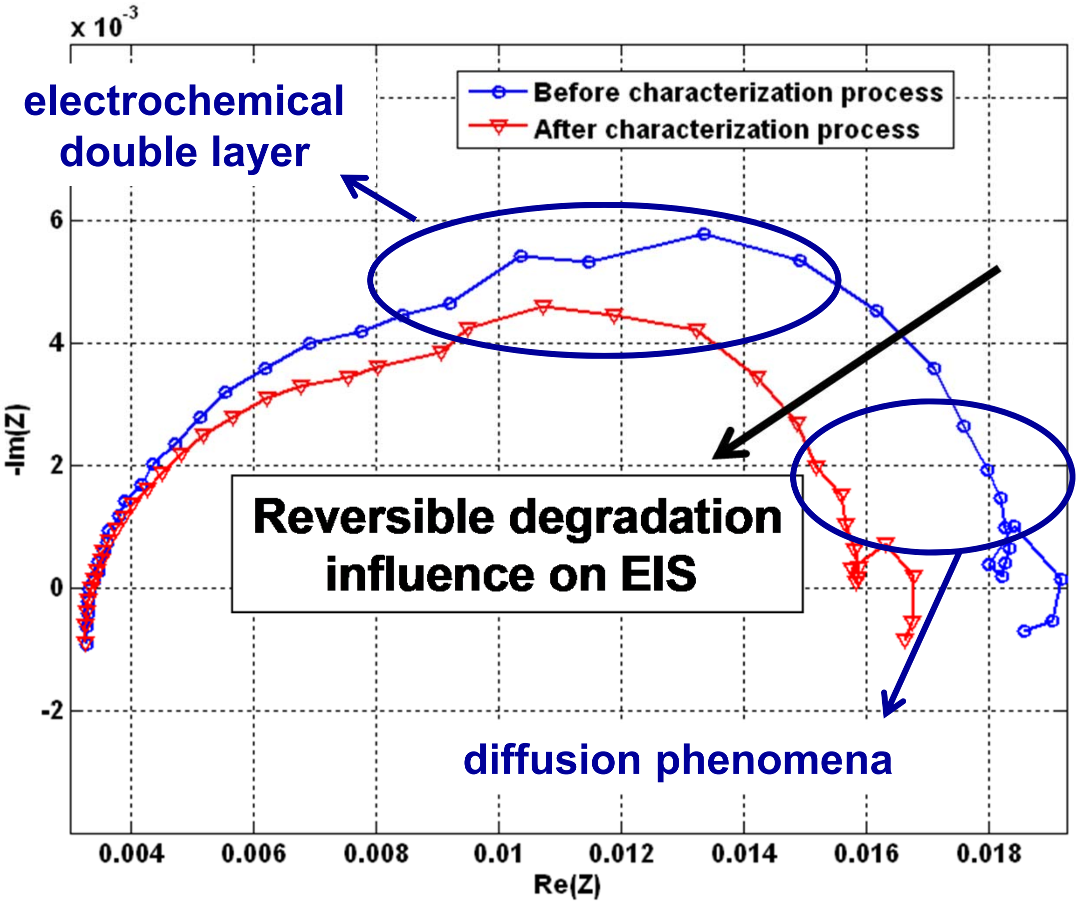


Examples of interactions system / stack

– **Impact of the converter – current ripple**

- **Reversible degradation?**
  - EIS before and after the characterization process





Reversible degradation
=
Water management on the active layer

Health monitoring and ageing

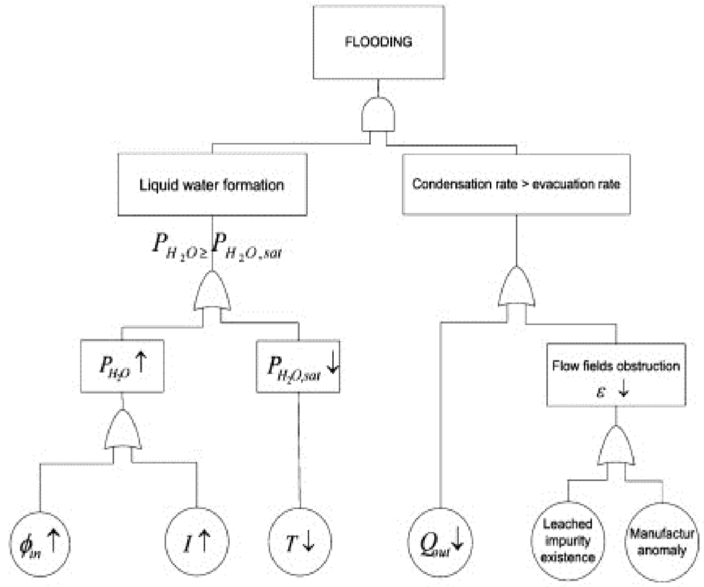
– Health monitoring

▪ Residual generation for health estimation (Steiner et al. 2010)

- Aim: diagnose flooding in PEMFC
- Procedure: analysis of a residual between
  - experimental pressure drop
  - estimated pressure drop (thanks to an Elman neural network)

- Step 1: output to be estimated
  - Thanks to a fault tree analysis
    - pressure drop ΔP (Darcy's law)

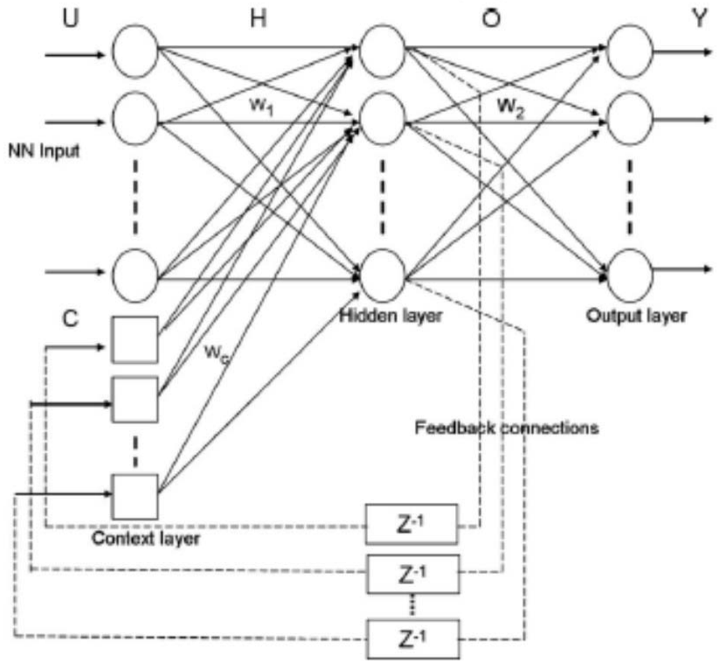
- Step 2: feature selection
  - Thanks to a fault tree analysis
    - current I
    - dew point temperature T_{dwpt} (inlet relative humidity)
    - stack temperature T
    - air inlet flow rate Q

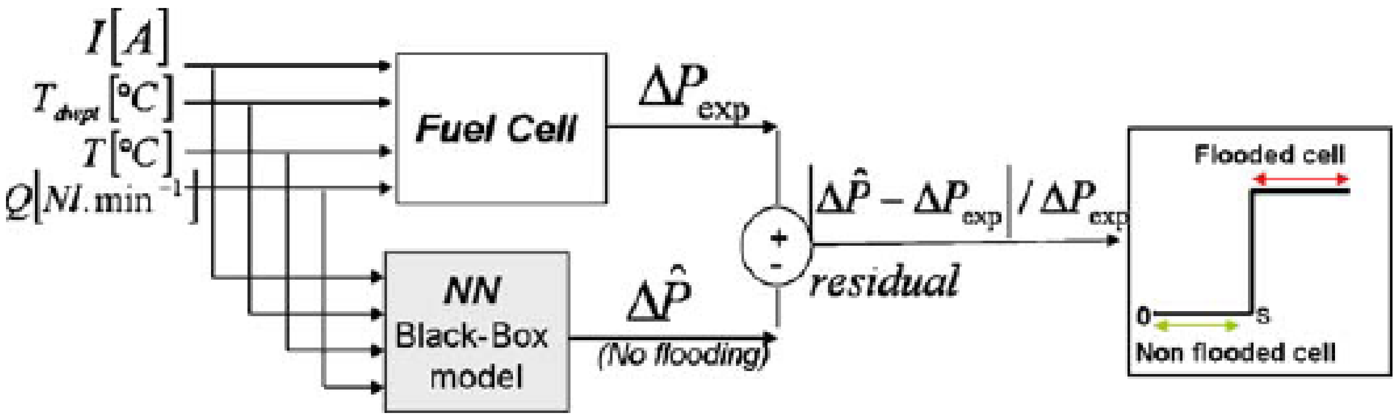


Health monitoring and ageing

– **Health monitoring**

- **Residual generation for health estimation (2)**
  - Step 3: estimation of the pressure drop
    - Elman neural network
  - Step 4: residual generation

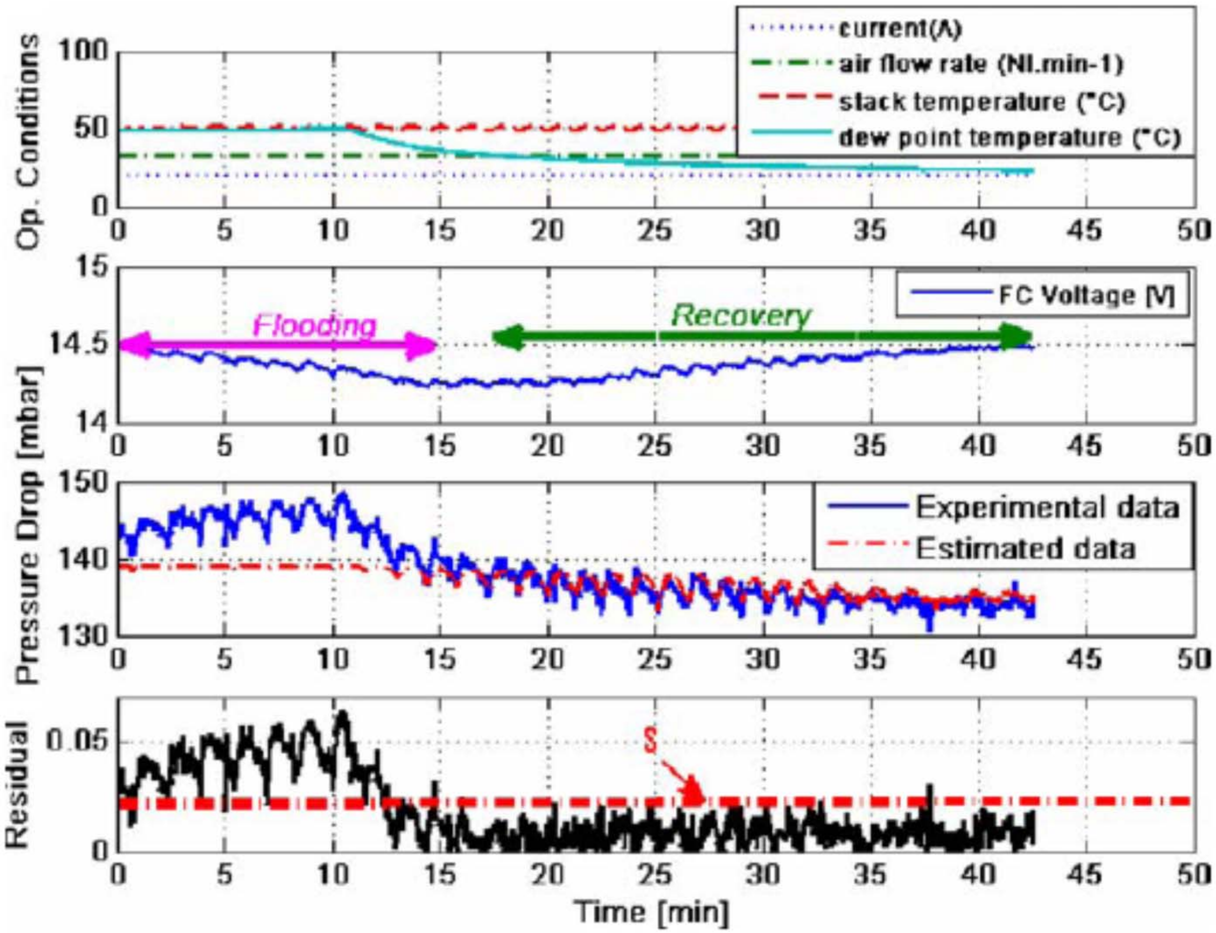




Health monitoring and ageing

– Health monitoring

▪ Residual generation for health estimation (3)



Input data

FC Voltage

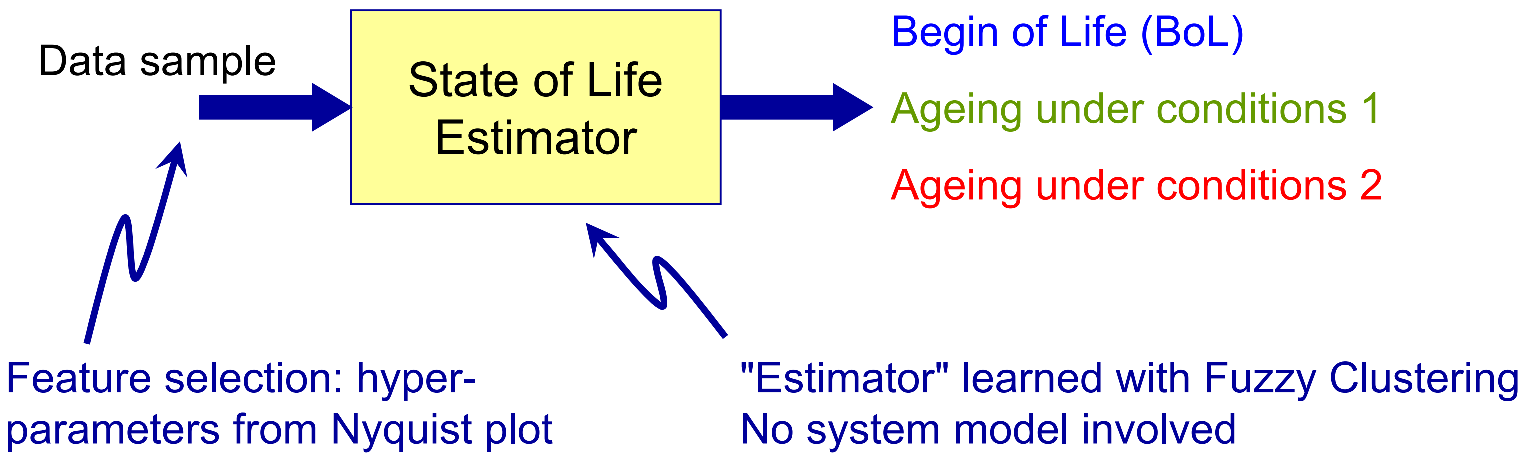
Pressure drop (actual / estimated)

Residual analysis

Health monitoring and ageing

– **Ageing estimation – condition monitoring**

- **Estimation of the age of a stack (Hissel et al. 2007)**
  - Aim: answering the following questions by carrying out low-cost experimental characterization
    – What is the age of the stack?
    – On which conditions it was operated?

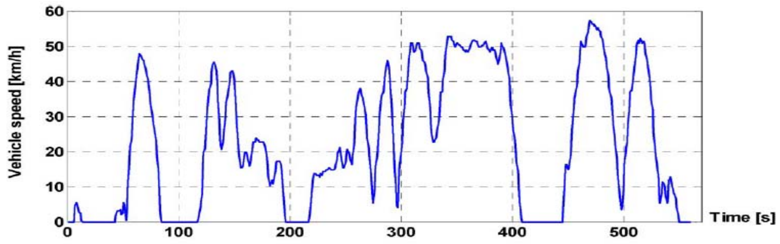


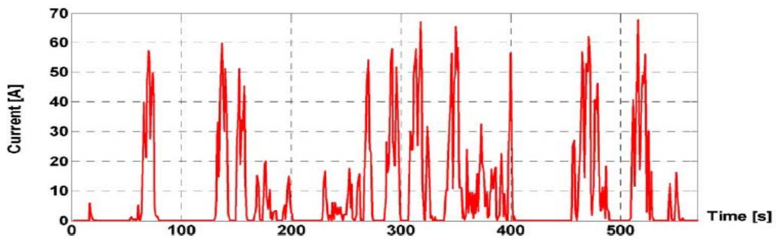
Health monitoring and ageing

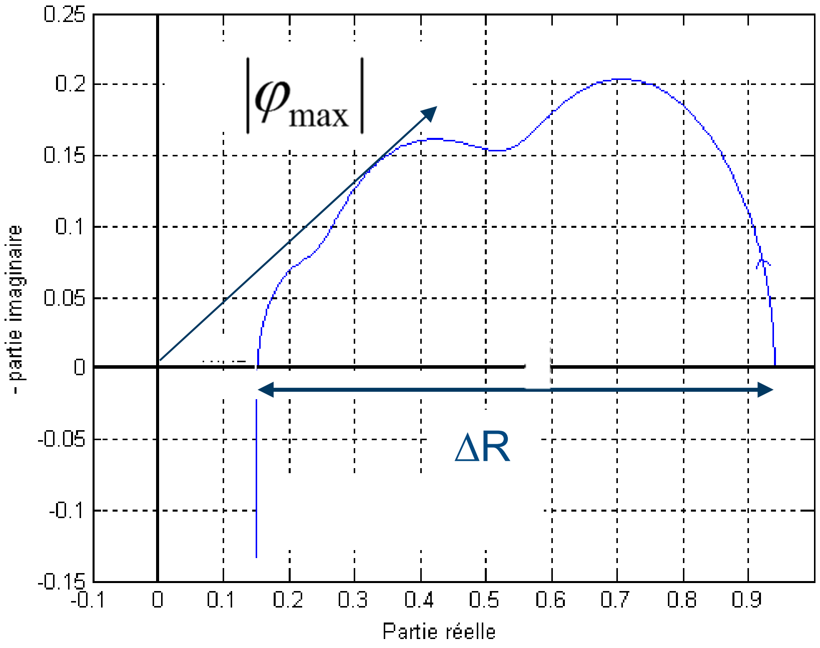
– Ageing estimation – condition monitoring

▪ Estimation of the age of a stack (2)

- Hyper-parameters
- Load conditions
  - Type 1: constant current 50 A
  - Type 2: dynamic current profile (from real car solicitation)







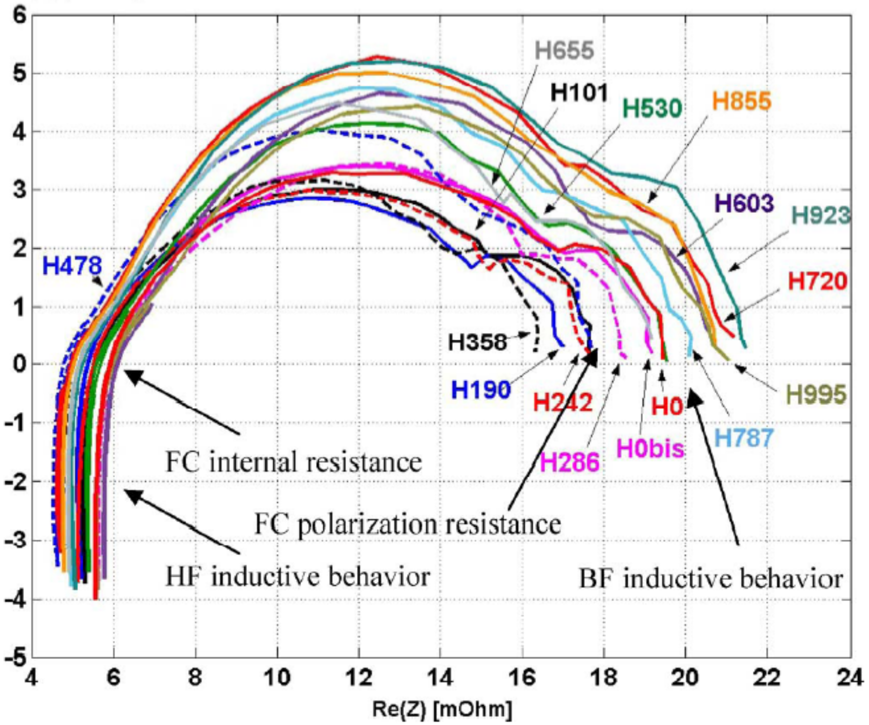
Health monitoring and ageing

– Ageing estimation – condition monitoring

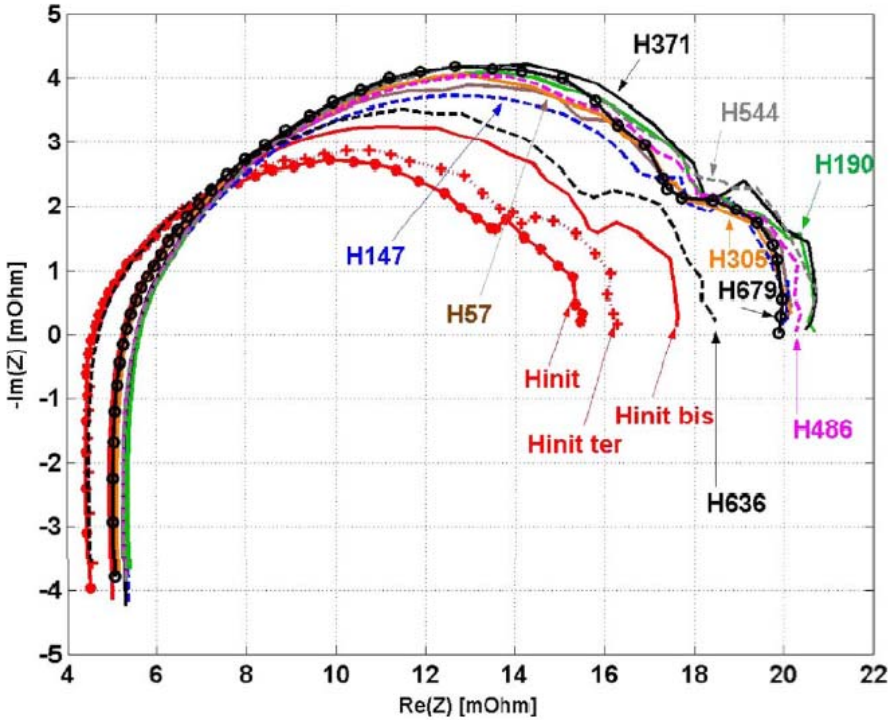
▪ Estimation of the age of a stack (3)

- Nyquist plot from both experiments

Stack 1 : **constant current 50 A**



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

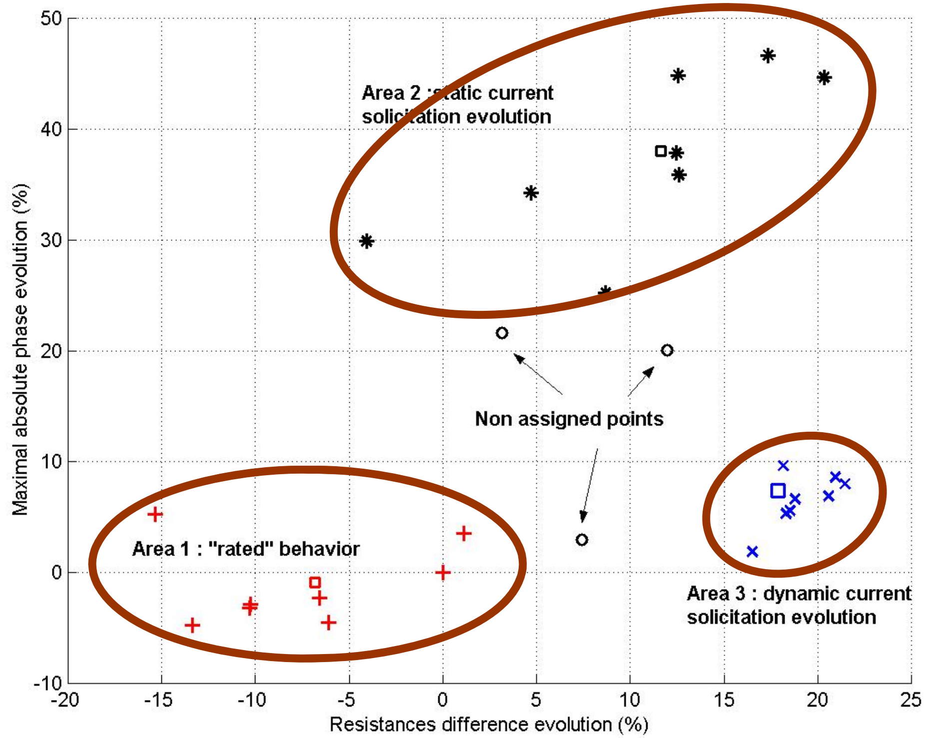


Health monitoring and ageing

– Ageing estimation – condition monitoring

▪ Estimation of the age of a stack (4)

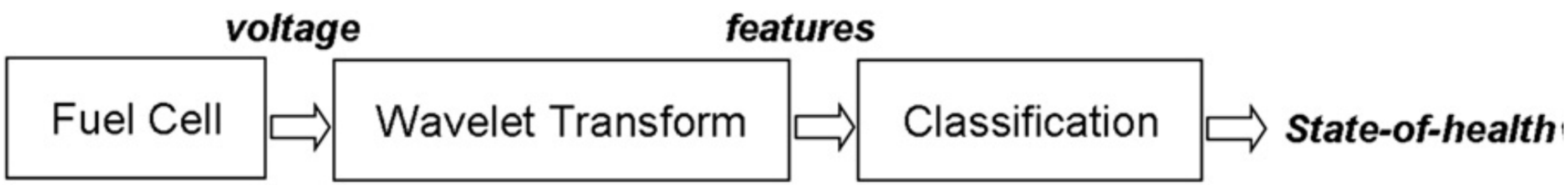
- Classification results
  - Typical degradation under static current solicitations
  - Typical degradation under dynamical current solicitations
  - Some “transient” operating points (non-assigned points)



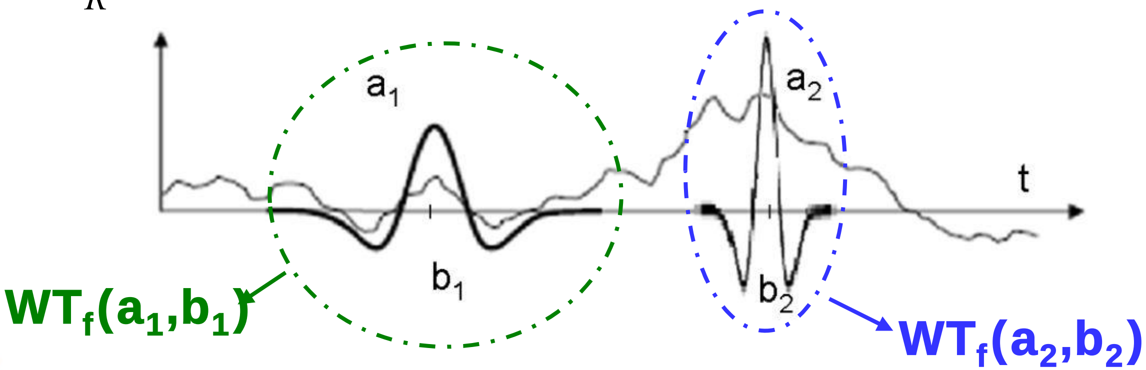
Health monitoring and ageing

– **Non intrusive diagnostic through wavelet packet analysis (1/3)**

- **Methodology (Yousfi-Steiner & al., 2010)**
  - Use directly the voltage signal to perform health assessment of the FC stack (in real time…)
  - Use time-scale signal treatment methods
  - Here Wavelet Transformation is considered
  - Principle : the time-varying signal is projected on a wavelet basis

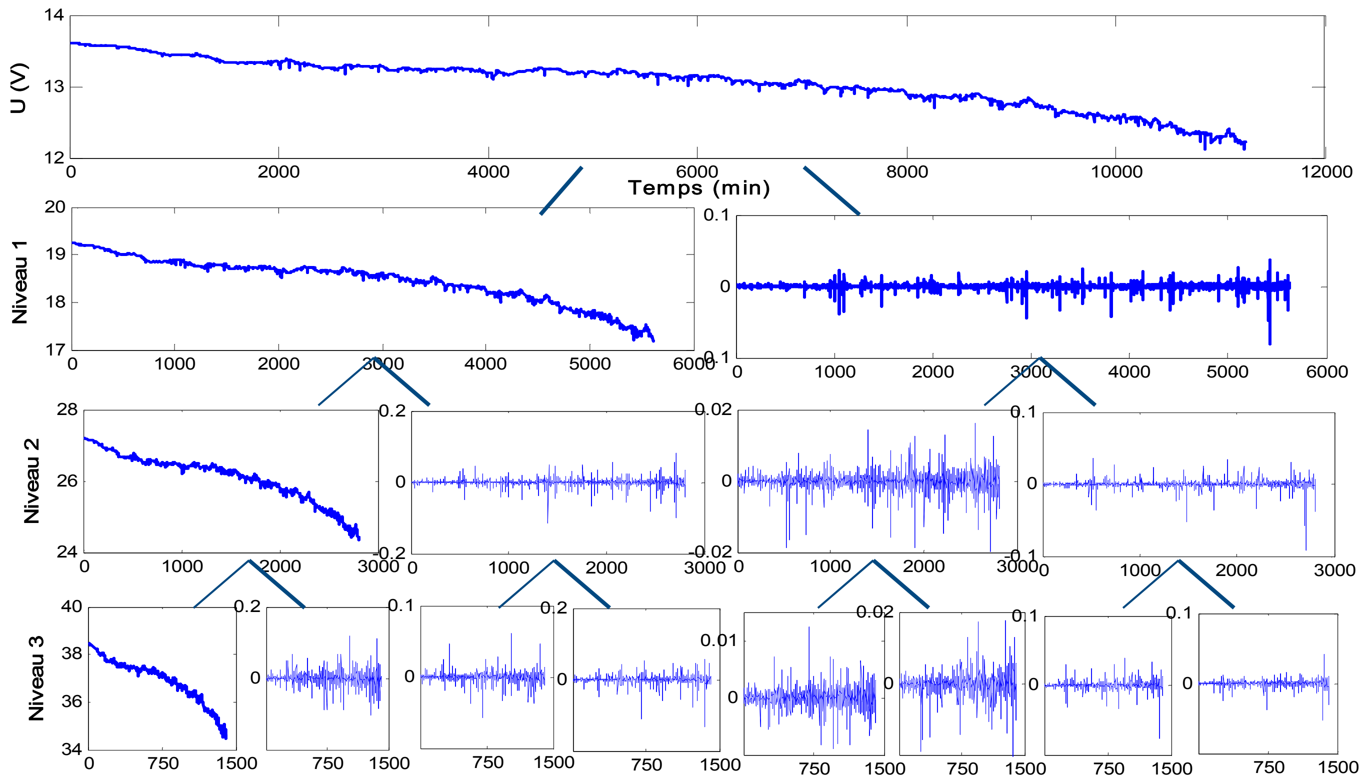


$$WT_f(a,b) = \int_R f(t)(\psi_{a,b}(t))^* dt \quad \text{with} \quad \psi_{a,b}(t) = \frac{1}{\sqrt{2^j}}\psi\left(\frac{t-2^j k}{2^j}\right), \quad (j,k) \in Z^2$$



Health monitoring and ageing

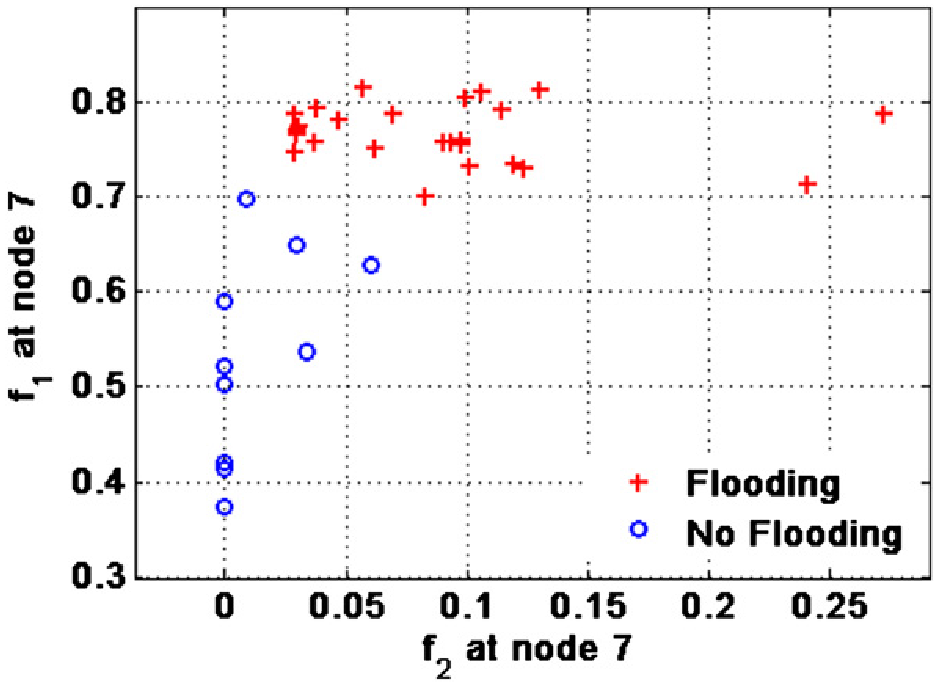
– **Non intrusive diagnostic through wavelet packet analysis (2/3)**
  - **Example :**
    - Experimental results on a PEMFC stack during cathode flooding
    - Here 7 levels are considered, i.e. 254 packets / measured signal



Health monitoring and ageing

– Non intrusive diagnostic through wavelet packet analysis (3/3)

- **Example :**
  - 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

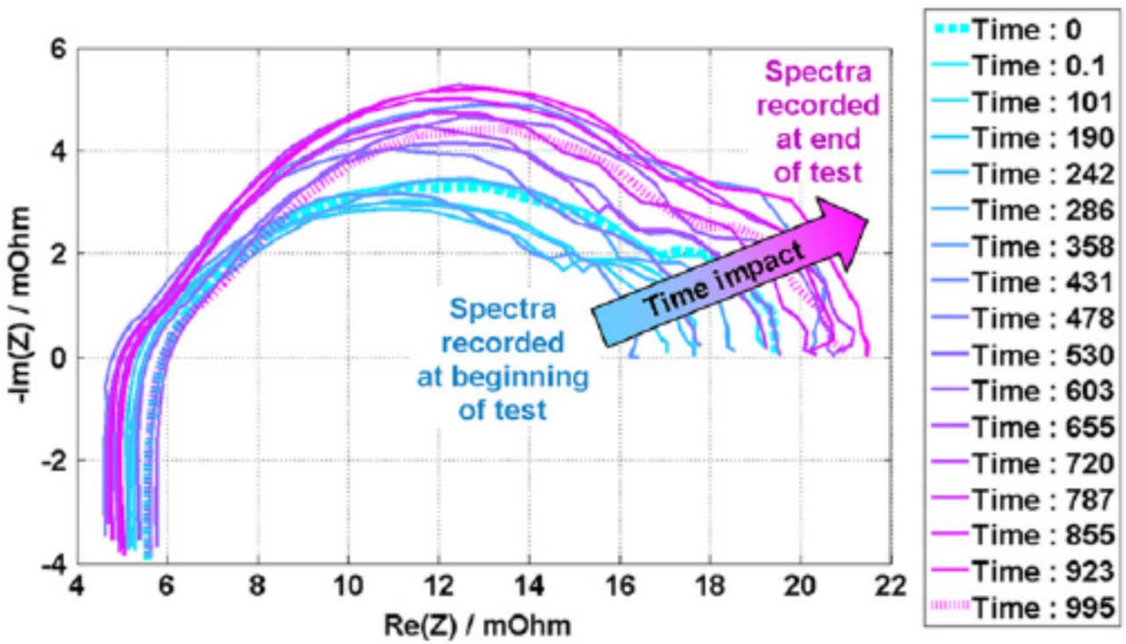


Health monitoring and ageing

– Ageing estimation – past operating time estimation

▪ Estimation of fuel cell operating time (Onanena et al. 2010)

- Aim
  - Estimate fuel cell operating time
  - Thanks to EIS measurements
- Procedure
  - Latent regression model
    - Automatically split the spectrum into segments
    - Segments are approximated by polynomials

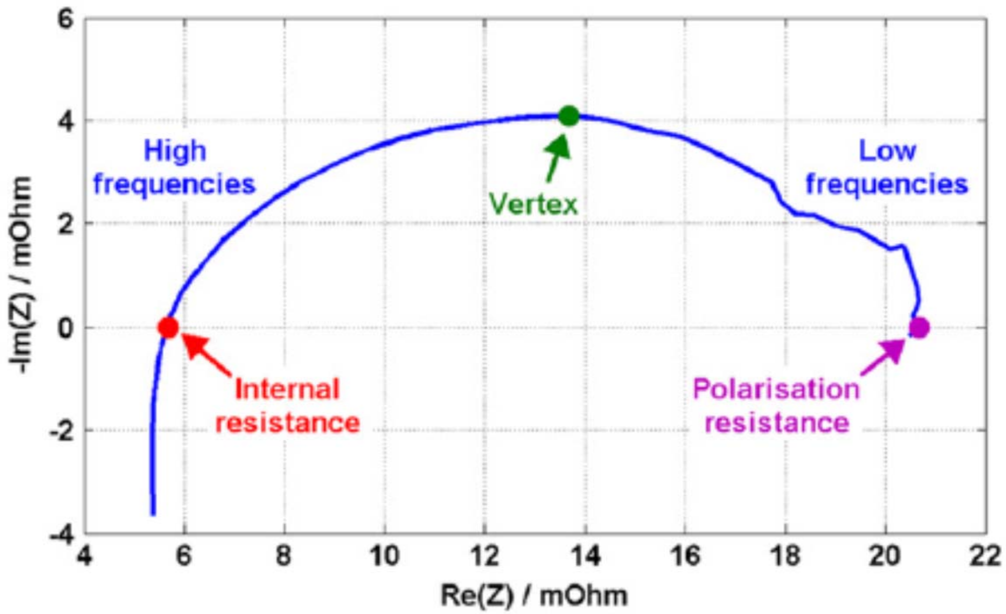


Health monitoring and ageing

– Ageing estimation – past operating time estimation

▪ Estimation of fuel cell operating time (2)

- Feature selection: 6 hyper-parameters
  - Polarization resistance value
  - Minimal value of the imaginary part in the impedance spectrum
  - Its corresponding real part values
  - Its occurring frequency
  - Internal resistance value
  - Its corresponding frequency of occurrence

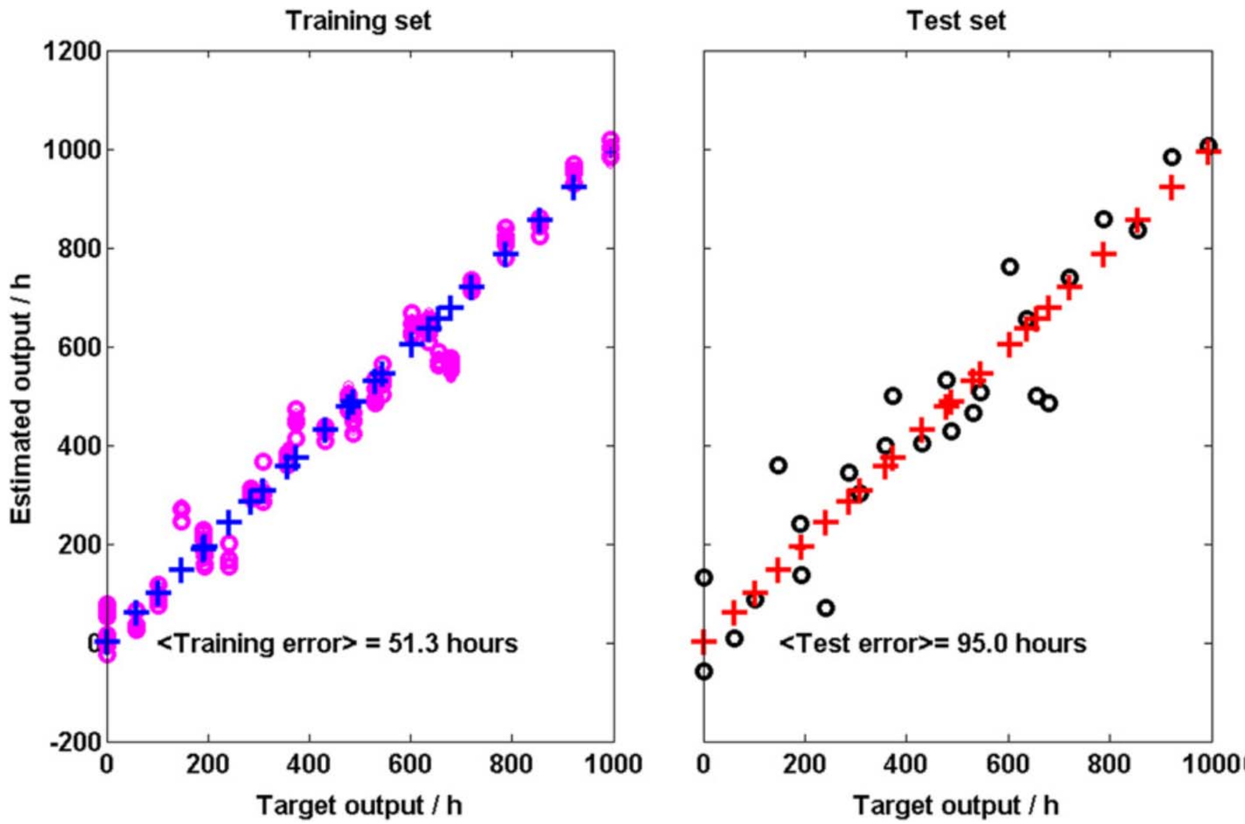


Health monitoring and ageing

– Ageing estimation – past operating time estimation

▪ Estimation of fuel cell operating time (3)

- Example of results



femto-st SCIENCES & TECHNOLOGIES

Prognostic, Diagnostic & Health Management of Fuel Cells – A state of the art

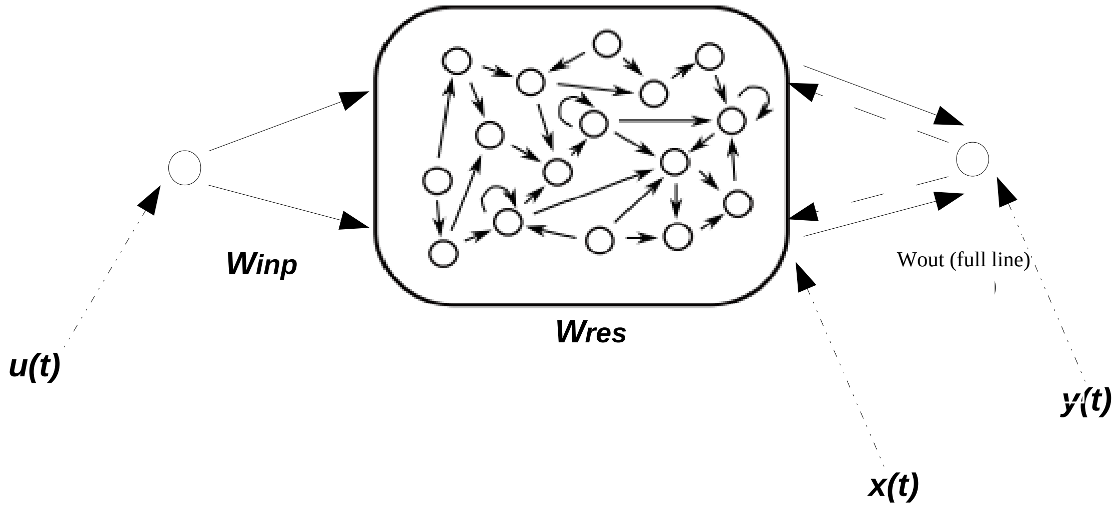
Part 5 – Ongoing works: prognostics of Fuel Cell Systems

FC LAB Research

Data-driven prognostics of PEMFC

– Echo State Networks for prognostics of FEMFC

- **Background**
  - Part of Reservoir Computing (H.Jaeger, 2001)
  - Better human brain paradigm than traditional ANN



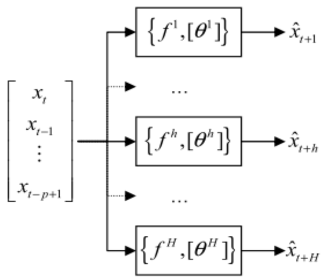
$$\tilde{x}(n) = f\left(W_{inp}.u(n) + W_{res}.x(n-1)\right)$$
$$x(n) = (1-\alpha).x(n-1) + \alpha.\tilde{x}(n)$$

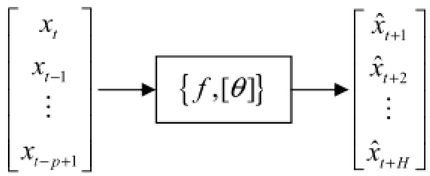
$$y(n) = W_{out}.x(n) + W_{feed}.y(n-1))$$
$$y(n) = f(W_{out}.x(n))$$

- **Outline**
  - Avoid algorithmic complexity ⇨ structural complexity
  - Learning phase in a single step: linear optimization (minimize MSE)

Data-driven prognostics of PEMFC

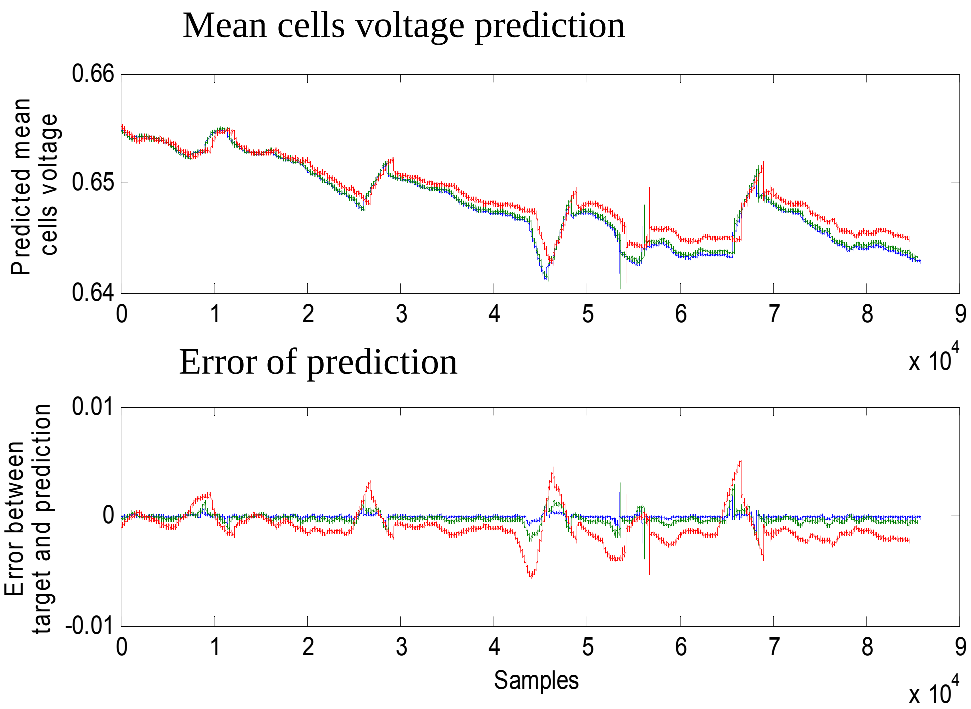
– Echo State Networks for prognostics of FEMFC



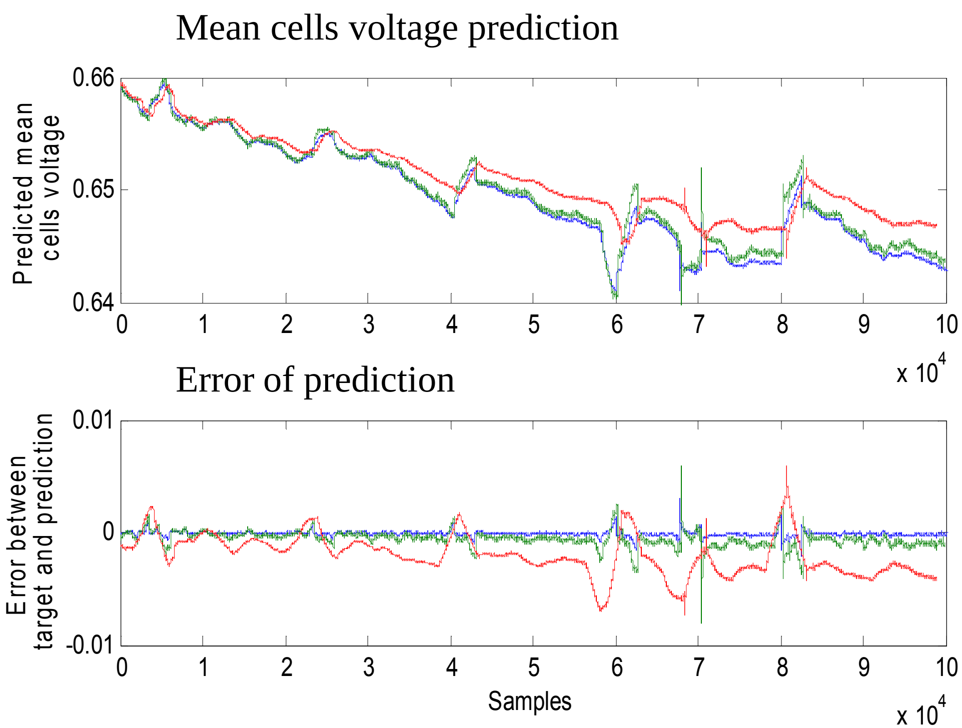


- **Application: prediction of a PEMFC degradation**
  - Horizon of prediction: 500,1000 and 2500 tu
  - Structure used: Direct and Parallel approach

Direct approach



Parallel approach



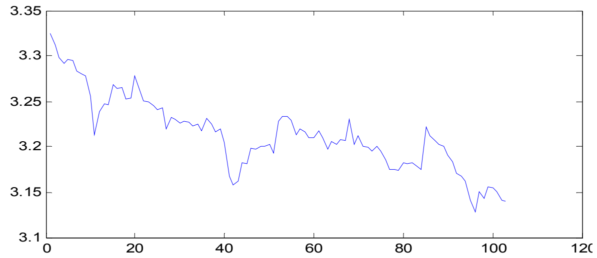
in blue: h=500, in green: h=1000, in red: for h=2500 samples

Hybrid prognostics of PEMFC

– Matching empirical degradation models

▪ Hypotheses

- / FC aging
  - – Irreversible with a long time constant
  - – Not measurable directly ⇨ deductible from another variable
  - ⇨ **Aging observed through voltage drop**



- / Operating conditions
  - – **Constant** current solicitation

- / Study framework
  - – Opening applicative limits: model
    - • Non-exact (unknown coefficients), Non-stationary (time varying), Non-linear a priori
    - • Non Gaussian noise
  - ⇨ **Bayesian Tracking – Particle filtering framework**

Hybrid prognostics of PEMFC

– **Matching empirical degradation models**

- **Formulation**
  - Hidden state model (degradation state)

$$x_k = f\left(x_{k-1}, \theta_k, \nu_k\right)$$

  - Observation model ⇨ Available measurements

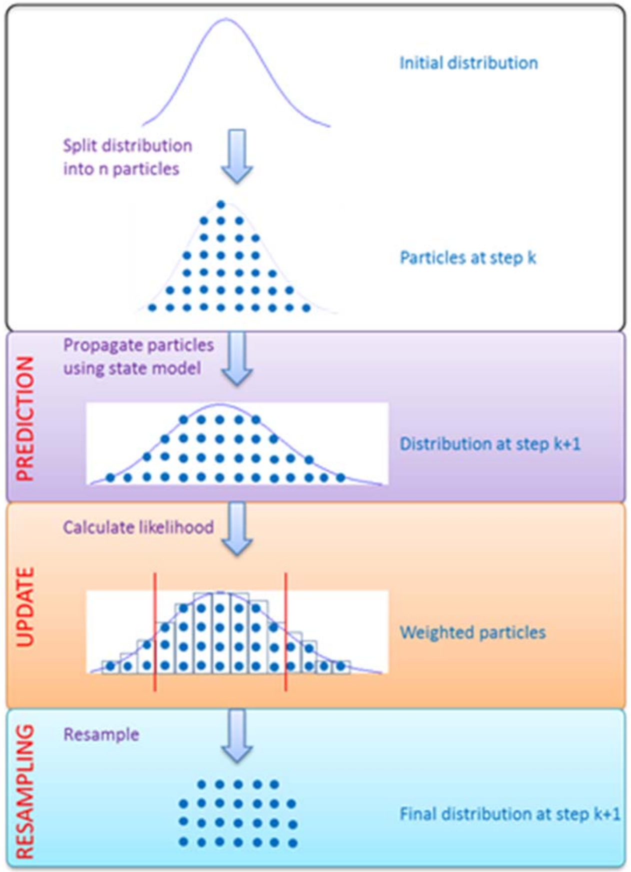
$$z_k = h\left(x_k, \mu_k\right)$$

- **Optimal Bayesian solution**
  - Initial state distribution is known $p(x_0 \mid z_0) \equiv p(x_0)$
  - Obtaining of $p(x_k \mid z_{1:k})$ in 2 steps (prediction / update)

$$p(x_k / z_{1:k-1}) = \int p(x_k / x_{k-1}).p(x_{k-1} / z_{1:k-1}).dx_{k-1}$$

$$p(x_k / z_{1:k}) = \frac{p(z_k / x_k).p(x_k / z_{1:k-1})}{p(z_k / z_{1:k-1})}$$

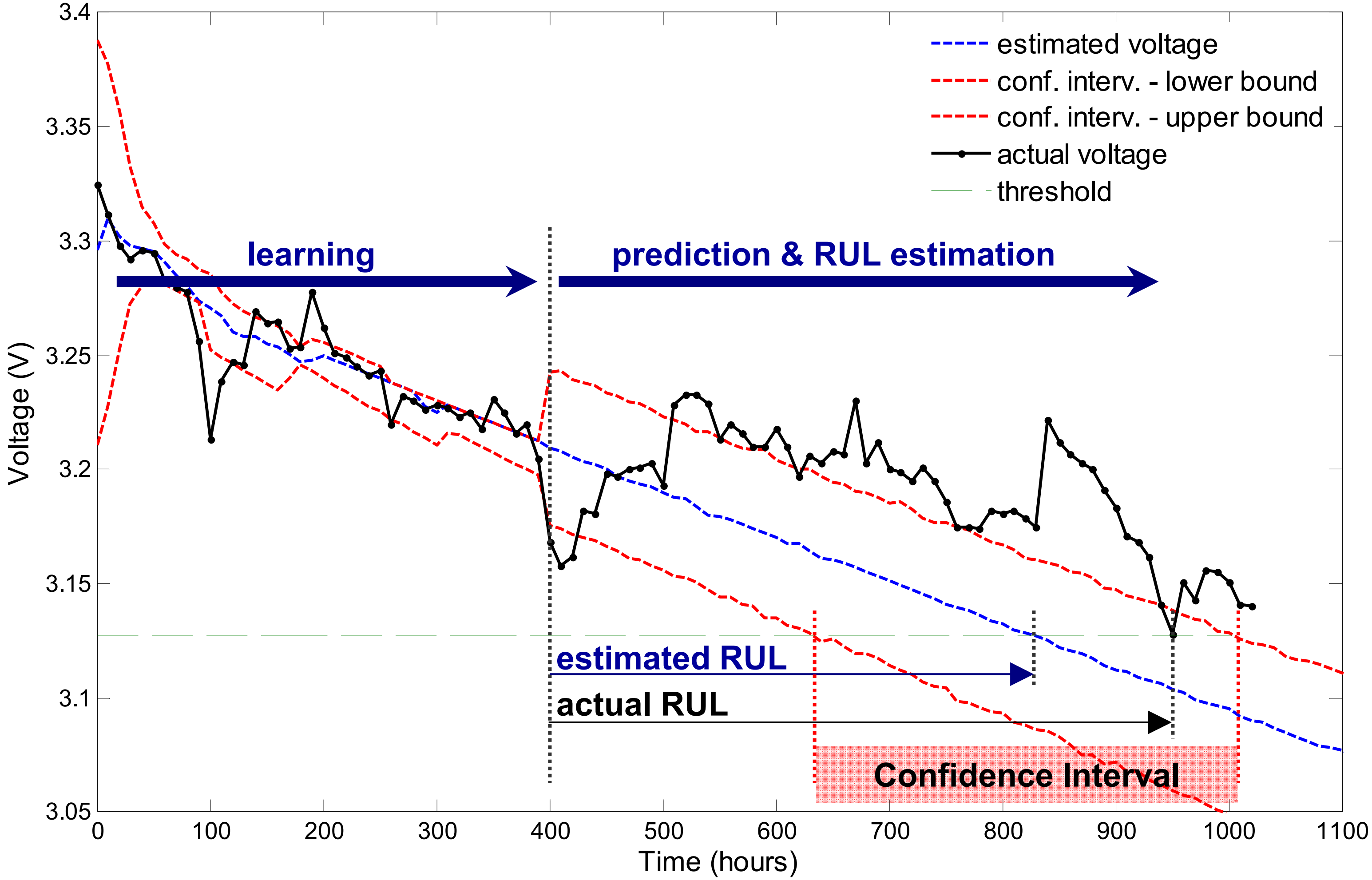
  - **Solving: particle filter**



Hybrid prognostics of PEMFC

– **Example of results**

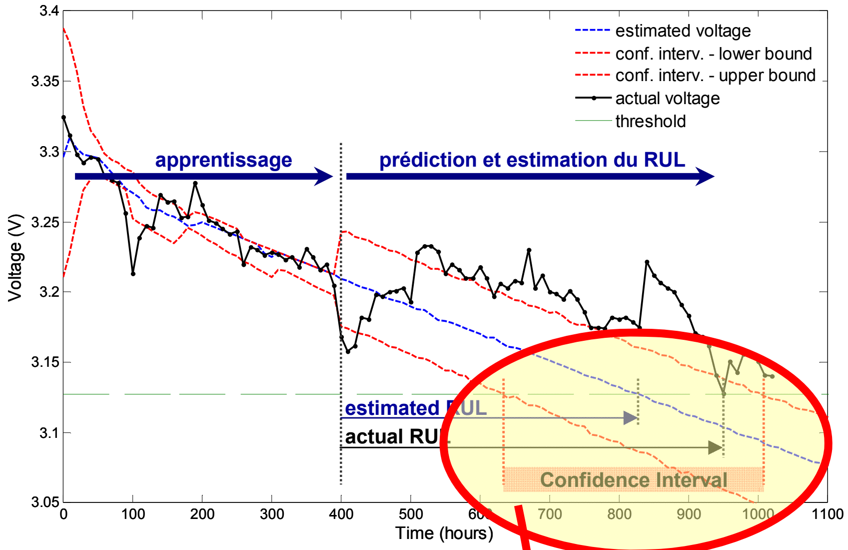
- **Estimations at t = 400 h**

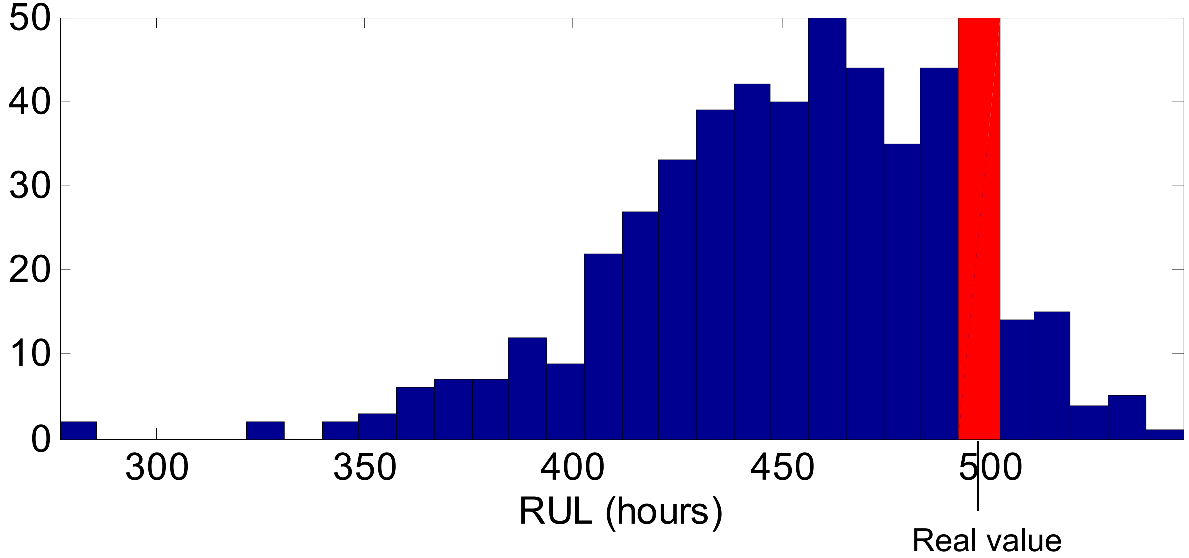


Hybrid prognostics of PEMFC

– **Example of results**

  ▪ **Prognostics at t = 400 h**

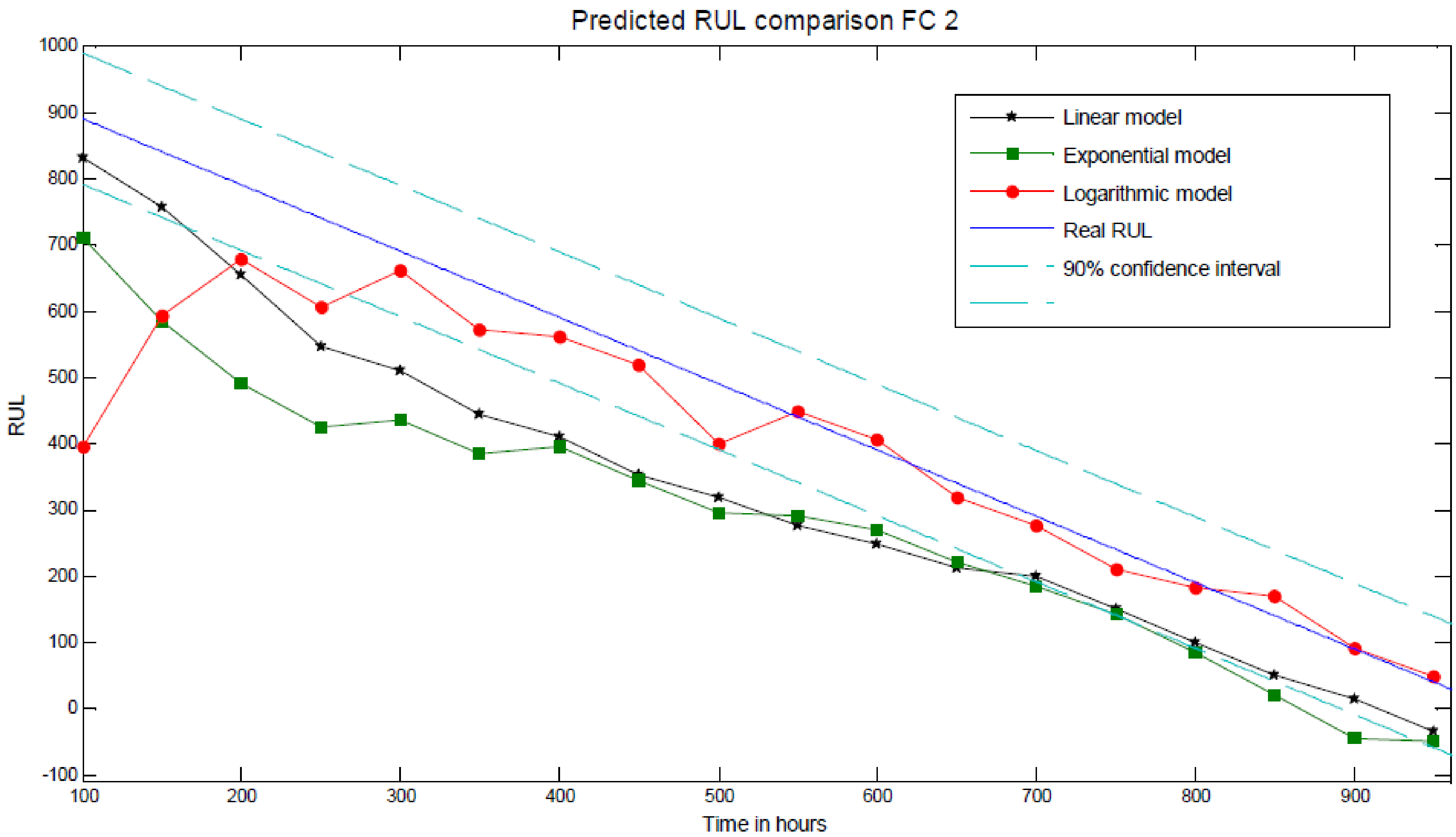




Hybrid prognostics of PEMFC

– Example of results

- **Accuracy of ± 90h on life time duration of 1000h**



Prognostic, Diagnostic & Health Management of Fuel Cells – A state of the art

Concluding remarks

FC LAB Research

Concluding remarks

– The interest of H2 technology

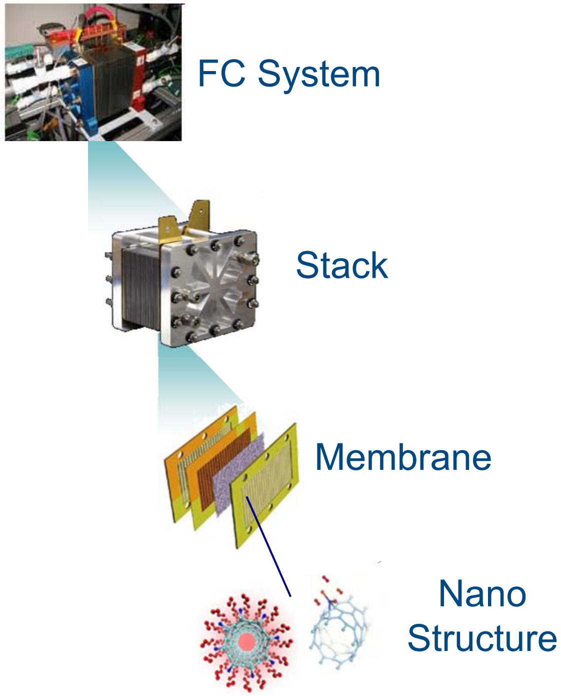
- **FC are promising energy converters**
  - High efficiency & low noise level
  - Possible heat recovery (especially for high temperature FC – SOFC)
  - Possibly no dependency to fossil fuels
  - Energy density is directly linked to the size & weight of the fuel tanks
  - Still issues on system-level
    - Interactions between the FC stack & their ancillaries
    - Reliability & durability, Diagnosis & Prognostic
    - Dedicated ancillaries on a tiny market

- **H2**
  - Best candidate for next generation fuel?
  - May play a key role in the future energy economy – electricity storage for renewable energies
  - Still issues on H2 production, public acceptability, on-board storage, distribution facilities

Concluding remarks

– **PHM of PEMFC – a challenging but exciting task!**

- **Issue: durability**
  - Increase limited lifespan of FCS
  - Ex. of PEMFC systems
    - Common life duration of around 2000 – 3000 hours
    - Where at least 5000 hours are required for transportation applications…

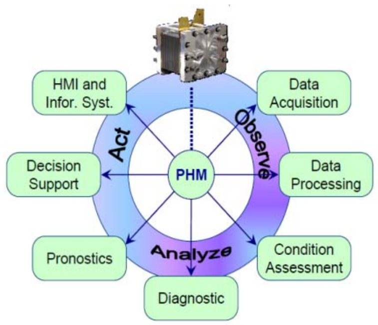


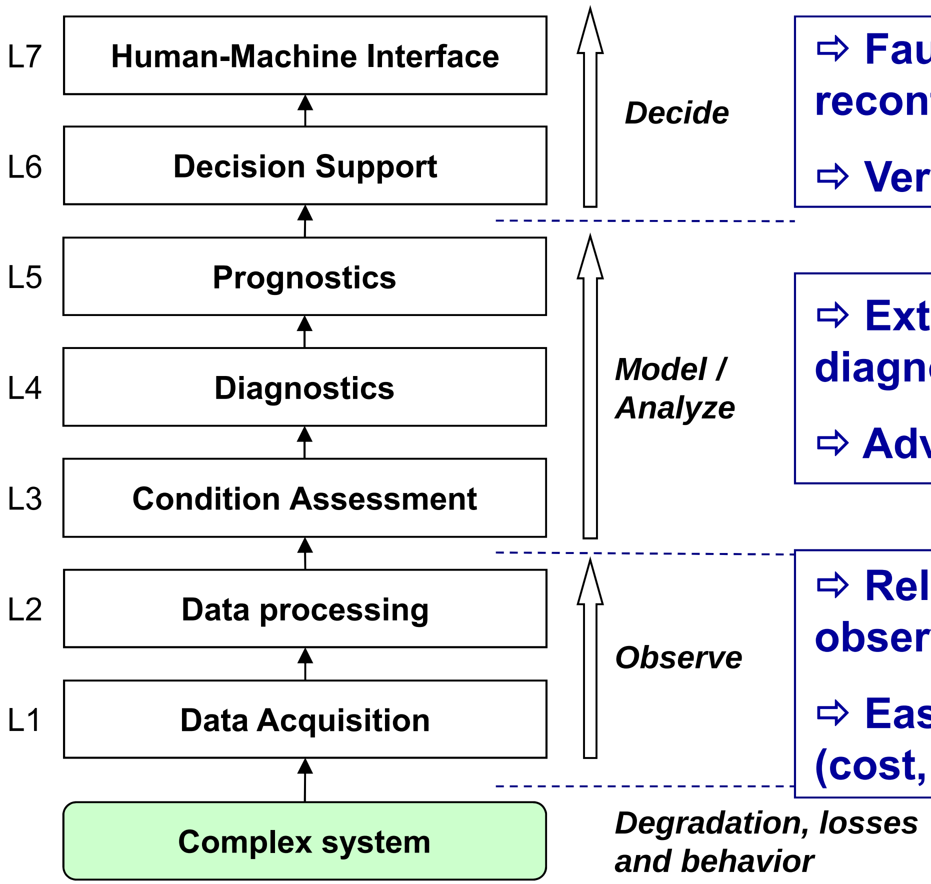
HOW ?

- Observe ageing
- Model the behavior
- Assess current health state
- Predict future health states
- Test, optimize and validate the approaches
- Prepare industrial transfer

Concluding remarks

– Open challenges





- ⇨ **Fault tolerant, self-adaptative and reconfigurable control system**
- ⇨ **Verification and validation procedures**

- ⇨ **Extended framework for detection and diagnostics approaches**
- ⇨ **Advanced prognostics models**

- ⇨ **Reliable, non-intrusive, non-damaging observation techniques**
- ⇨ **Easily implementable technology (cost, volume, online, etc.)**

Concluding remarks

– **FCLAB ? … Develop this research field**

- **FCLAB has been granted with different funding (ongoing…)**
  - Regional Government (Franche-Comte Region) – PHM-PAC project (2012)
  - ANR :
    - PROPICE (www.propice.ens2m.fr) (2012). Prognostics and Health Management of PEM Fuel Cell Systems.
    - DIAPASON2 (2010) (https://diapason2.eifer.uni-karlsruhe.de/). Diagnostic of PEM fuel cell systems.
  - European Project
    - FCH-JU SAPPHIRE (https://sapphire-project.eifer.kit.edu/) (2012). System Automation of PEMFCs with Prognostics and Health management for Improved Reliability and Economy.
    - FCH-JU D-CODE (http://www.d-code.unisa.it/) (2009). DC/DC Converter-based Diagnostics for PEM systems.

- **2014: IEEE PHM 2014 Data Challenge**
  - http://eng.fclab.fr/ieee-phm-2014-data-challenge/
  - Competition opens in December…
  - June 22-25, 2014: 2014 IEEE Int. Conf. on PHM (Spokane, WA, USA)

IEEE ReliabilitySociety PHM FC LAB Research

Prognostic, Diagnostic & Health Management of Fuel Cells – A state of the art

Rafael Gouriveau, Daniel Hissel

FEMTO-ST Institute, UMR CNRS 6174
FCLAB Research Federation, FR CNRS 3539

rafael.gouriveau@femto-st.fr
daniel.hissel@univ-fcomte.fr