PHM of Fuel Cell Systems – A state of the art

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About us…

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- Director of the FCLAB (Fuel Cell Lab) Research Federation
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- Head of “Fuel Cell Systems” research axis, French CNRS research grouping on Hydrogen & Fuel Cells
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PHM of a Fuel Cell System

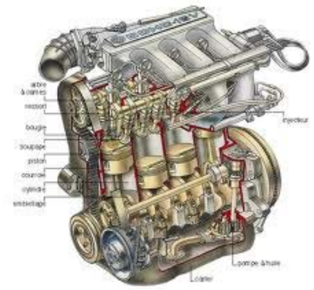
PHM of Fuel Cell Systems – A state of the art

Motivations

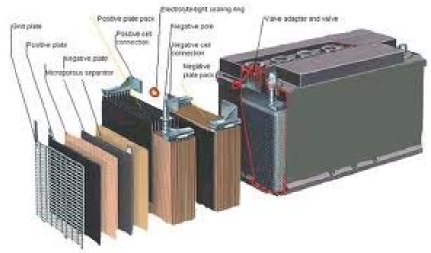
Towards FC systems

– Switching to fuel cell?

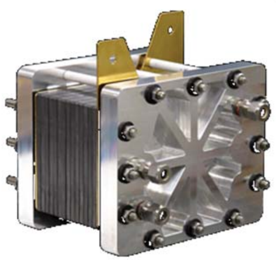
- **The age of utilizing exclusively fossil fuels comes to an end**
  - Resource reduction
  - Exhaust gases (GHG) from the internal combustion engine



- **First alternative: rechargeable batteries**
  - Significant progress has been made BUT
  - Mostly "hybrid" systems because of limited autonomy and cumbersome recharging operations
  - ⇨ Reduce rather than eliminate the dependence on fossil fuels…

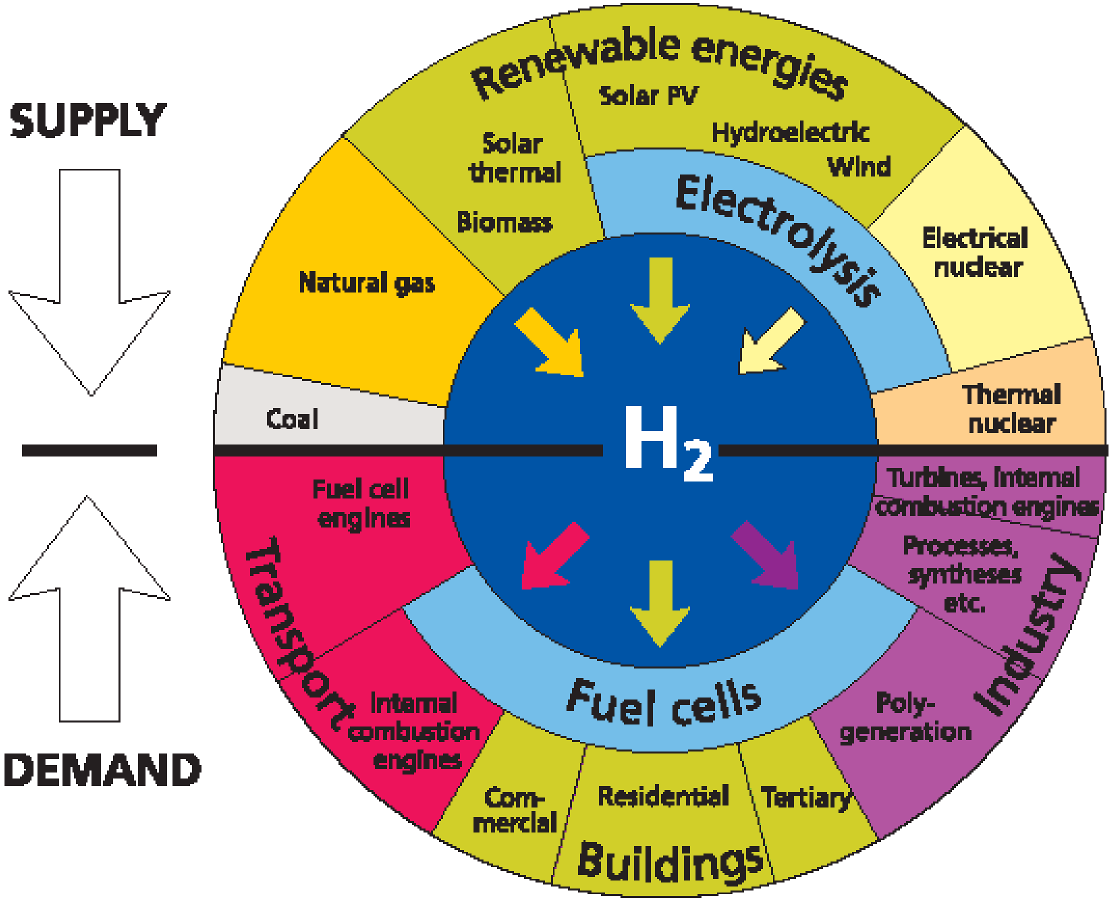


- **Second alternative: fuel cell systems**
  - When combined with oxygen, hydrogen produces electricity
  - Residues: water and heat
  - (*Theoretical & in-situ*) pollutant emissions is zero
  - ⇨ **Attractive alternative**
  - ⇨ **High energy density (but linked to H2 storage)**



Hydrogen as an energy vector

– **Justifying the increasing interest: hydrogen as an energy vector**



http://ec.europa.eu/research/rtdinfo/42/01/article_1315_en.html

- **Hydrogen**
  - Very abundant "elementary" resource at global level (oceans, rivers, organics, biomass)
  - Never in an isolated state: hydrogen must be produced
  - Once produced, hydrogen can be stored and transported

⇨ **"production-storage-transport"**

⇨ **hydrogen is not seen as a "direct" fuel but as an energy vector**

⇨ **duality with electricity (FC – electrolysis)**

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 ?

PHM of Fuel Cell System – A state of the art

Part 1 – Prognostics & Health Management

FC LAB Research

PHM as an enabling discipline

– Avoid failures

↗ Reliability
↗ Availability
↗ Security
↘ Costs

PHM →

⇨ Monitor
⇨ Predict
⇨ Master
the health state

– A definition of PHM (CALCE Center)

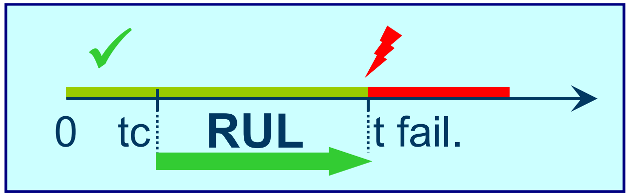
- … the means to **predict and protect** the integrity of equipment and complex systems, and **avoid unanticipated** operational **problems** leading to mission **performance deficiencies, degradation, and adverse effects to mission safety.**

Prognostics as a key process

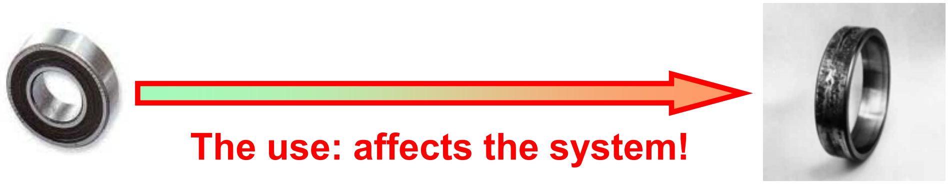
– **WHAT: prognostics concept**

- **Perform prognostics ≈ estimate the RUL (Remaining Useful Life)**
  - ISO 13381-1:2004 - "*estimation of the operating time before failure and the risk of existence or later appearance of one or more failure modes*"

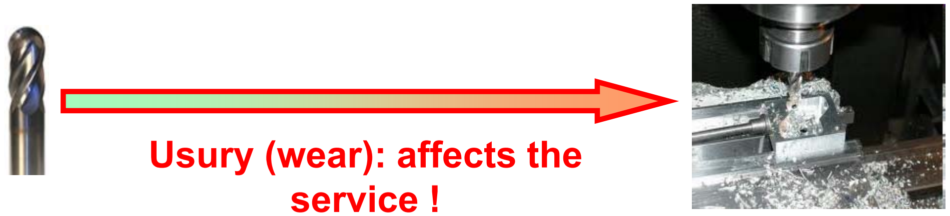
- **Main objectives**
  - Estimation of the Remaining Useful Life (RUL)
  - Estimation of the probability of a system to fail at a given time



- **Applicative areas**
  - Prognostics of components



  - Prognostics of performances (QoS)



Prognostics as a key process

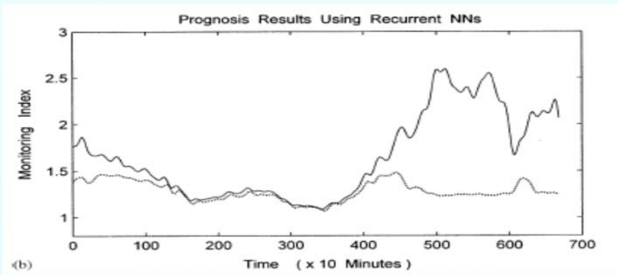
– HOW: approaches for prognostics

Model based	Data-driven	Hybrid
• Analytical models for behavior and degradation • Few data required • Accurate estimates • Requires insight (knowledge) about the system • Extremely case specific • Hard to build models • Computationally expensive	• Transform raw data into relevant behavior models • No a priori model of the degradation • Good capability to cater non-linearity • Requires large amounts of data	• Takes benefit from both • Improved learning scheme • Better uncertainty management • Can be complex and computationally expensive

Model based:

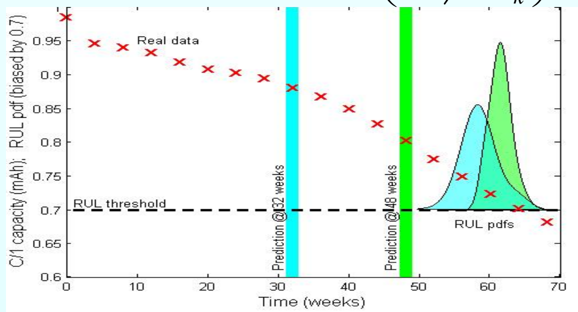
$$\begin{cases} \dot{x} = \left(x, \lambda(\theta), u\right) \\ \dot{\theta} = \varepsilon g\left(\theta, x\right) \\ y = Cx + Du + v \end{cases}$$

Data-driven:



Hybrid:

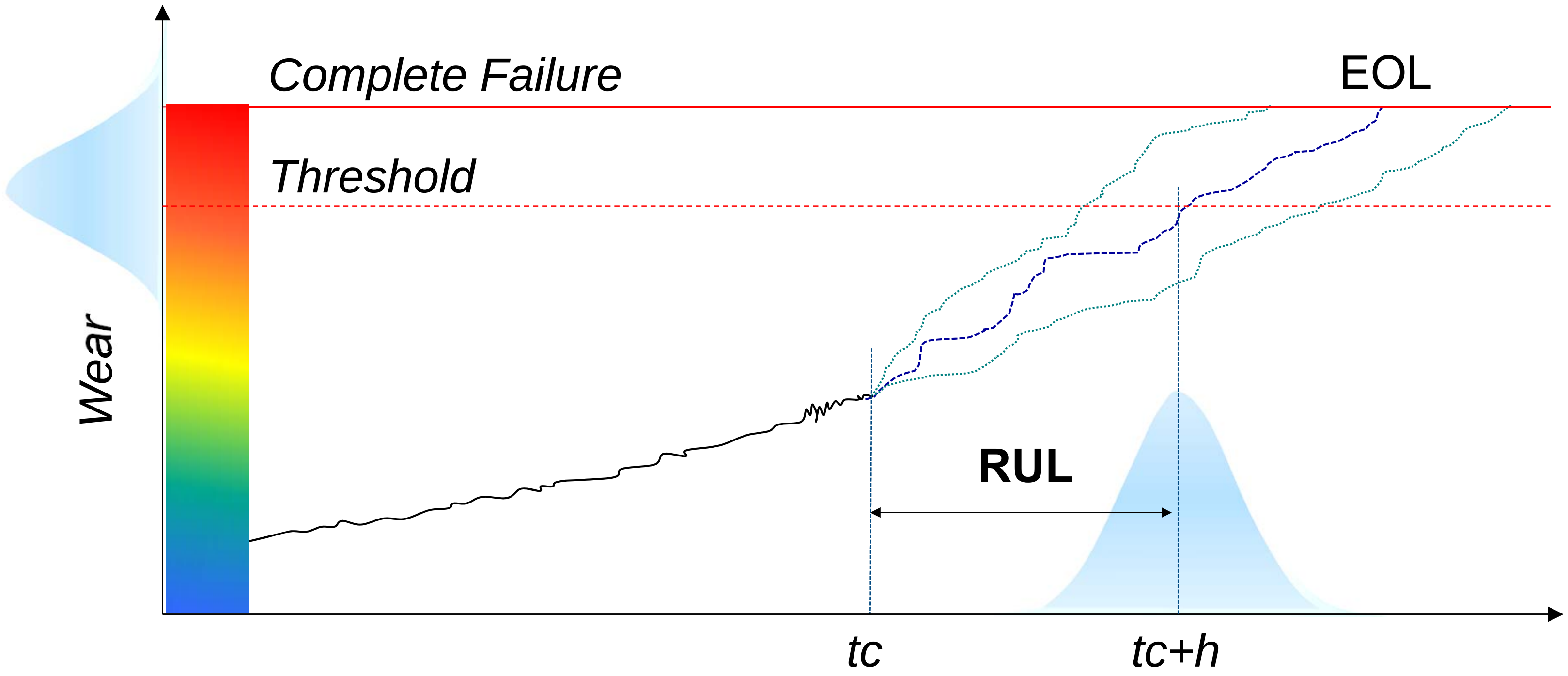
$$C_{k+1} = \eta_c C_k + \beta_1 \cdot \exp\left(-\beta_2 / \Delta t_k\right)$$



Prognostics as a key process

– **Prognostics and uncertainty**

- **Uncertainty is central to any prognostic work**
  - Give a confidence value of the estimated RUL



Implementing prognostics

– **From raw data to RUL: system must be "observed"…**

  - **Leaving apart historic of failures, monitoring is often (always) necessary to**
    - Gather real data (SCADA, health monitoring, supervision…)
    - A posteriori understand failure behaviors and be more efficient in the future (diagnosis)
    - Anticipate failure (prognostics)

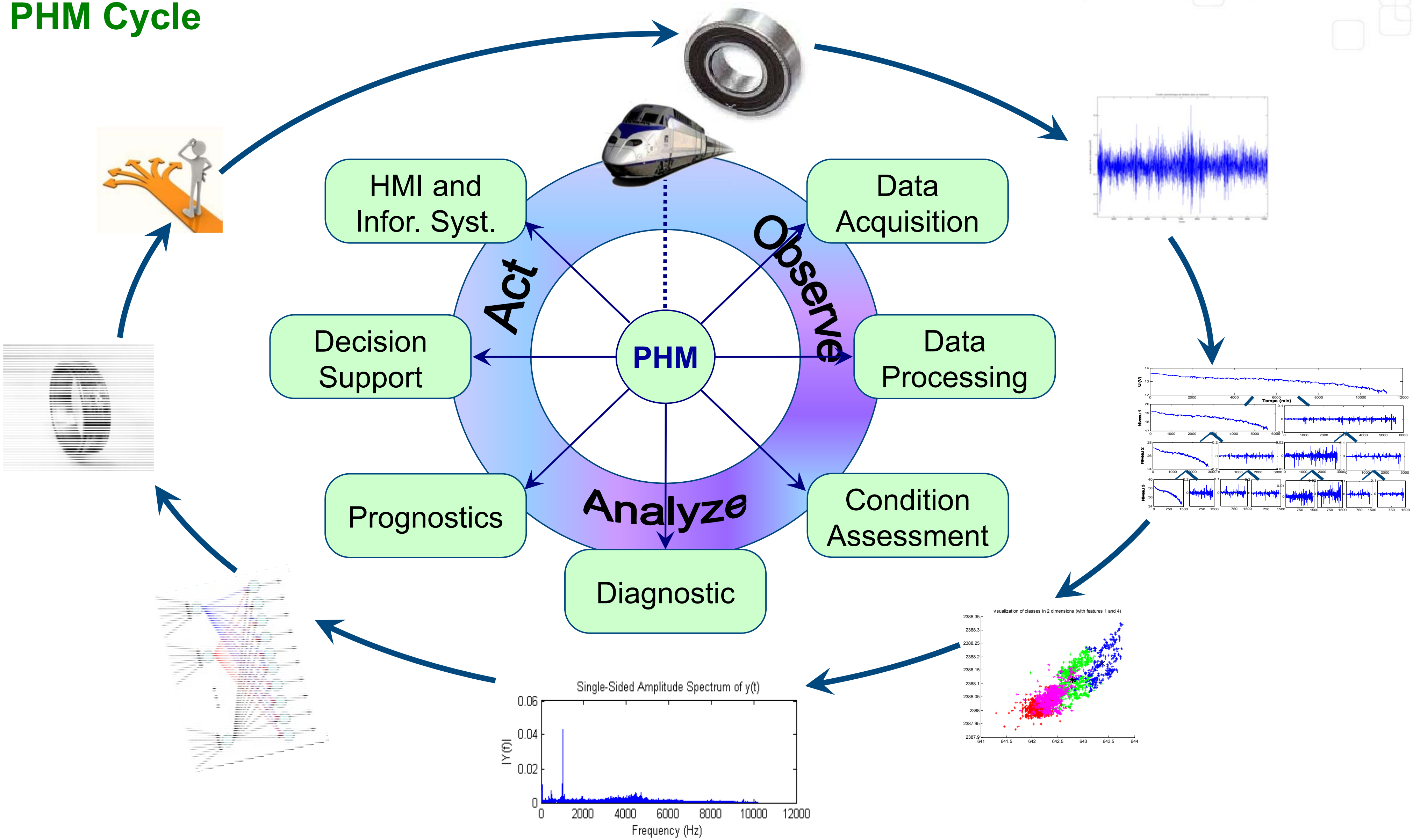
– **From RUL to mitigation actions: decision making is required…**

  - **Estimate the RUL isn't a goal in itself! Must enable deciding from mitigation actions**
    - Control strategy
    - Maintenance policies

PHM Cycle

Implementing prognostics

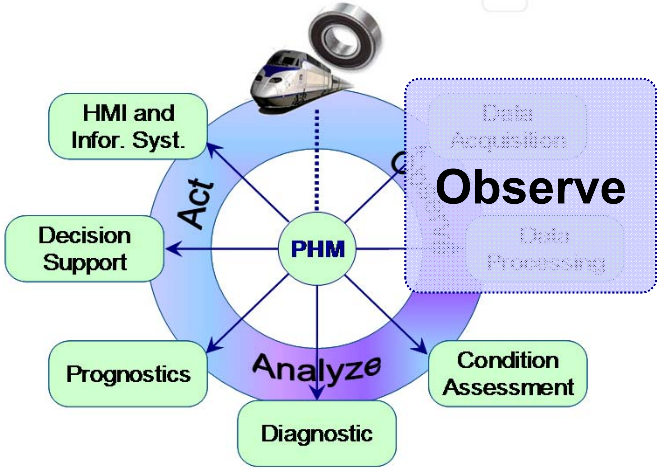
– **PHM Cycle**

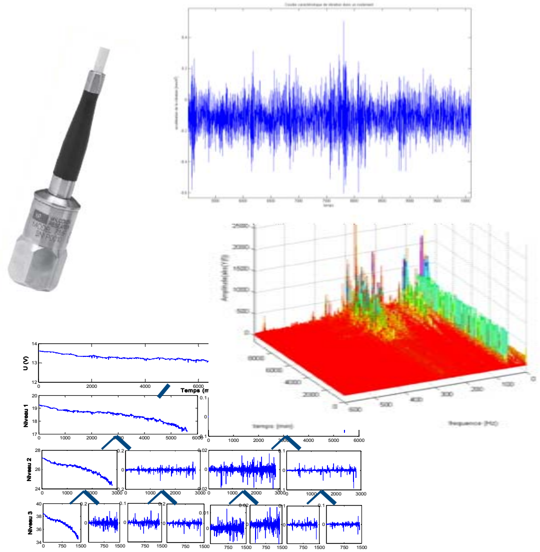


Scientific issues (a flavor)

– **Observe: data acquisition and processing**

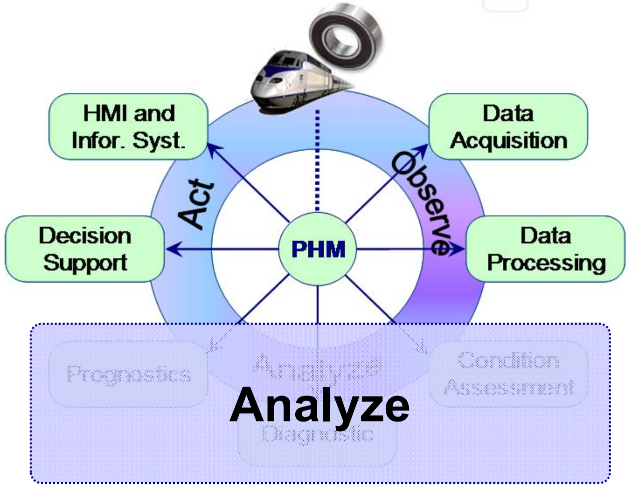
- **Objectives**
  - Gather useful data from the system
  - Physical phenomena identification
  - Health indicator generation
- **Underlying problems**
  - Sensors specification and placement: instrumentation
  - De-noising and data characterization
  - Feature extraction/selection and construction
  - Management of dataflow
- **Approaches**
  - Signal processing algorithms
  - Multivariate statistics, machine learning, genetic algorithms
  - Fusion algorithms
  - …





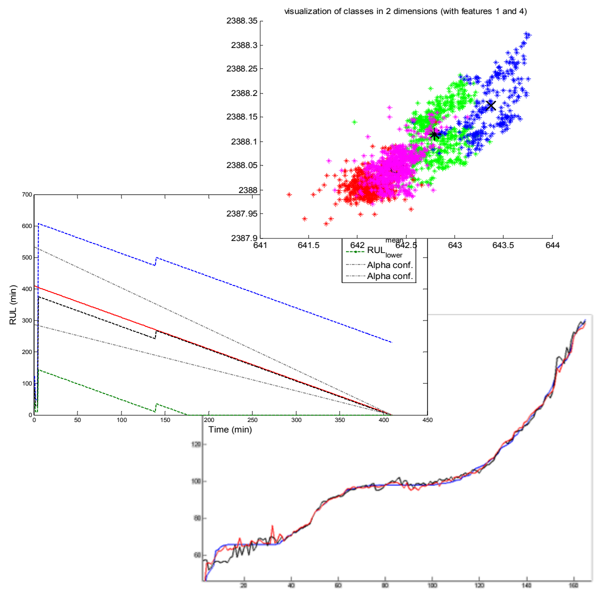
Scientific issues (a flavor)

– Analyze: condition assessment, diagnostic and prognostics



- **Objectives**
  - Estimate the health state of the system
  - Predict the Remaining Useful Life
  - Provide confidence interval

- **Underlying problems**
  - Modeling of degradation, behavior and threshold definition
  - Integrate variability of condition loads / reversibility
  - Management of uncertainty and incompleteness of data
  - Clustering, classification, approximation and prediction

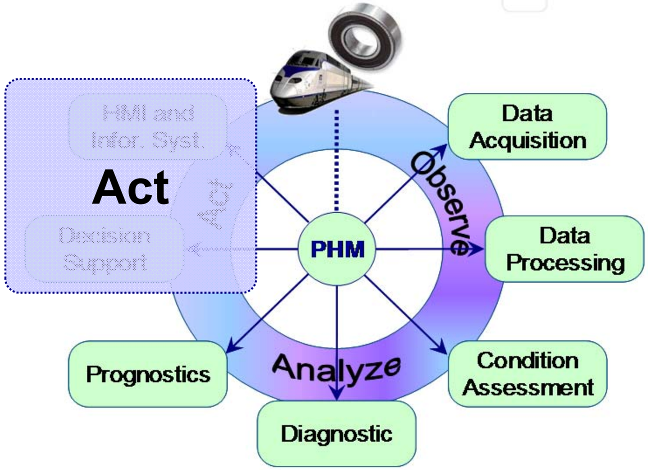


- **Approaches**
  - Markov models, Bayesian networks, particles filtering
  - Neural networks, neuro-fuzzy systems, SVM, SVR
  - Case-Based Reasoning
  - Probability and evidence theories
  - …

Scientific issues (a flavor)

– **Act: decision support, HMI and information access**

- **Objectives**
  - Ensure mission achievement (QoS)
  - Increase useful life
  - Reduce life cycle cost
  - Optimize maintenance strategy
- **Underlying problems**
  - Decision modeling
  - Mathematical complexity analysis
  - Scheduling and assignment problems
  - Capitalization and traceability
- **Approaches**
  - Multicriteria optimization, operational research techniques
  - Combinatorial optimization, heuristics and metaheuristics
  - Case-based reasoning (CBR) / Knowledge based
  - …



PHM of Fuel Cell Systems – A state of the art

Part 2 – Fuel Cell technology and PEMFC Systems

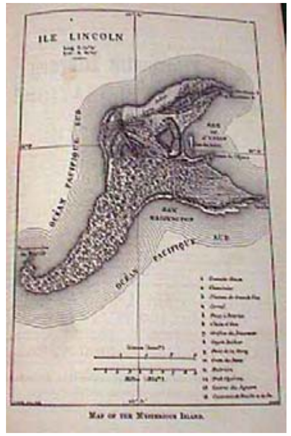
Fuel Cell technology

– Is Science Fiction becoming Reality ?

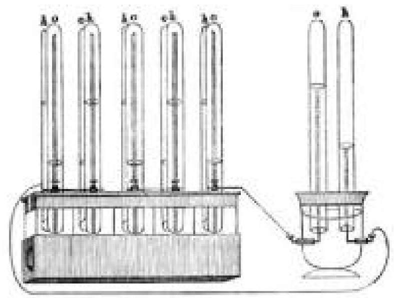
- **Jules Verne, 1875: "*The Mysterious Island*"**

  « … 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... "

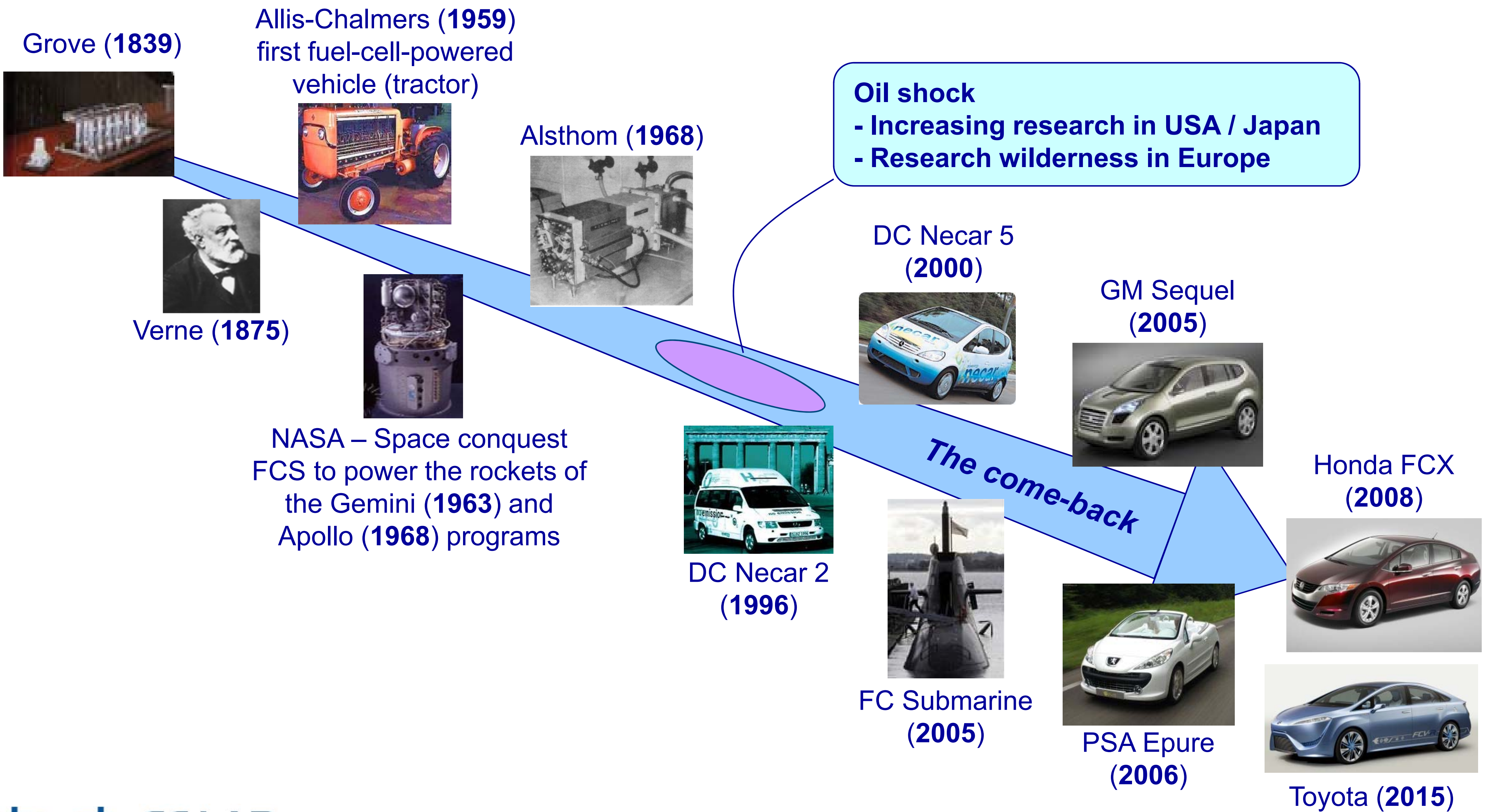


- **Basic principle discovered and demonstrated in 1839**
  - British physicist William Grove
  - For more than a century, the priority given to the development of thermal machines and electrical batteries overshadowed this invention.



Fuel Cell technology

– Brief history

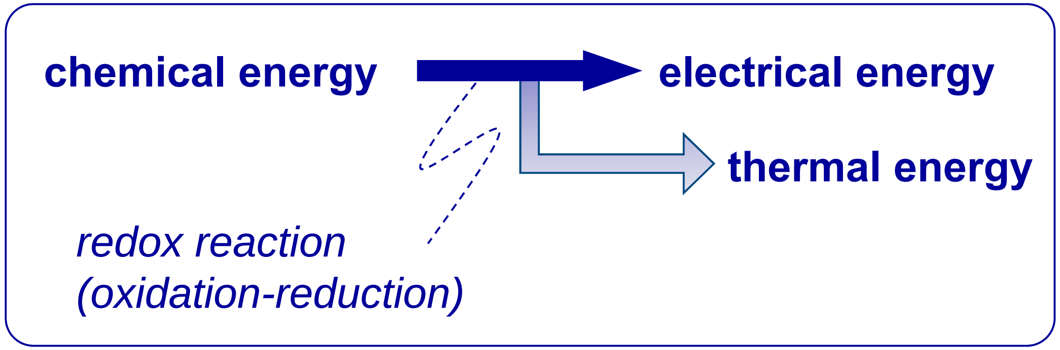


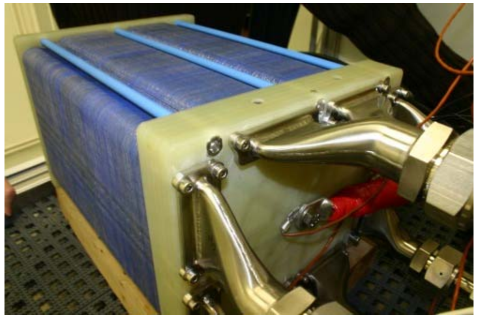
Fuel Cell technology

– 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

– Principle of a fuel cell

▪ Operating principle

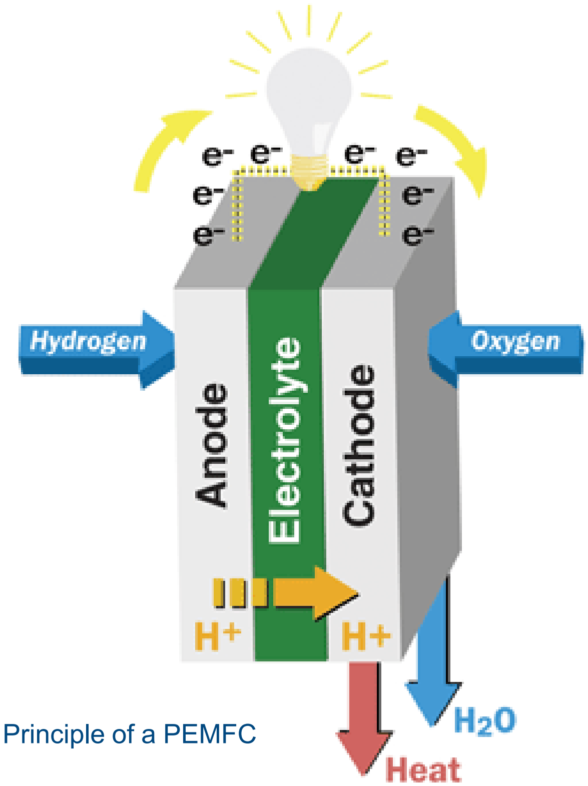
- Simple electrochemical reaction
  - Two electrodes connected externally by an electric circuit and separated by an electrolyte
  - Anode supplied with a reactant Ra
    - Ra either contains, either is hydrogen…
  - Cathode supplied with an oxidizer Oc
    - Oc either contains, either is oxygen
  - The Reactant atom at the anode breaks down to form a proton and an electron
    - The electron runs through the electrical circuit, **producing a current**
  - The ion migrates through the electrolyte to the cathode where it combines with the Oxidizer
    - This reaction **forms water and emits heat**

Anode : Fuel Oxidization (Ra)

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

Cathode : Reduction of fuel oxidizer Oc

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



Principle of a PEMFC

Fuel Cell technology

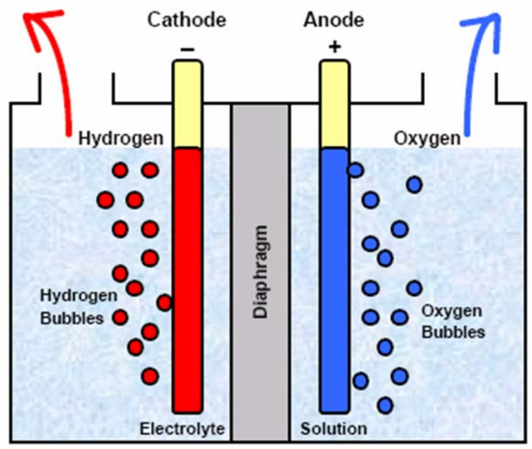
– Principle of a fuel cell

▪ Commonly used reactant and oxidizer

- Electrochemical reaction
  - Two Redox couples (Ra, Oa) & (Oc, Rc)
  - Two reactants Ra & Oc
  - Four chemical species and electrons

- Fuel cells commonly considered
  - Fuel: hydrogen
  - Fuel oxidizer: oxygen

→ Inverse principle of water electrolysis



Standard Electrolysis

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

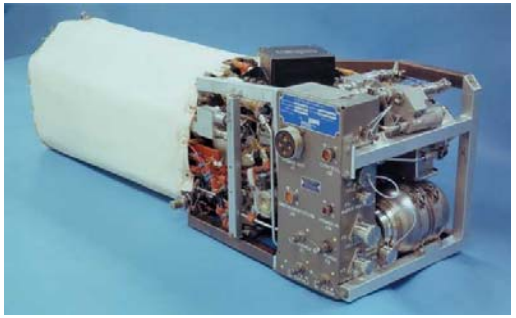
  *« I believe that water will one day be employed as fuel, that **hydrogen** and **oxygen** of which the water is constituted will be used, simultaneously or in isolation, to furnish an inexhaustible source of heat and light… »*

Fuel Cell technology

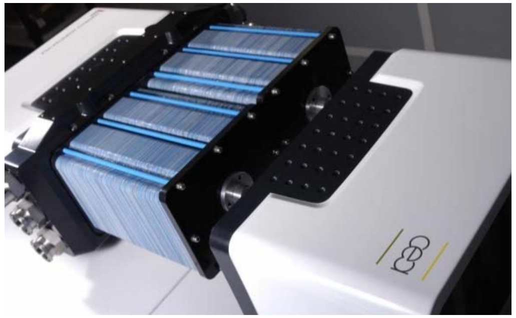
– Taxonomy of Fuel Cell

- **AFC – Alkaline Fuel Cell**
  - Fuel / Fuel Oxidizer: H_2 / O_2 (pure)
- **PEMFC – Polymer Exchange Membrane Fuel Cell**
  - Fuel / Fuel Oxidizer: H_2 (pure or reformed) / Air or O_2
- **DMFC – Direct Membrane Fuel Cell**
  - Fuel / Fuel Oxidizer: Methanol (CH_3OH) / Air
- **PAFC – Phosphoric Acid Fuel Cell**
  - Fuel / Fuel Oxidizer: H_2 (pure or reformed) / Air
- **MCFC – Molten Carbonate Fuel Cell**
  - Fuel / Fuel Oxidizer: H_2 (pure or reformed) / Air
- **SOFC – Solid Oxide Fuel Cell**
  - Fuel / Fuel Oxidizer: H_2 (pure or reformed) or CO / Air

AFC – Apollo (NASA)



PEMFC – Car Appl. (CEA)



Fuel Cell technology

– Taxonomy of Fuel Cell

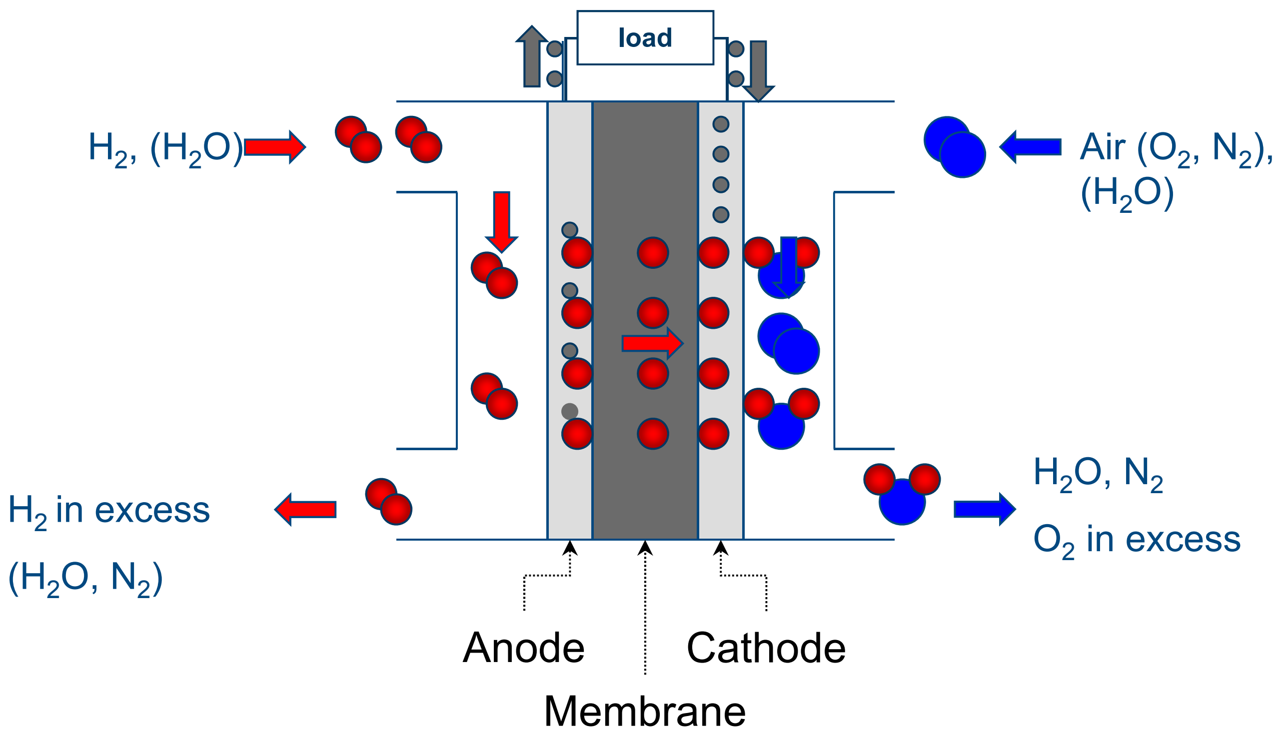
	Oper. Temp. (°C)	Power range (W)	Main application area
DMFC	20 – 90	1 – 100	Low-power portable applications (mobile phones, computers)
PEMFC	30 – 100	1 – 100k	**Automobile / Transport** Low-power stationary appl. (residential sector)
AFC	50 – 200	500 – 10k	Spaceships
PAFC	~220	10k – 1M	Domestic heat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

Zero emissions
high efficiency

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

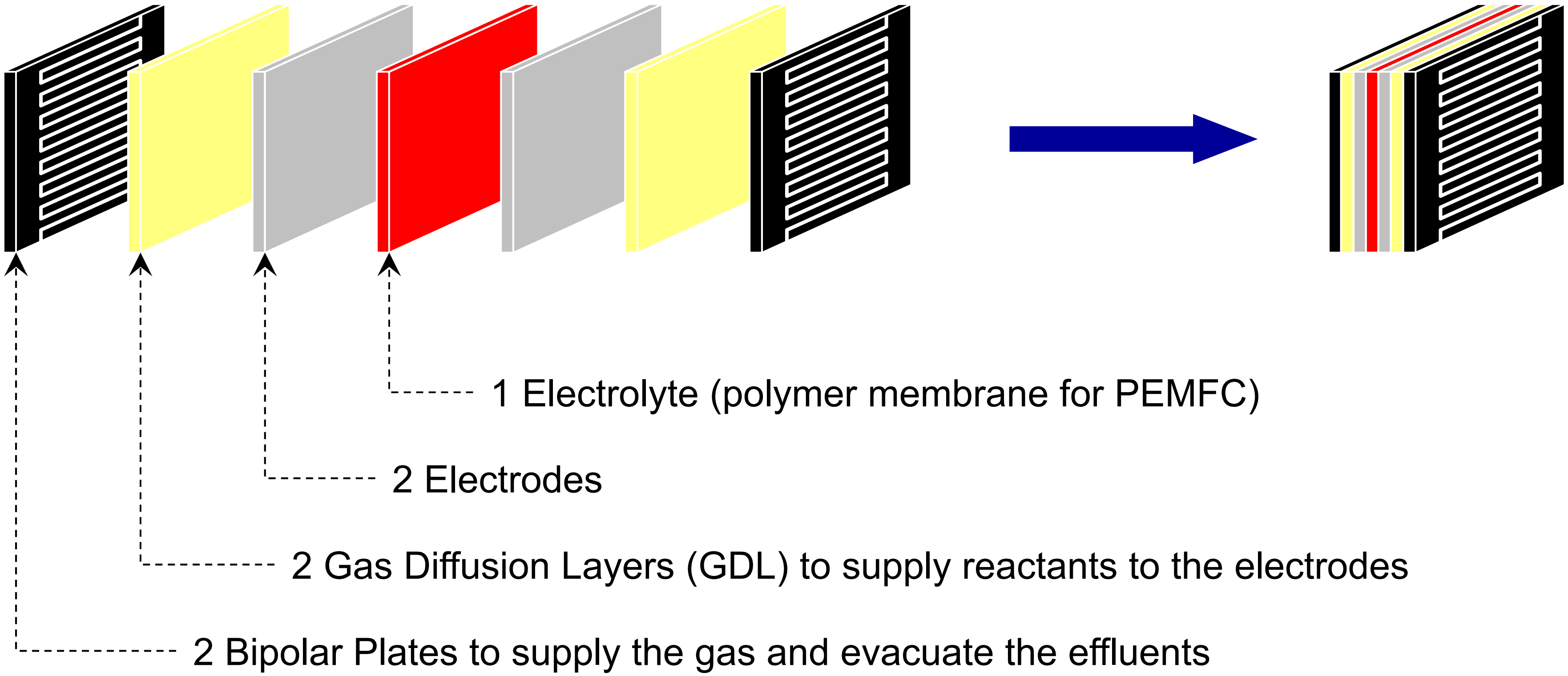
$2H_2 + O_2 \rightarrow 2H_2O$ + electricity + heat

PEMFC Systems

– Structure

▪ Structure of a single cell

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

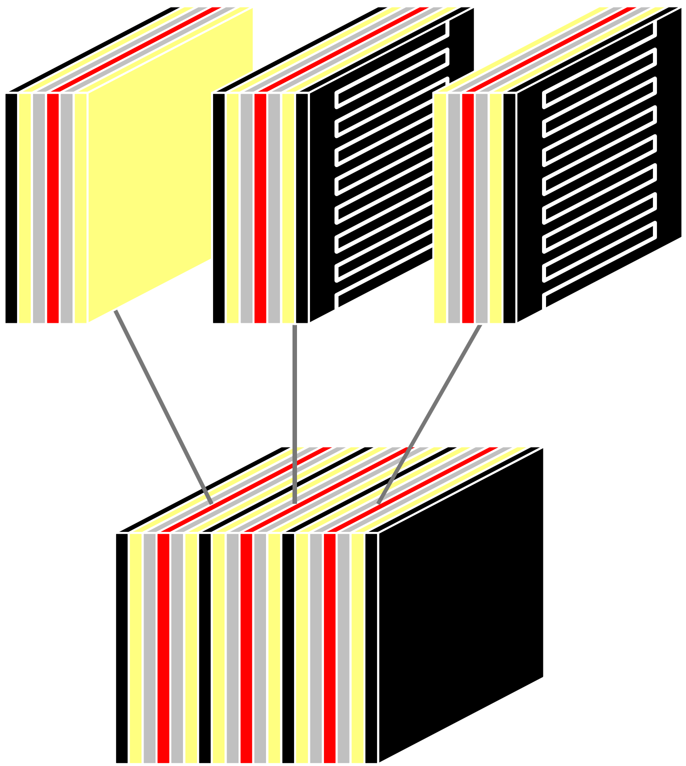


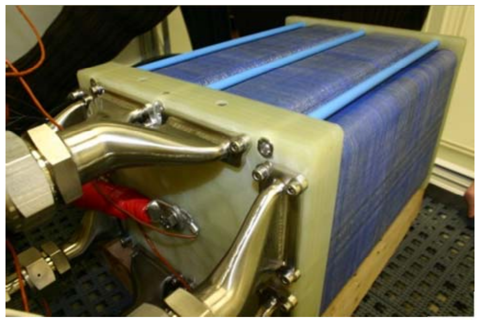
PEMFC Systems

– Structure

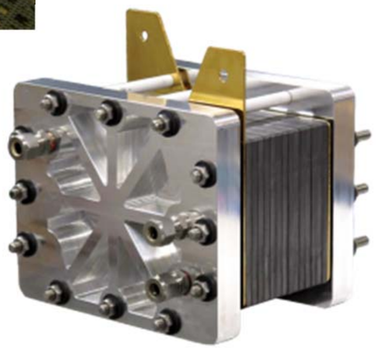
▪ Structure of a stack

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





CEA



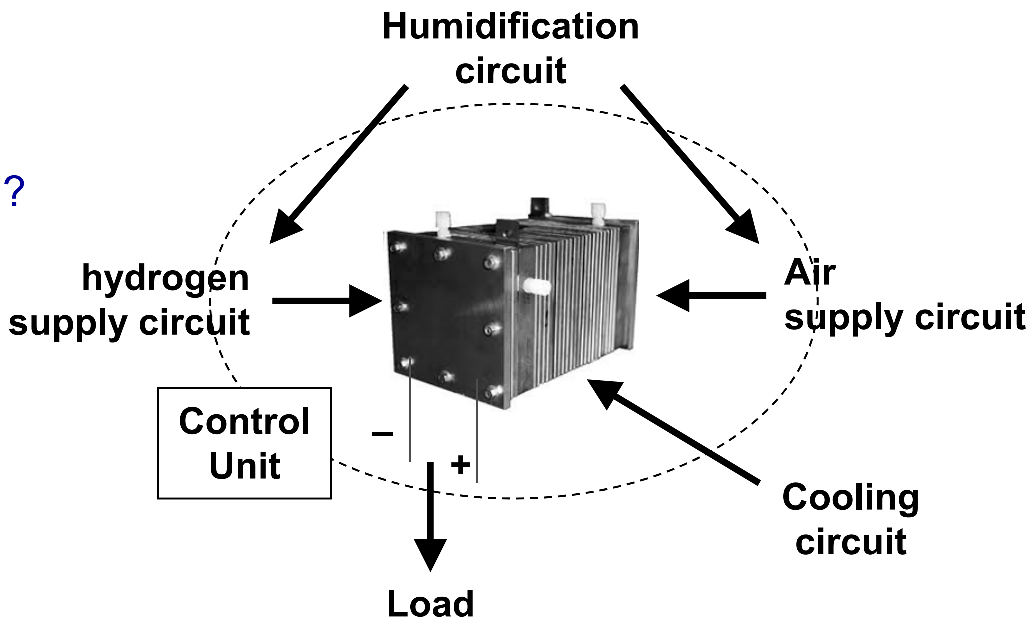
Pragma Ind.

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?

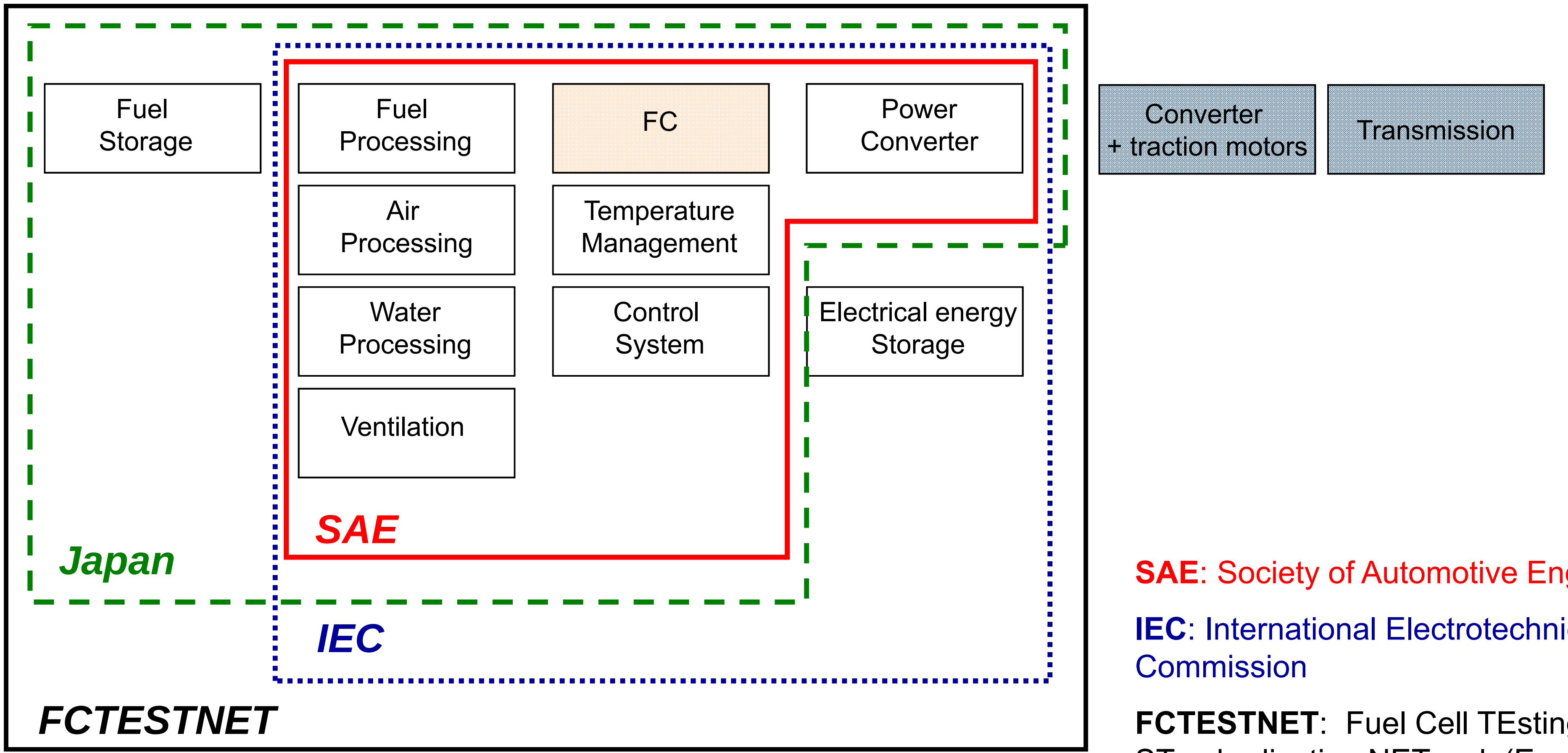
⇨ **FC System = Stack + Ancillaries**



PEMFC Systems

– **Where are the limits of a FC System?**

- **Example of embedded FC Systems**



SAE: Society of Automotive Engineers

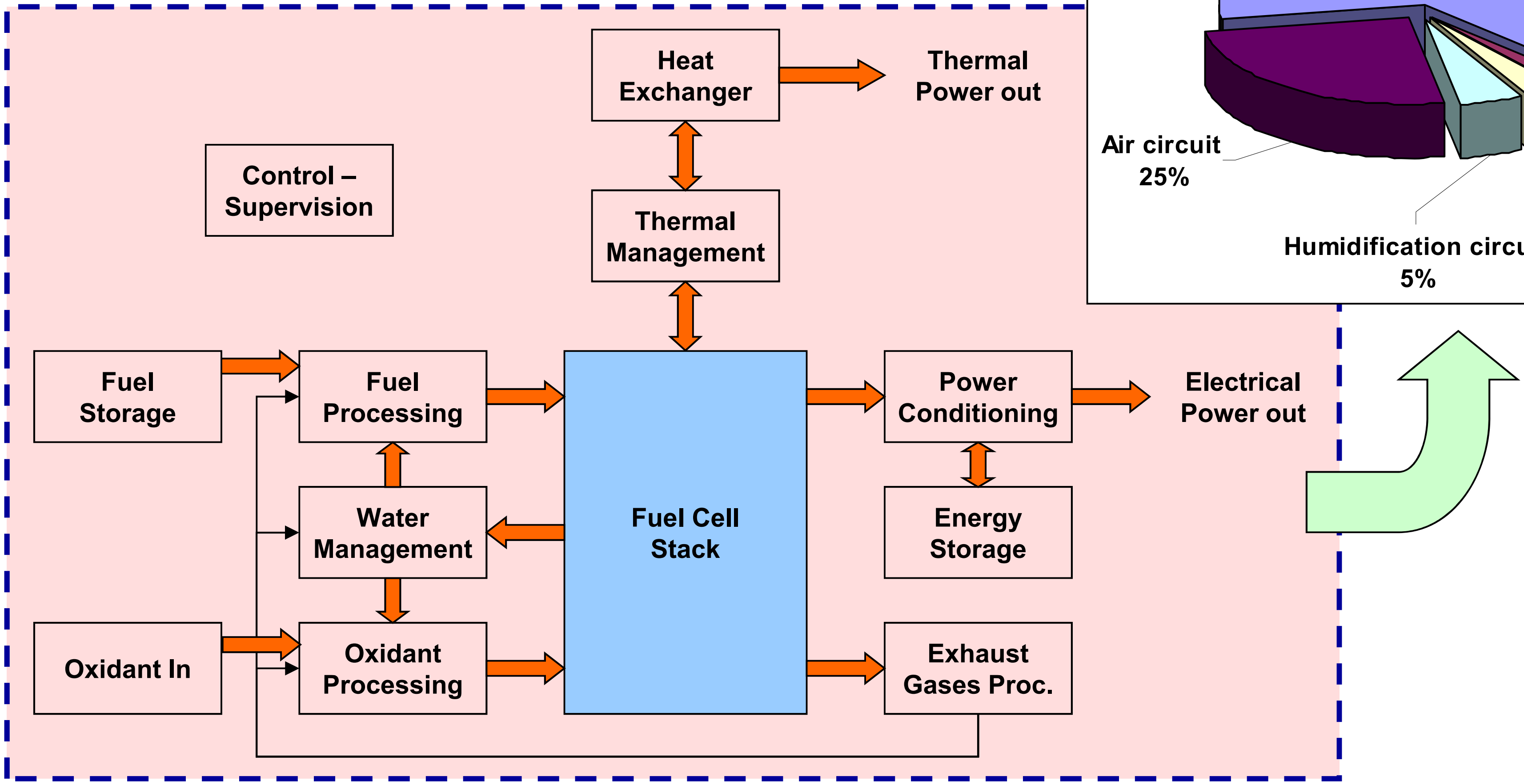
IEC: International Electrotechnical Commission

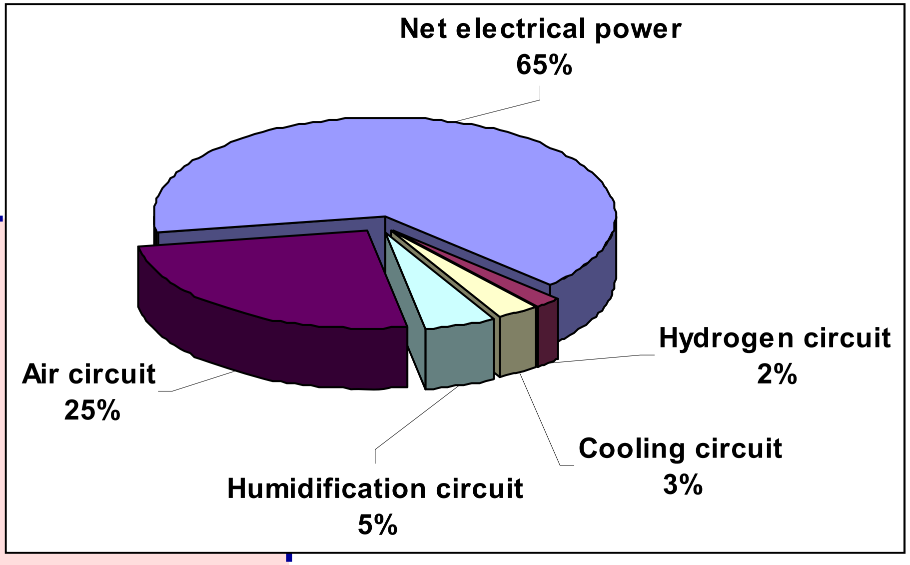
FCTESTNET: Fuel Cell TEsting and STandardization NETwork (Eur.Project)

PEMFC Systems

– **Drawback from FC system's ancillaries**

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





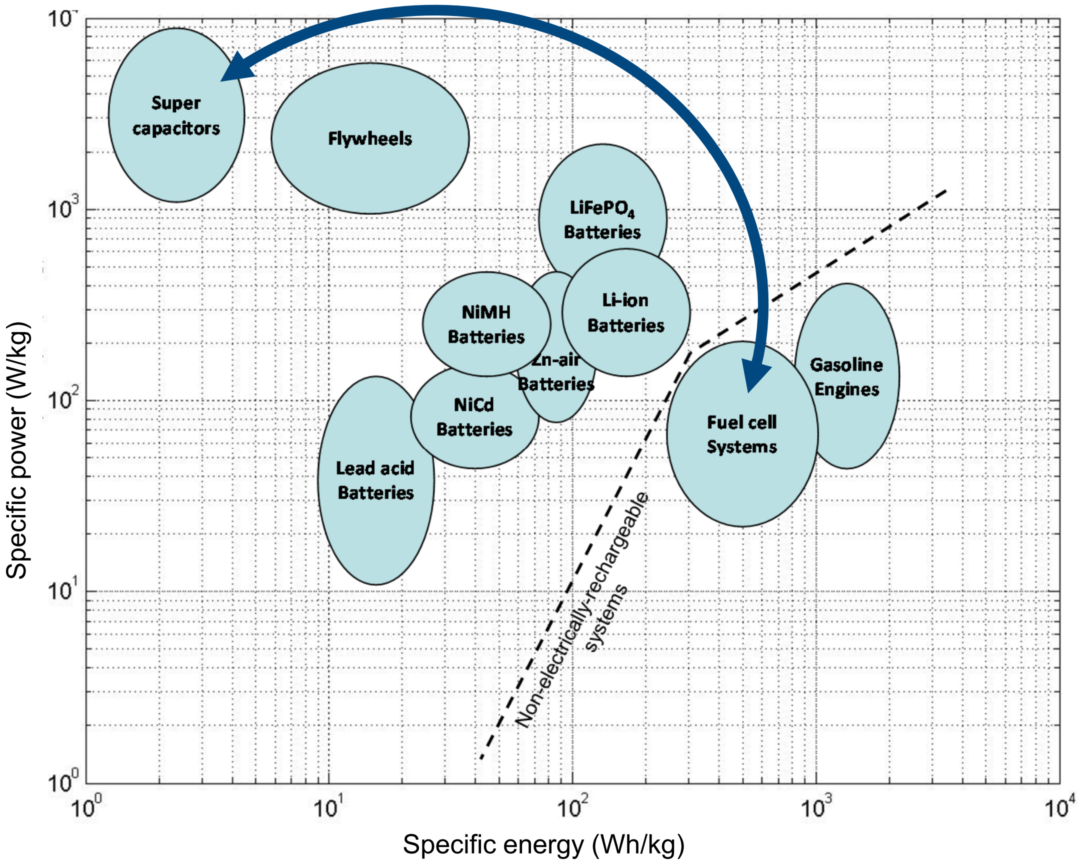
PEMFC Systems

– Whole PEMFC System

- **The need of electrical hybridization…**
  - FC = non electrical rechargeable system
  - FC = no possibility of recovering braking energy

➔ Ragone plot…

➔ Hybridization with supercapacitors / flywheels / power batteries?

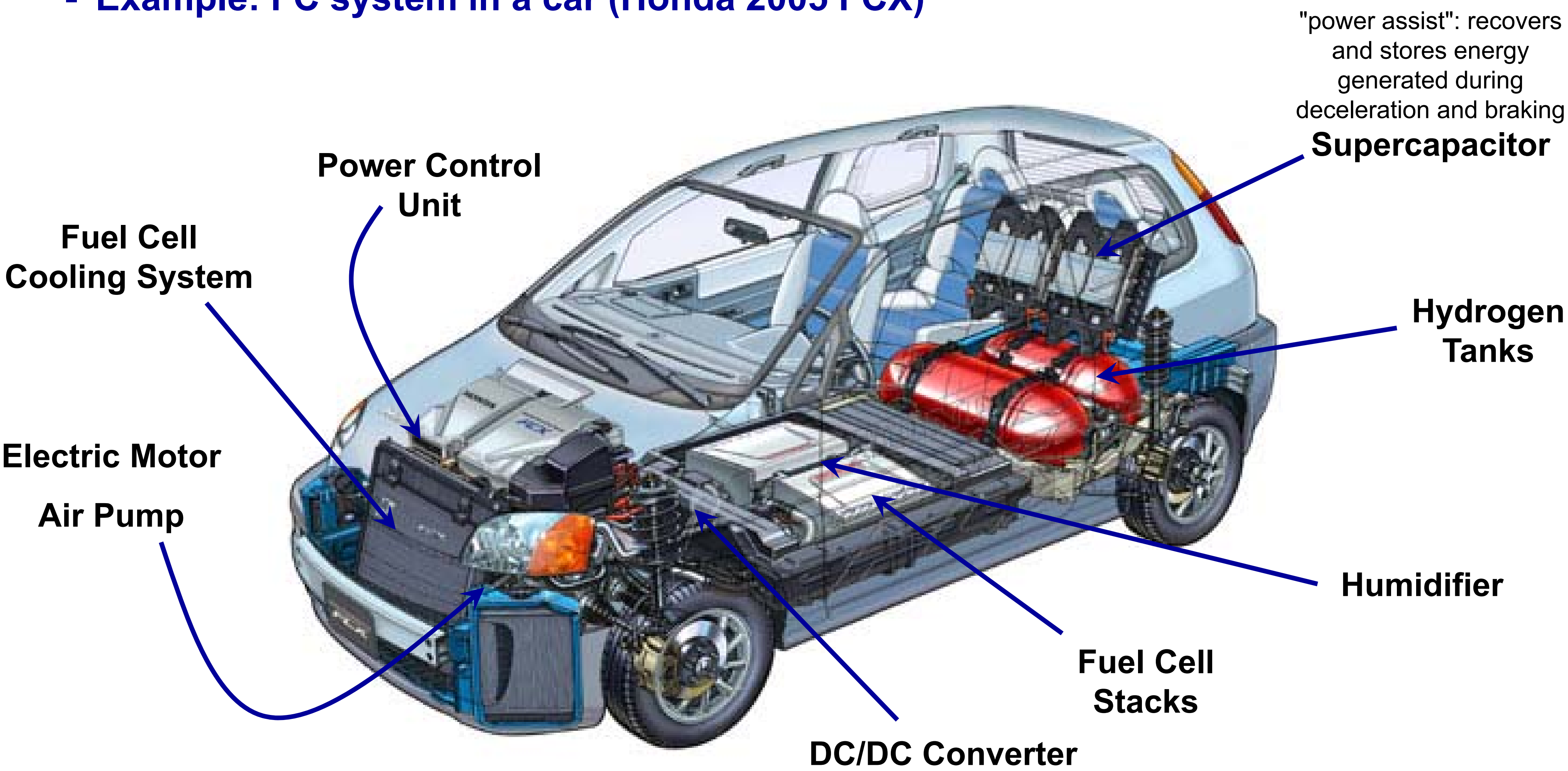


MC.Péra, D.Hissel, H.Gualous, Ch.Turpin, "Electrochemical components", Wiley, 2013.

PEMFC Systems

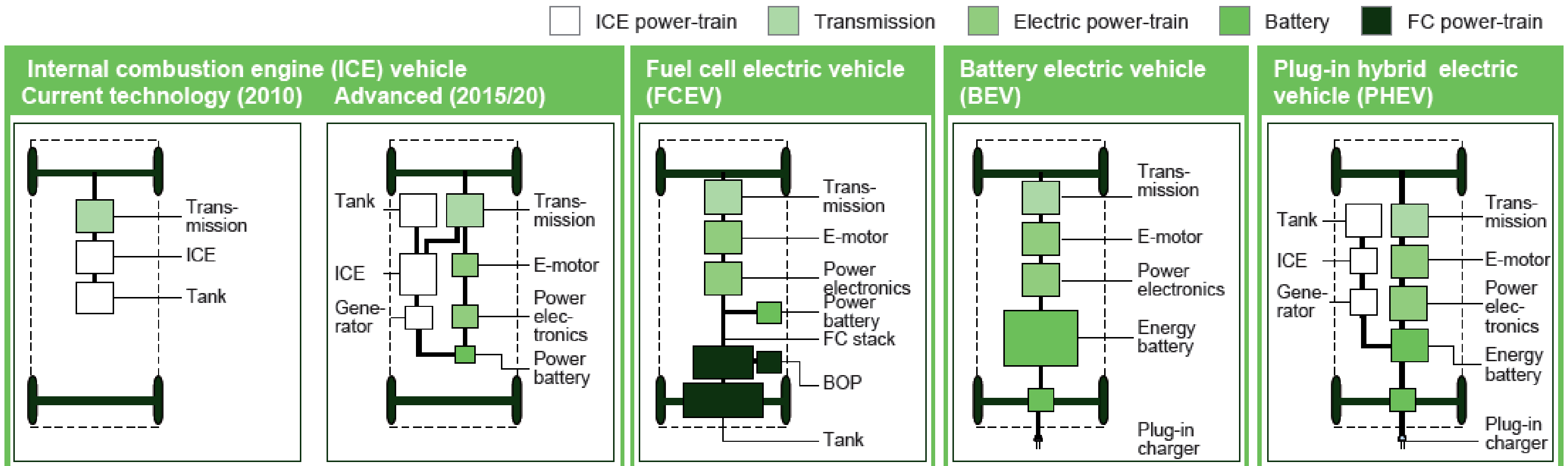
– Whole PEMFC System

- Example: FC system in a car (Honda 2005 FCX)



PEMFC Systems

– Interest for PEMFC systems in vehicles…



Internal combustion engine (ICE) vehicle – Current technology (2010)

- **Conventional** internal combustion engine
- **No dependency** on electric infrastructure
- **High fuel consumption** and exhaust emissions
- **High range**: typically 800-1200 km

Internal combustion engine (ICE) vehicle – Advanced (2015/20)

- **Parallel** hybrid configuration of electric and ICE drive; also known as hybrid electric vehicle (HEV)
- **ICE is primary mover** of the vehicle with support from small electric motor
- **Small battery** charged by the ICE
- Fully electric driving only at **low speed** for **smaller distances** (<5 km)
- **Better fuel economy** than conventional ICE

Fuel cell electric vehicle (FCEV)

- **Series** configuration of fuel cell system and electric drive
- **Fuel cell stack** based on PEM technology
- Hydrogen tank pressure typically 350 or 700 bar
- **Medium range**: typically 400-600 km

Battery electric vehicle (BEV)

- **Purely electric** drive
- Large battery capacity, Li-ion technology
- Only charging of battery **from the grid** while stationary[1]
- **Short range**: typically 150-250 km (based on battery weight of 70-180 kg[2])

Plug-in hybrid electric vehicle (PHEV)

- **Series hybrid** configuration of electric and ICE drive[3]
- **Smaller battery capacity** than BEV, (Li-ion)
- Vehicle can be **plugged-in** to charge from the grid
- **Small ICE**-based generator for larger range ('range extender')
- **Short range**: typically 40-60 km) electric driving. (based on battery weight of 20-80 kg[2])

1 Exchange of battery pack is possible, but not considered in this study
2 2020 values averaged over A/B, C/D and J segments – a ~50% decrease over 2010. Although considerable cost improvements in battery technology are considered in the study, it is not expected to achieve significantly lower specific volumes or weights beyond 2020
3 Other configurations are possible
SOURCE: Study analysis

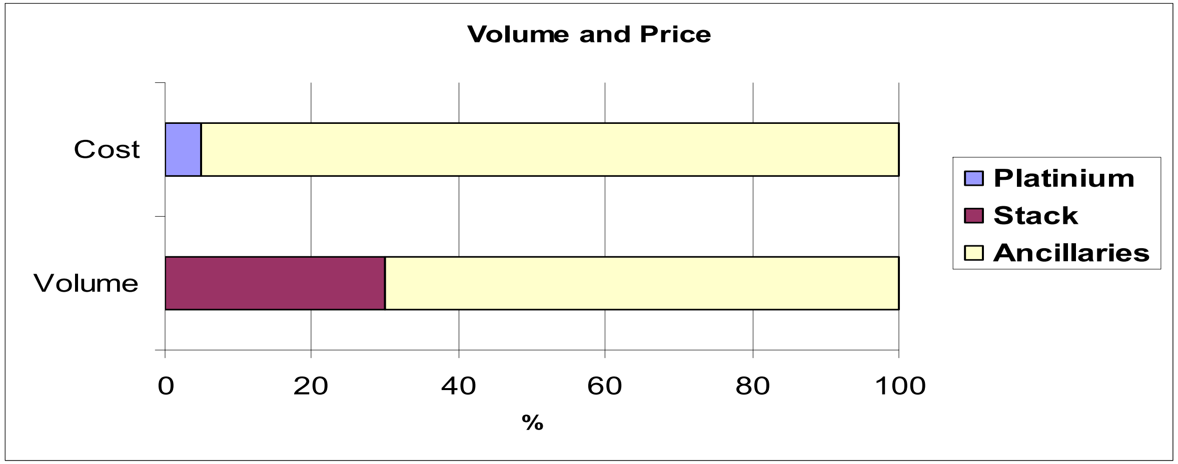
"Portfolio for powertrains in Europe : a fact-based analysis", McKinsey, 2013.

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

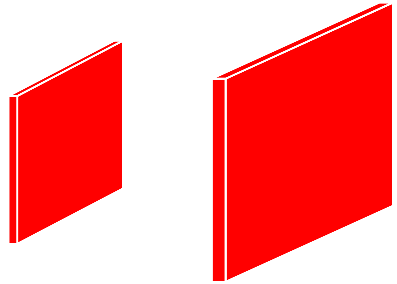
- **Volume and prize**
  - Fuel cell stack volume ≈ 30% of the fuel cell system volume (70% is linked to ancillaries)
  - Fuel cell stack price ≈ ancillaries' price
  - Platinum price (within catalyst) ≈ only about 5% of the price of a whole PEMFC power generator



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

PHM of Fuel Cell Systems – A state of the art

Part 3 – Behavior and losses of PEMFC

Behavior and losses of PEMFC

– PEMFC as a complex system

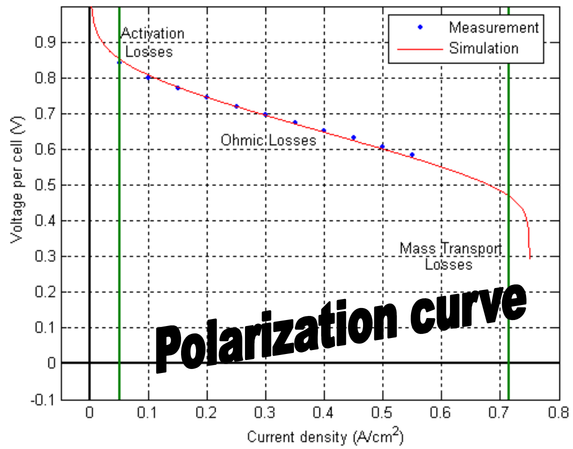
- **Building behaviors models would be of prime importance for design, control, diagnostics, optimization… BUT**
- **FC = highly multiphysics and multiscale systems**
  - Multiphysics = electrical, mechanical, thermal engineering, electrochemistry…
  - Multiscale = from the µm to the m
  - Multiscale = 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".

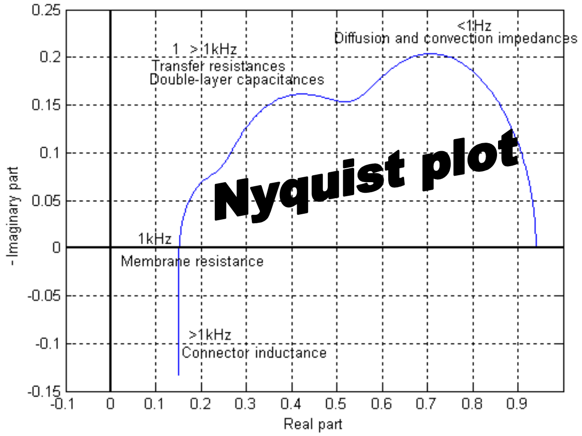
Behavior and losses of PEMFC

– 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)



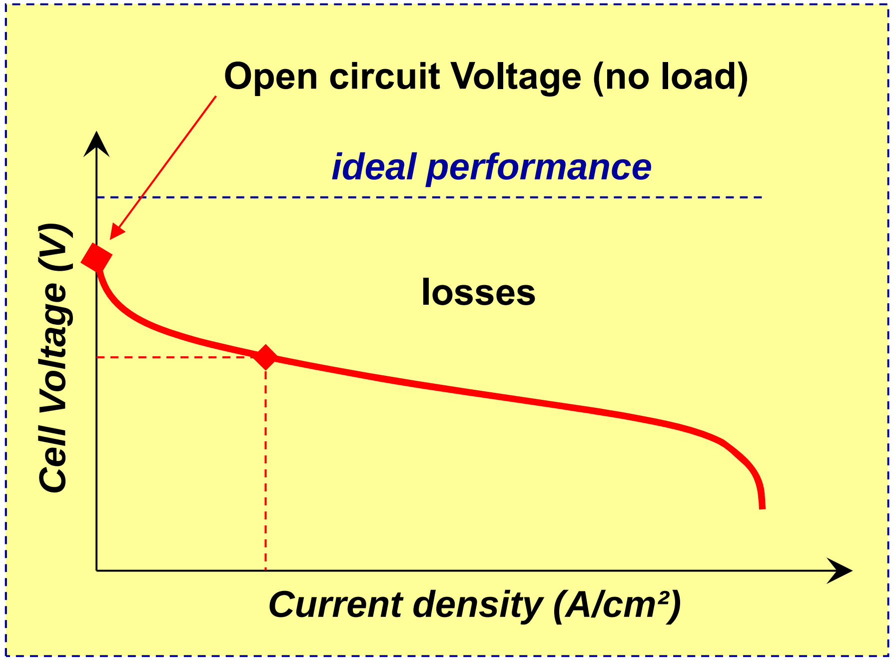
Behavior and losses of PEMFC

– **Polarization curve**

- **Performed at stationary operational conditions**
  - Shows the DC voltage delivered at the cell terminals as a function of the current density (current per unit area of membrane) being drawn by the external load.

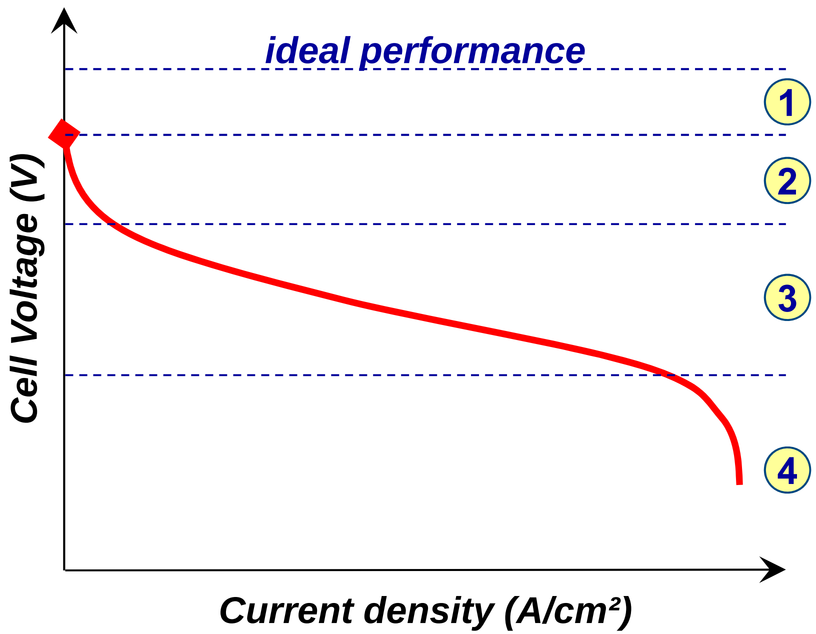
- **Polarization?**
  - In reality fuel cells achieve their highest output voltage at open circuit (no load) conditions and the voltage drops off with increasing current draw.

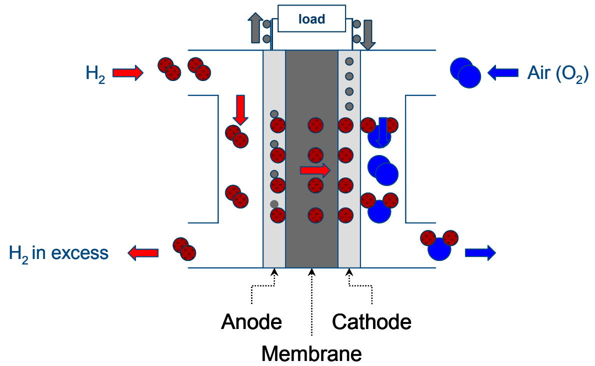
- **Depicts the performance of a fuel cell**
  - Measure of the energy conversion efficiency of a fuel cell
    - Ratio of the actual voltage at a given current density to the maximum voltage obtained under no load (open circuit) conditions.



Behavior and losses of PEMFC

– Losses depicted by the polarization curve





1. Fuel Crossover Losses
Losses that result from the waste of fuel passing through the electrolyte and electron conduction through the electrolyte.

2. Electrochemical aspect: Activation Losses
These losses are caused by the slowness of the reaction taking place on the surface of the electrodes. A proportion of the voltage generated is lost in driving the chemical reaction that transfers the electrons.

3. Electrical aspect: Ohmic Losses
The voltage drop due to the resistance to the flow of electrons through the material of the electrodes. This loss varies linearly with current density.

4. Fluidic aspect: Concentration Losses (Mass transport)
Losses that result from the change in concentration of the reactants at the surface of the electrodes as the fuel is used.

5. Thermal aspect
Coupled with all previous phenomena

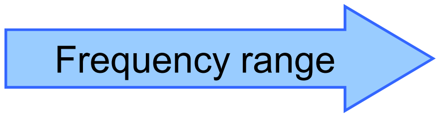
Behavior and losses of PEMFC

– EIS: Electrochemical Impedance Spectroscopy

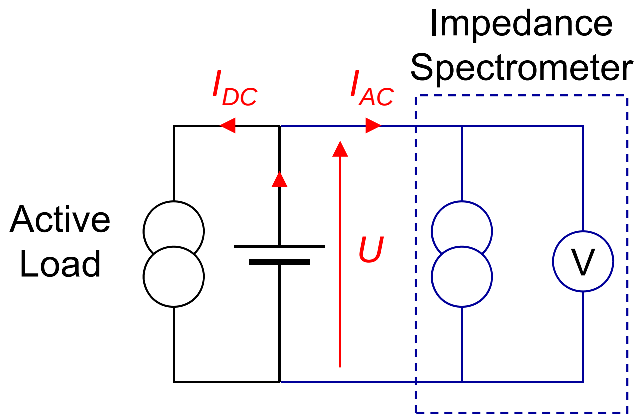
▪ Principle and aim

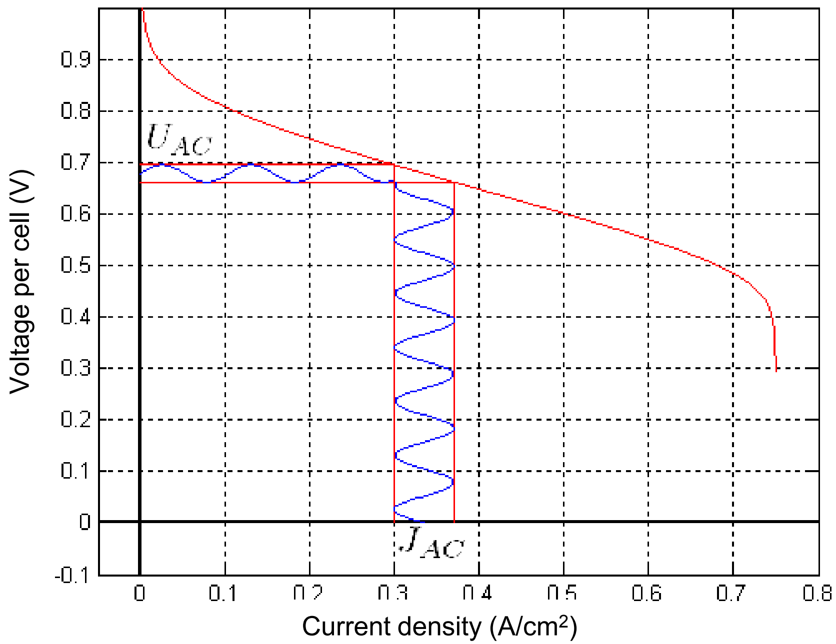
- While polarization curve gives information about the static behavior of the FC, EIS is used in order to obtain relevant information about its dynamical behavior
  - – FC is operated at its standard (static) operating point
  - – Additional small amplitude signals are applied
  - ⇨ Measures the impedance of a system over a range of frequencies

- DC components : I_{DC}, U_{DC}
- AC sinus components : I_{AC}, U_{AC}
⇨ Computation of the electrochemical impedance
$Z_{PEM}(p)=U_{AC}(p) / J_{AC}(p)$



Impedance spectrum



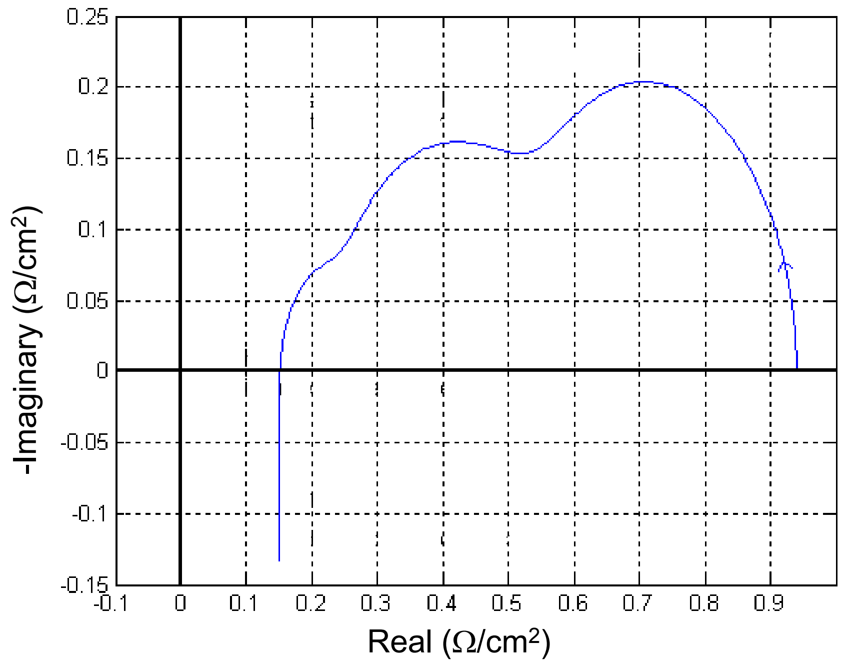


Behavior and losses of PEMFC

– Spectrum in a Nyquist plan

▪ Principle and aim

- Polar plot of the frequency response function of a linear system
  - Plot of the transfer function $G(j\omega)$
    - Real part of the transfer function on X axis
    - Imaginary part on Y axis
  - Depends upon frequency (frequency is a parameter)

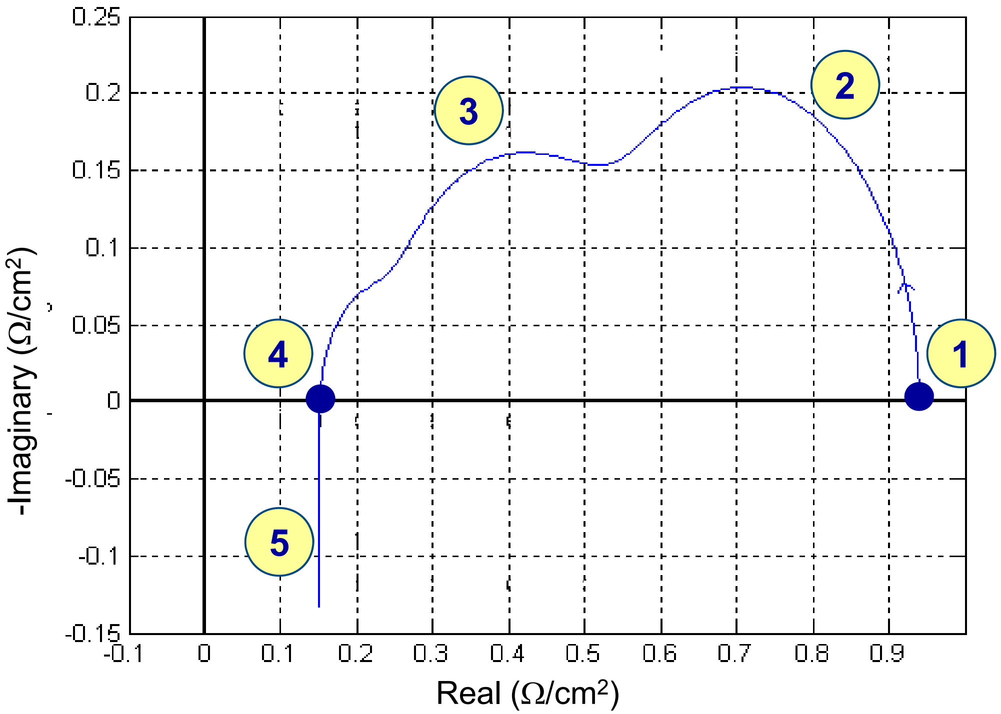


- Enables characterizing the stack in dynamical conditions
  - Properties of energy storage: capacitor
  - Dissipation properties: resistor

- Useful for ageing analysis…

Behavior and losses of PEMFC

– Behavior depicted by the Nyquist plot



1. Polarization resistance

Global sum of the resistances linked with physical internal phenomena

⇨ A higher polarization resistance leads to a lower stack voltage

2. First capacitive arc (low frequencies: 0.2 – 130 Hz)

Capacitive behavior due to mass transport (ions)

⇨ A larger arc diameter means that the diffusion of the species occurs with some problems (insufficient gas supply, accumulation of water in the GDL – flooding)

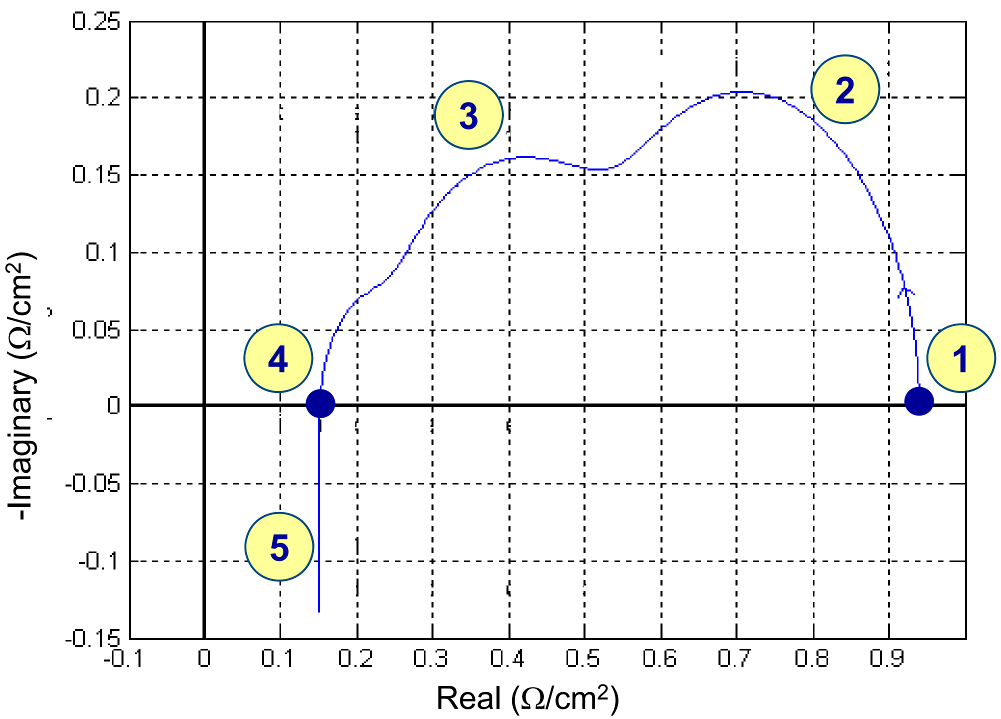
3. Second capacitive arc (medium frequencies: 130 Hz – 4 kHz)

Corresponds mainly to charge transfer phenomena (electrons and protons)

⇨ A larger arc suggests a difficult transfer of the electrical charges (accumulation of charges at the electrode/electrolyte interface)

Behavior and losses of PEMFC

– **Behavior depicted by the Nyquist plot**



4. Internal resistance: membrane (~ 1 kHz)
An insufficient humidification of the membrane (drying phenomenon) leads to an increasing internal resistance
⇨ A higher internal resistance brings worse FC performance.

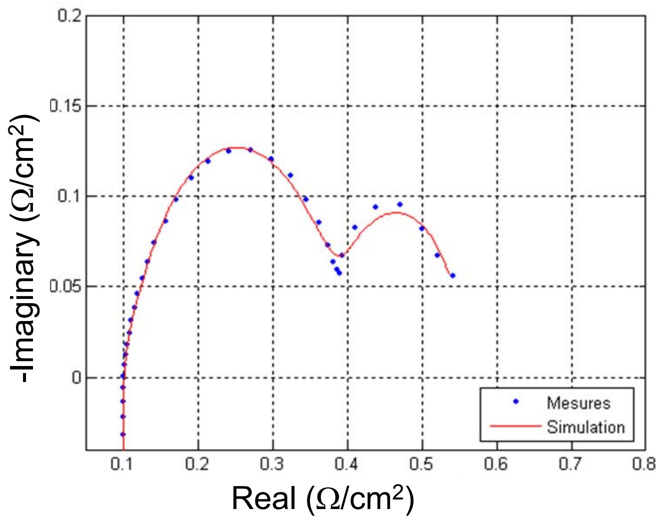
5. HF inductive part (high frequencies: 4 – 130 kHz)
Can be associated with the pseudo-inductance part due to all connections of the complete FC stack

Behavior and losses of PEMFC

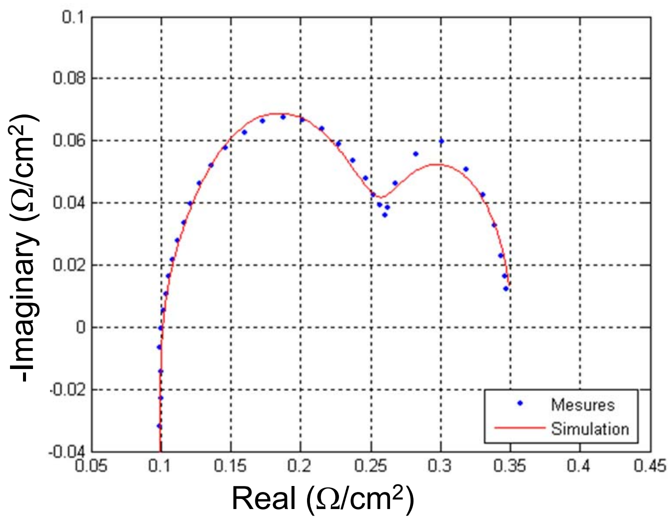
– **Nyquist plot – example**

- **5 cell-stack**
  - Reactant gas: pure H2, air ; Ano/Cath pressures: 1600 mbar ; Gas flow: FSA=2, FSC=2
  - Relative humidity: 100% ; Temperature : 70°C
  - 3 loads conditions

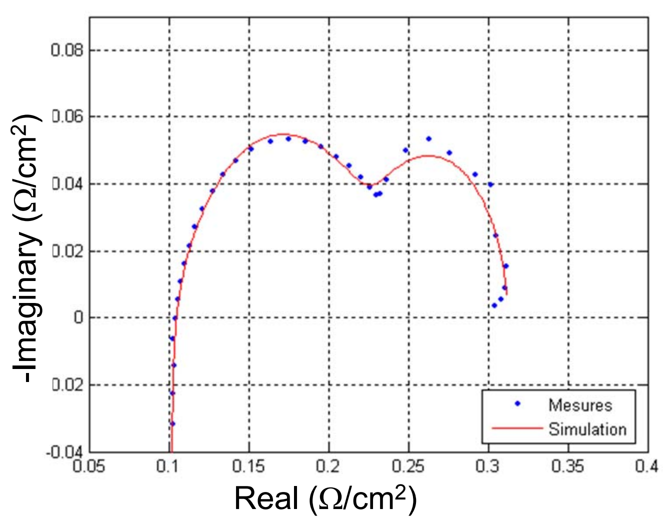
I_{DC} = 0.2 A/cm²



I_{DC} = 0.4 A/cm²



I_{DC} = 0.7 A/cm²

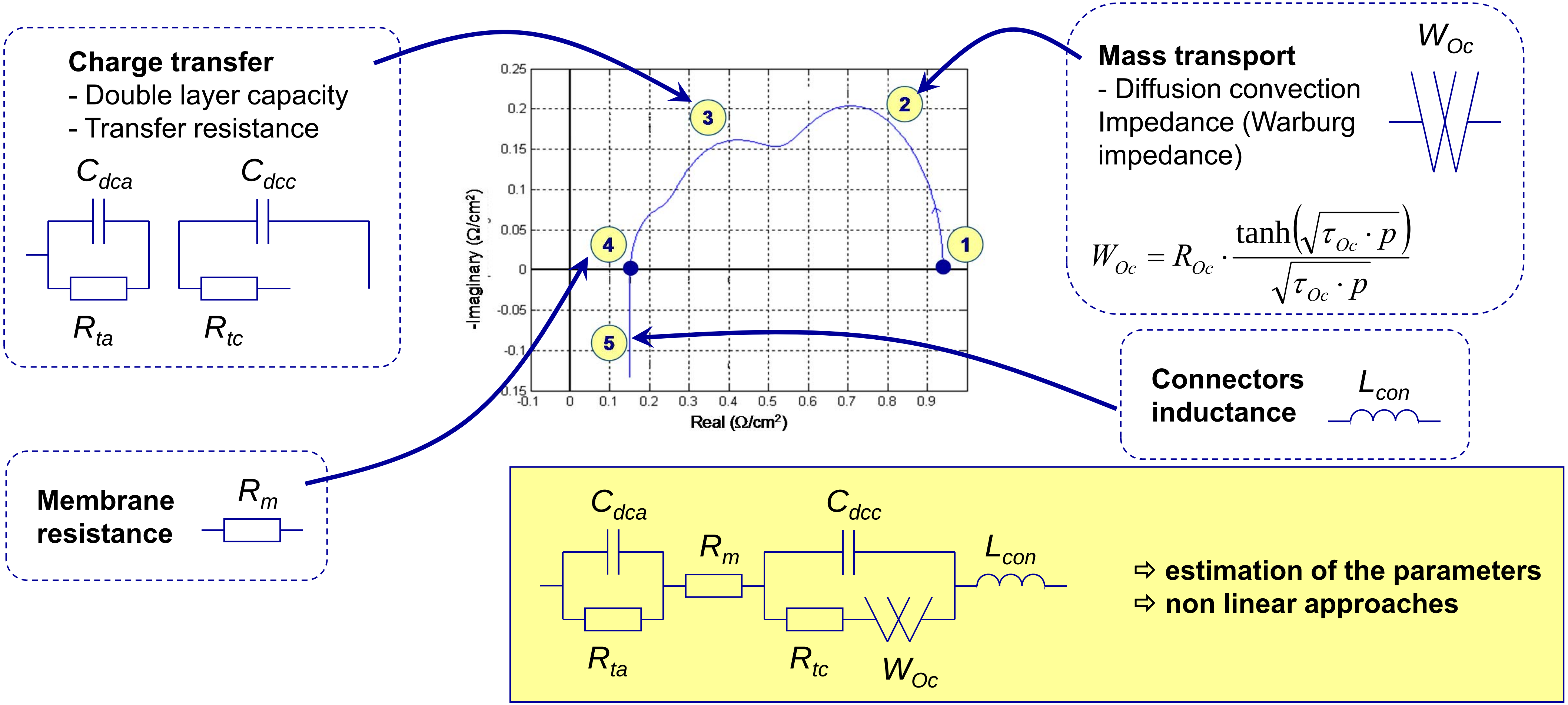


⇨ **Results not only depends on operating conditions (fluidic and thermal), but also on current density**

Behavior and losses of PEMFC

– Towards modeling

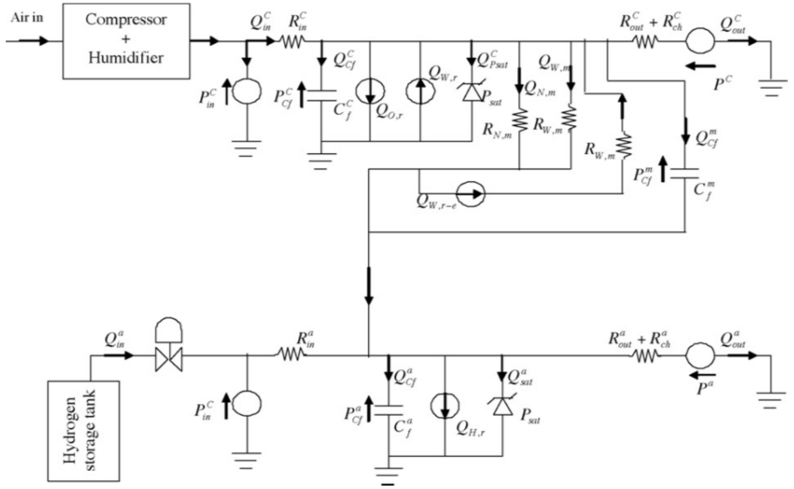
- **Electrical behavior - however insufficient / all normal-faulty possible modes…**



Behavior and losses of PEMFC

– Other modeling approaches

Electrical equivalence



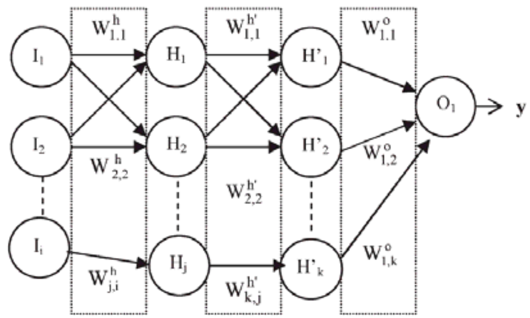
M.Becherif et al., Journal of Power Sources, 2010.

State space model

$$
\begin{cases}
\dfrac{dP}{dt} = RTV\left(2UP + \begin{pmatrix}\bar{P}^c - \frac{m^c_{in}}{\sigma^c_{in}} \\ \bar{P}^a - \frac{m^a_{in}}{\sigma^a_{in}}\end{pmatrix}^T UX + IB + DP + CP + P_{sat}\begin{bmatrix}C_{ev} \\ C_{ev}\end{bmatrix}\right) \\
\dfrac{dV_{H_2O,l}}{dt} = 1.8 \times 10^{-5}\left(c_{ev}\left(C_1 P - P_{sat}\right) - \dfrac{V_{H_2O,l}}{V^c}\sigma^c_{out}\dfrac{m^c_{in}}{\sigma^c_{in}}\left(\bar{P}^c - P_{atm}\right)\right)
\end{cases}
$$

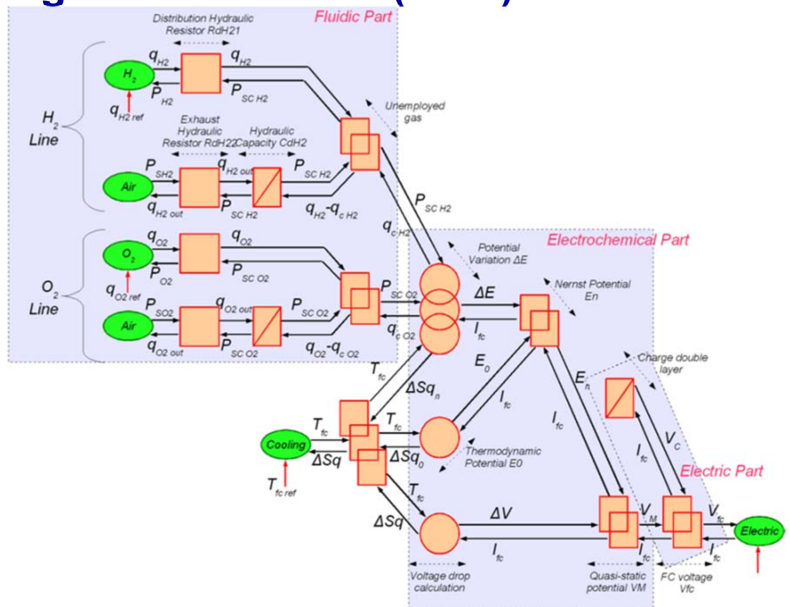
A.Hernandez et al., Fuel Cells, 2006.

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.

PHM of Fuel Cell Systems – A state of the art

Part 4 – A flavor of PHM oriented works

FC LAB
Research

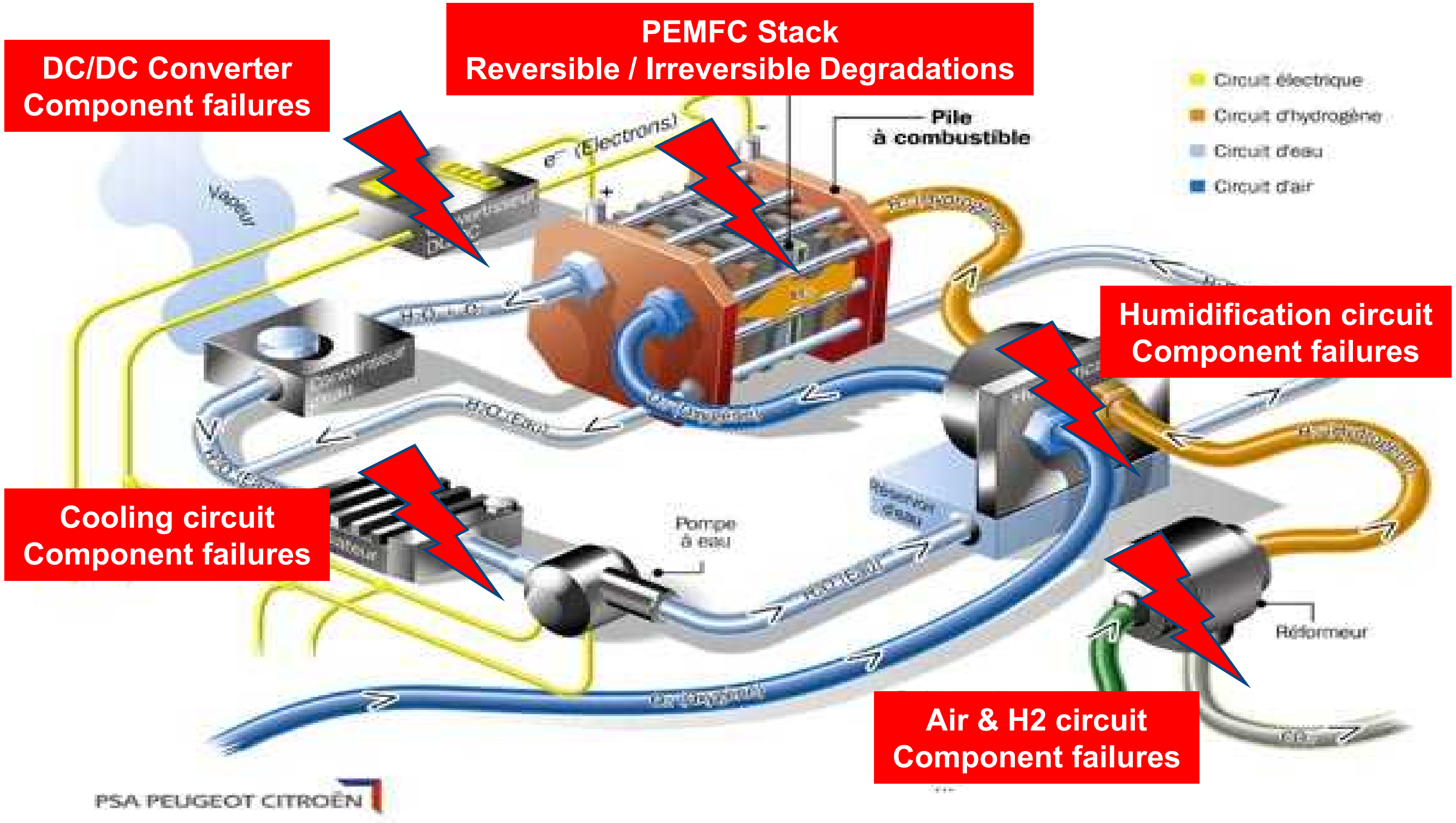
Failure mechanisms

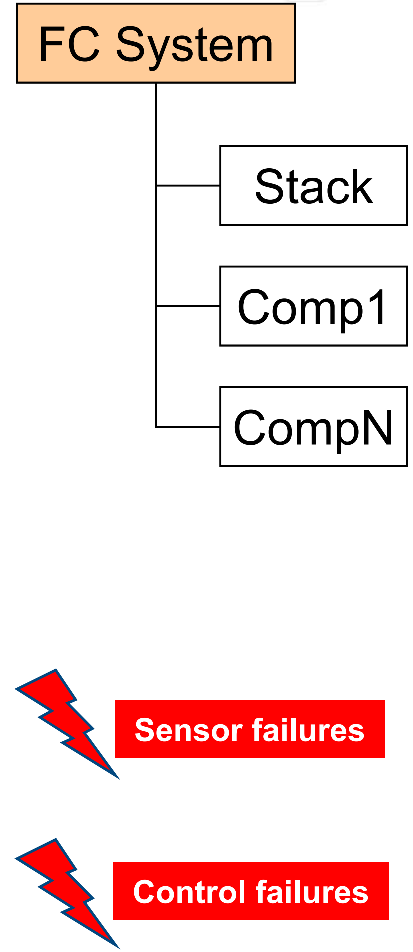
– Enhancement are required!

- **Durability of FC systems**
  - Approximately 2500 hours obtained today for PEMFC systems
  - Transport applications
    - 5000 h are required for light vehicles!
    - 30000 h are required for trucks
  - Power generation
    - 100000 h are required for rail and stationary power generators!

Failure mechanisms

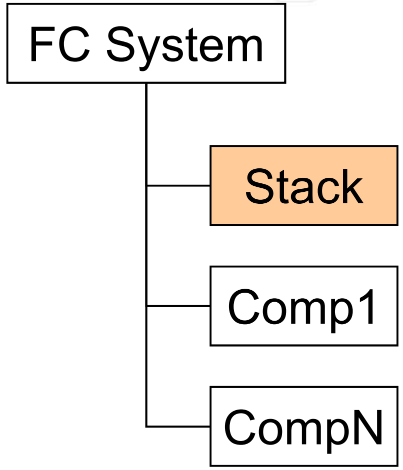
– **Degradations/failures at system's level**





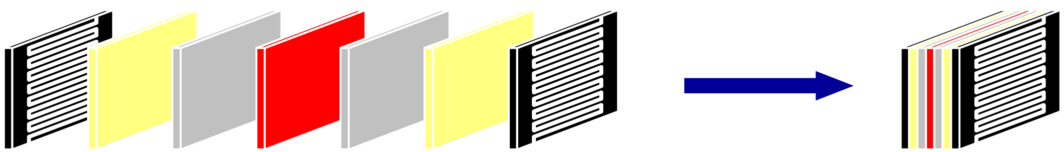
Failure mechanisms

– Degradations of the stack



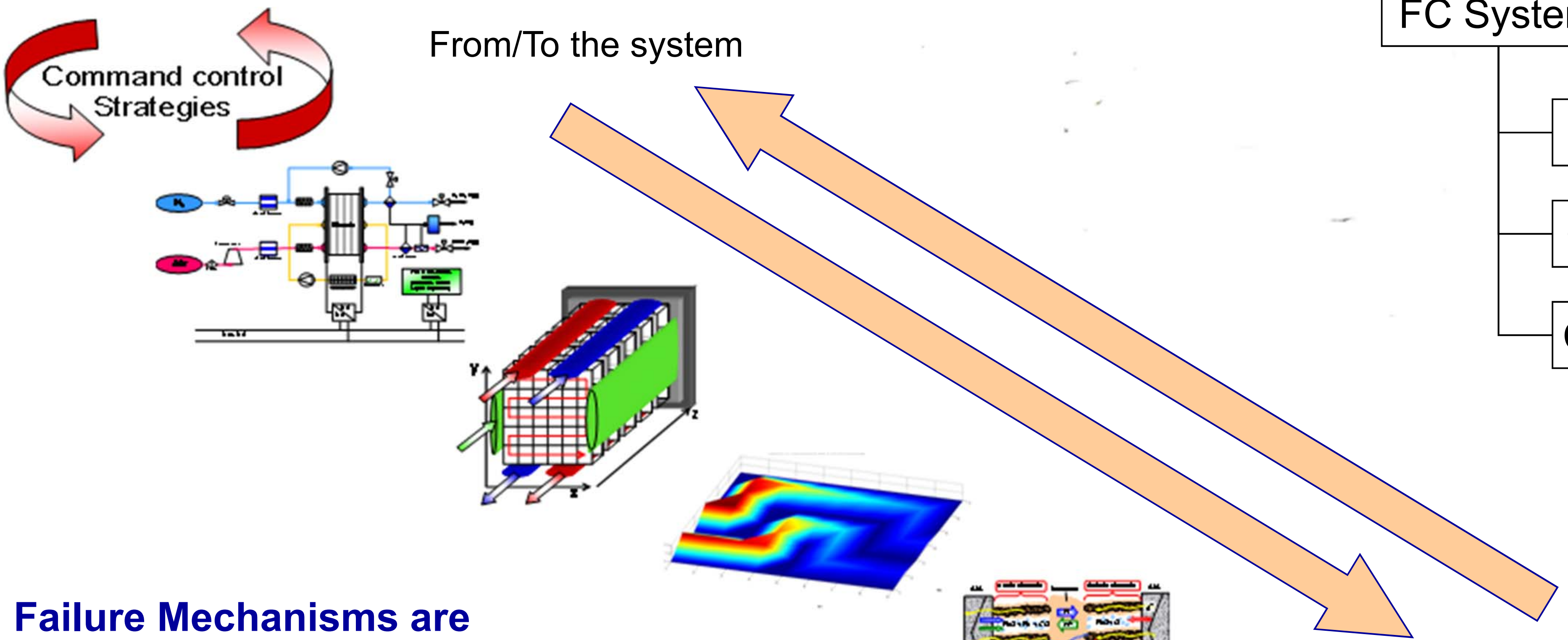
- **Taxonomy / nature of the degradation**
  - Mechanical degradation
    - – Mainly due to improper manufacturing processes (crack…)
    - ⇨ Often the cause of early failure
  - Thermal degradation
    - – Use of the cell outside the its optimal operating range (T°…)
    - ⇨ Involves changes at micro/nano 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

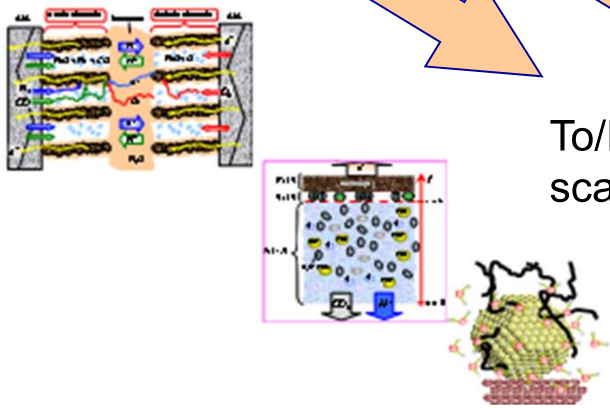


Failure mechanisms

– **Influence of the environment on the stack**



FC System
- Stack
- Comp1
- CompN



To/From the nano-scale structure

Failure Mechanisms are complex and multi-dimensional…

Failure mechanisms

– Degradation modeling?

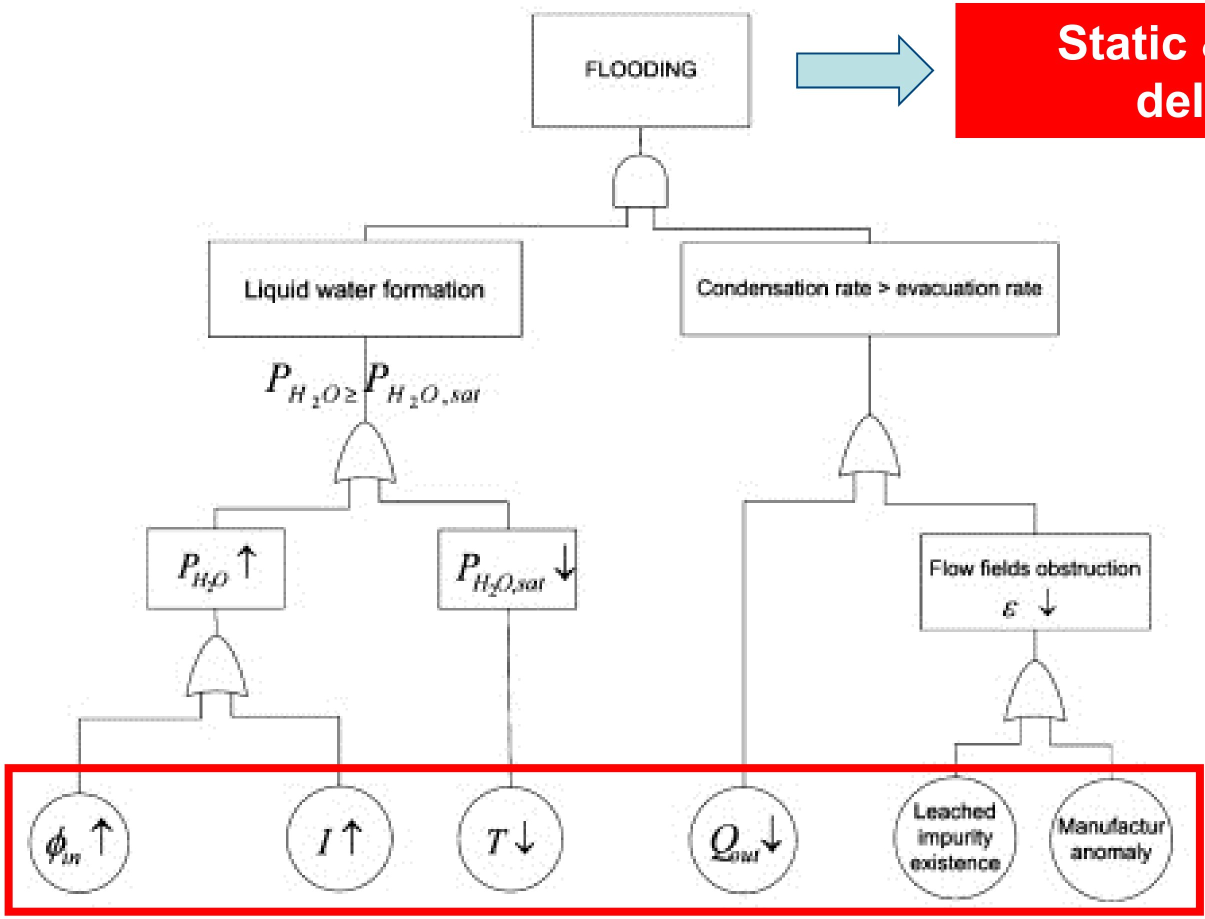
- **Parameters reducing the FC lifetime**
  - Fuel impurities (sulfur, CO for PEMFC, …)
  - Oxidant impurities (oil from the compressor, salt from environment, …)
  - Fuel and oxidant stack starvation (linked to the dynamic and the control of the system)
  - Temperature supervision (linked to the system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

– **Degradation modeling? – Fault tree analysis**

- **Example 1: water management – flooding (Steiner et al. 2008)**



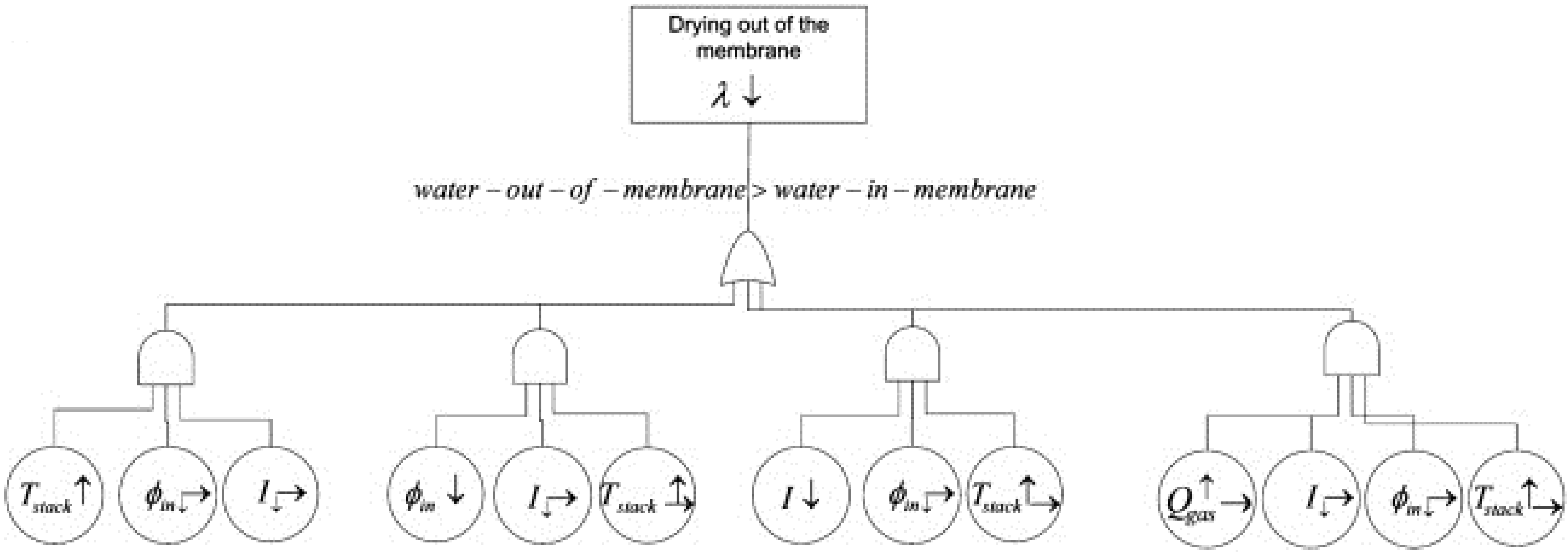
Static & dynamic evolution of delivered electrical power

Multiphysics parameters

Failure mechanisms

– **Degradation modeling? – Fault tree analysis**

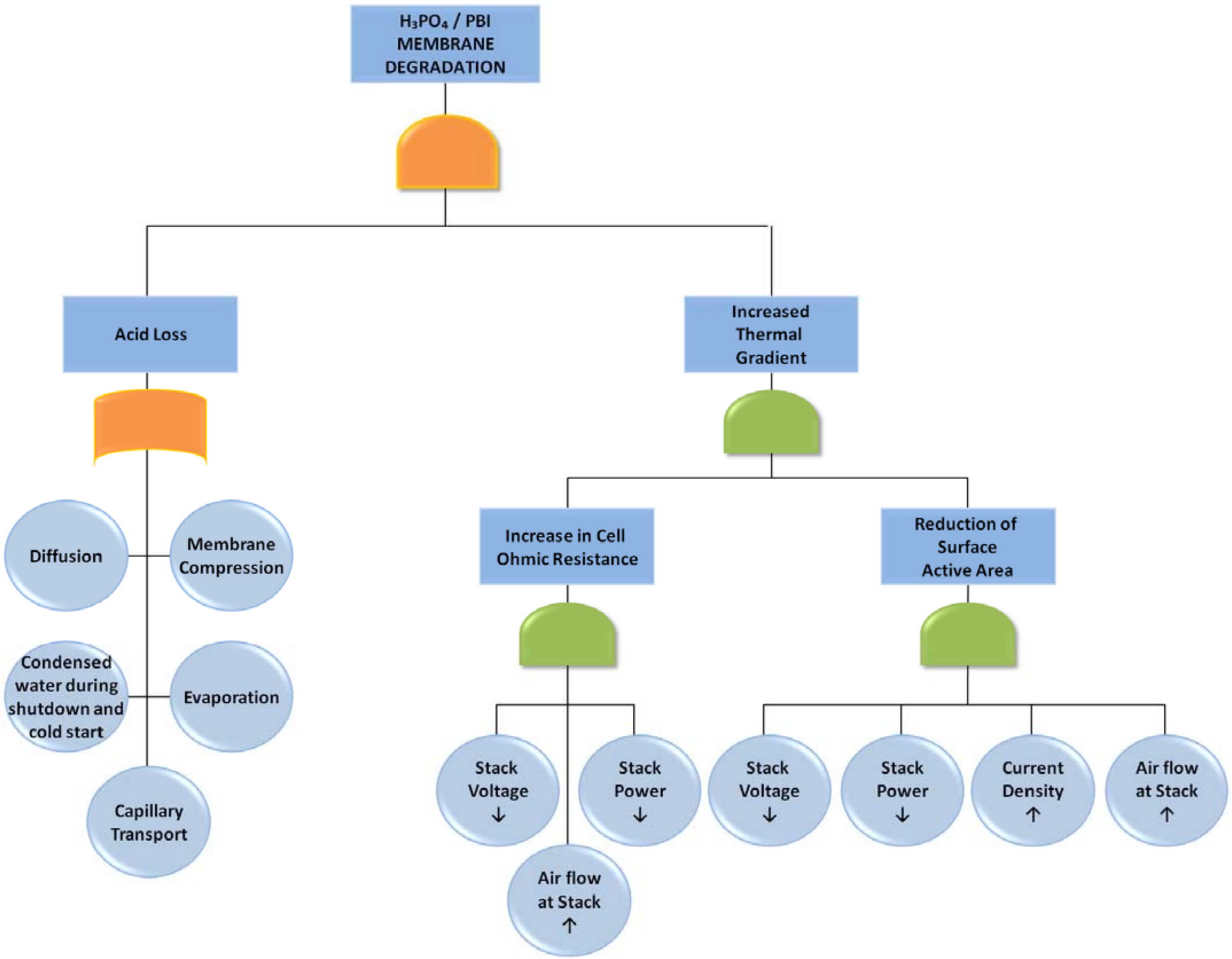
  - **Example 2: water management – drying out (Steiner et al. 2008)**



Failure mechanisms

– **Degradation modeling? – Fault tree analysis**

- **Example 3: membrane degradation (Silva-Sanchez 2011)**



Failure mechanisms

– **Data to be gathered?**

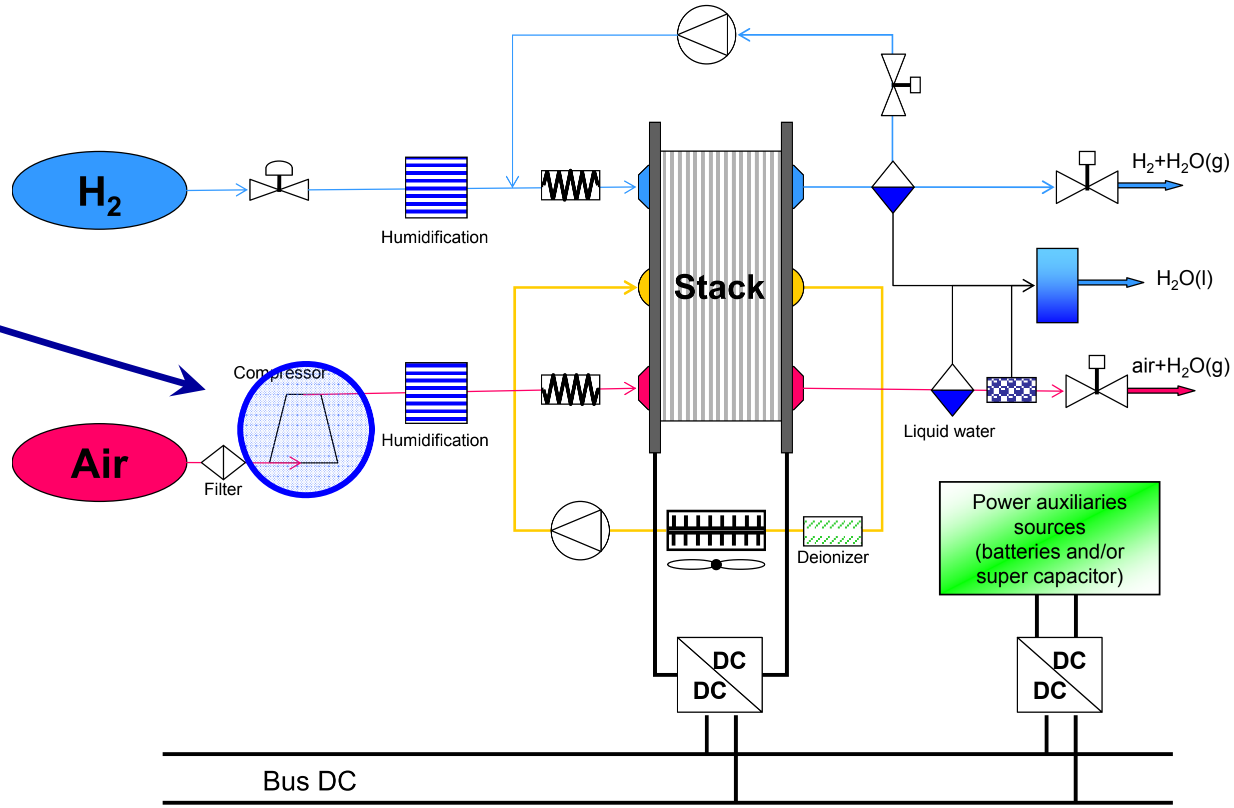
- **Real data are required to assess the health state of the system**
  - Use of a minimum number of actual sensors (linked to feasibility, cost, reliability, dynamic…)

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

Examples of interactions system / stack

– Impact of compressor failure – oxidant circuit

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

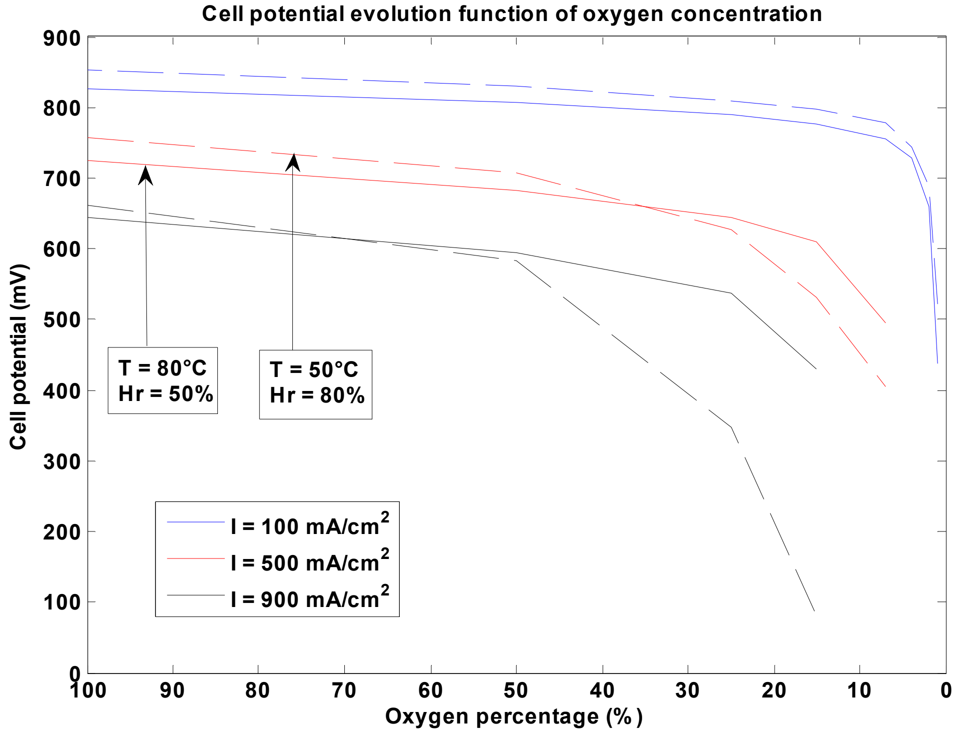


Examples of interactions system / stack

– 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

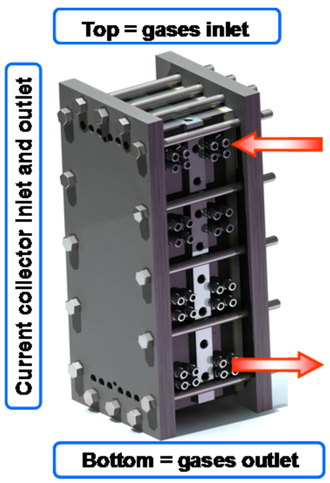
- **Performance Evaluation**
  - Whatever the operating conditions :
    – Potential collapse when oxygen concentration is very poor
    – This collapse is linked to current density
    – Air hygrometry can increase or decrease the phenomena…

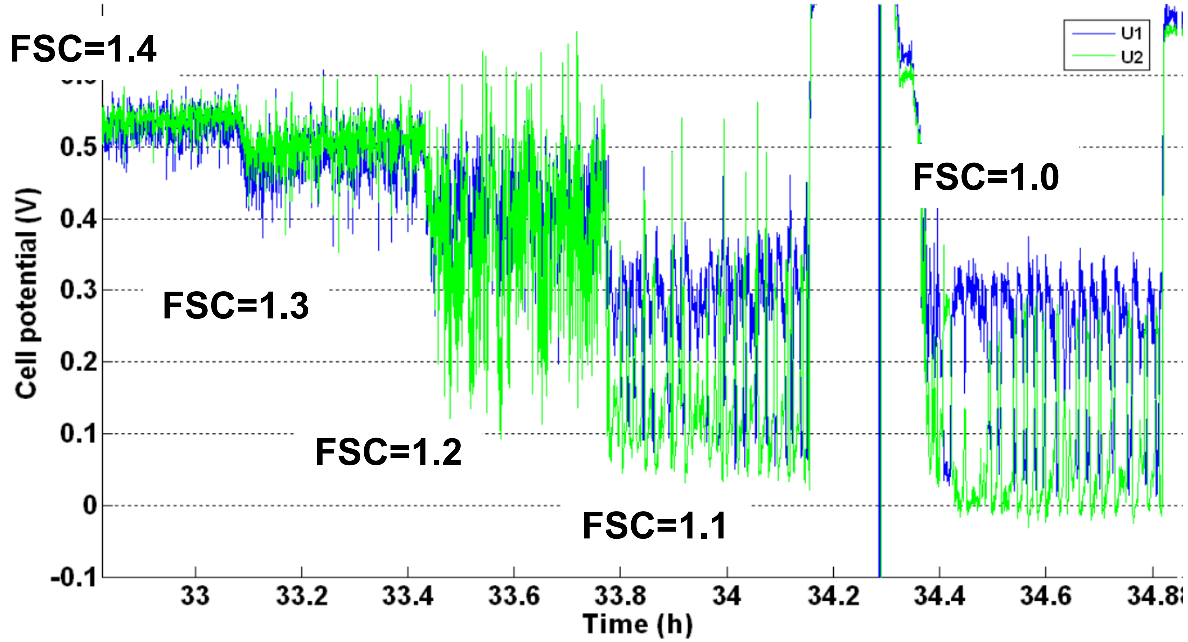


Examples of interactions system / stack

– **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

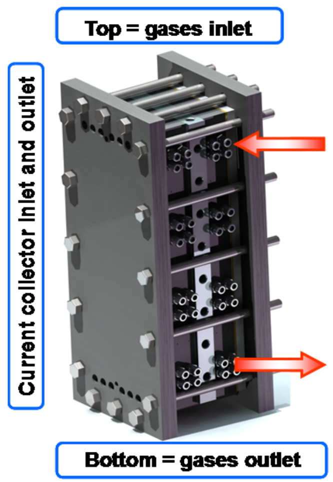


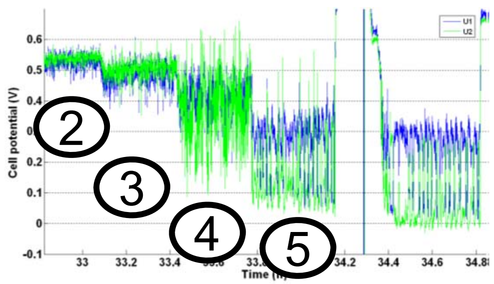


Examples of interactions system / stack

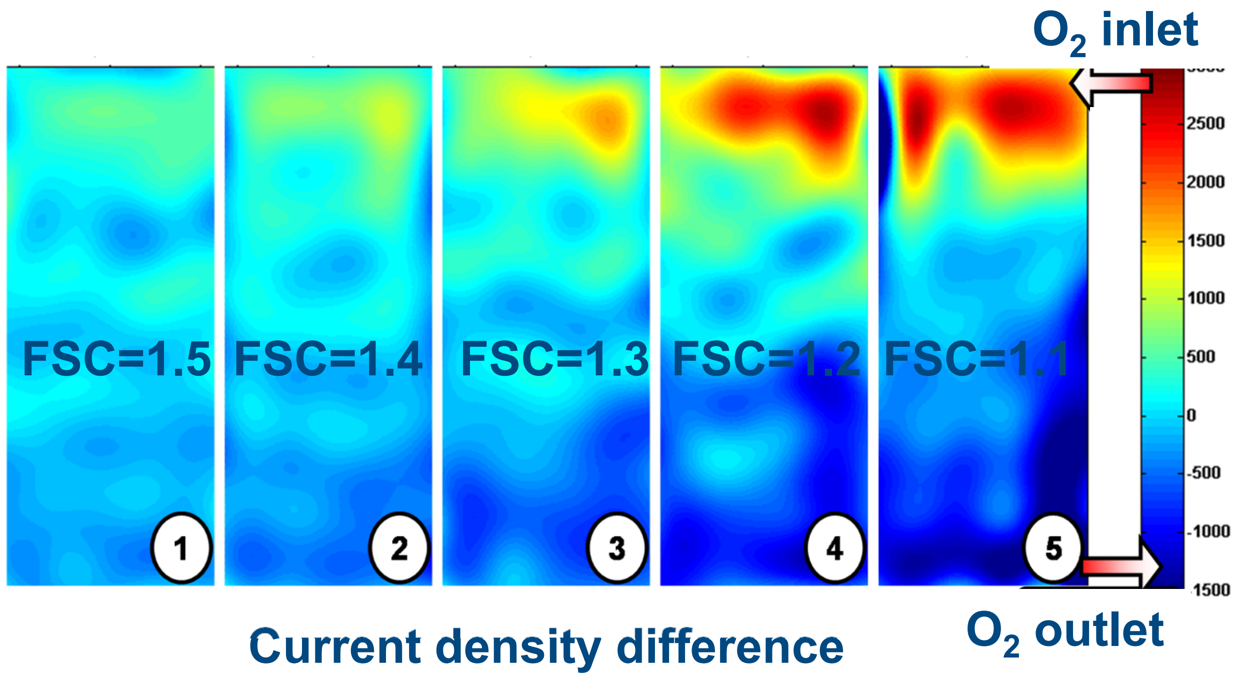
– **Impact of compressor failure – oxidant circuit**

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





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

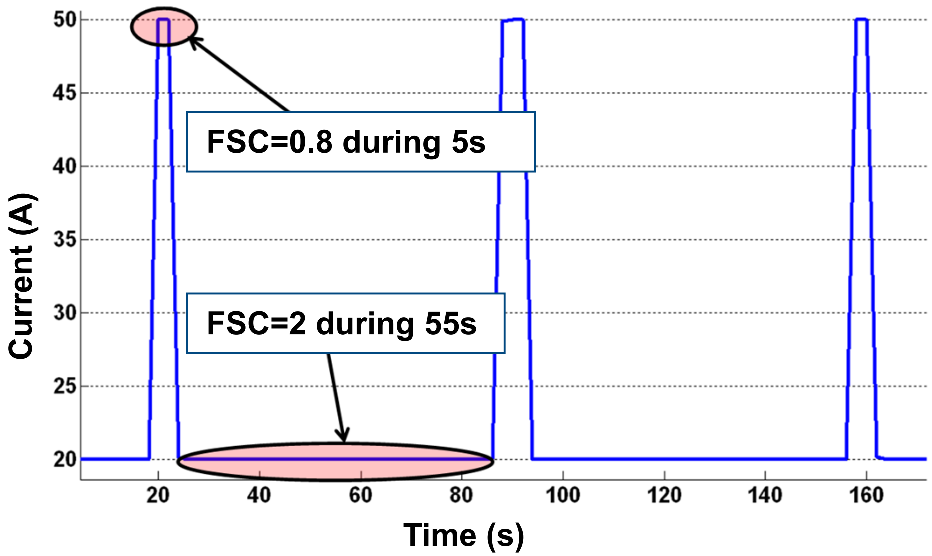


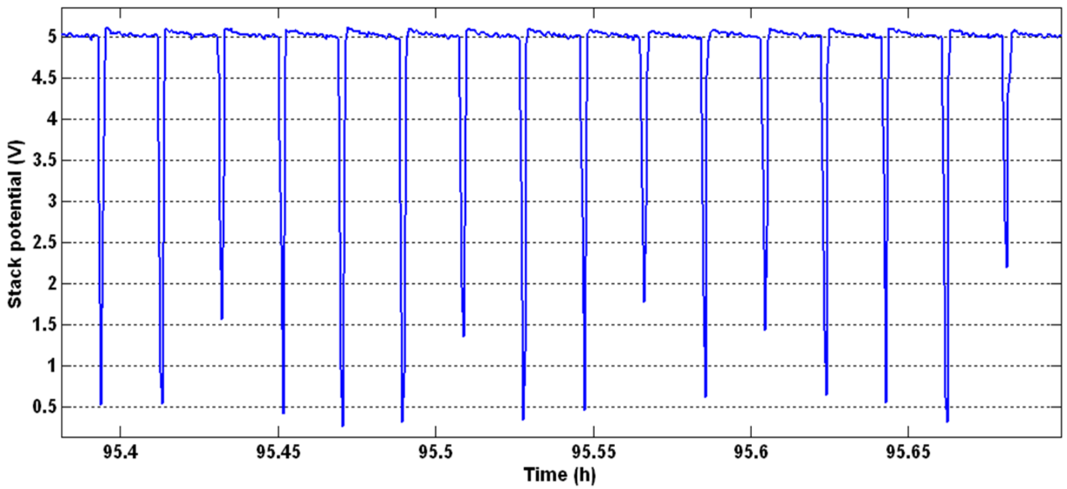
If O2 flow is poor, displacement of the current at the inlet

Examples of interactions system / stack

– Impact of compressor failure – oxidant circuit

- **Consequences on ageing (Gérard et al. 2010a)**
  - Durability test: 6-cell stack
  - Objective = 1000 h of tests

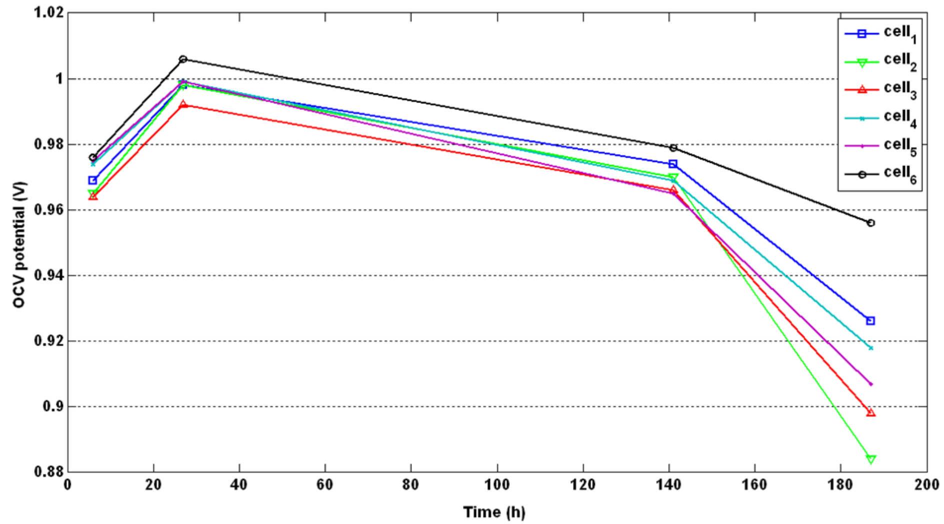


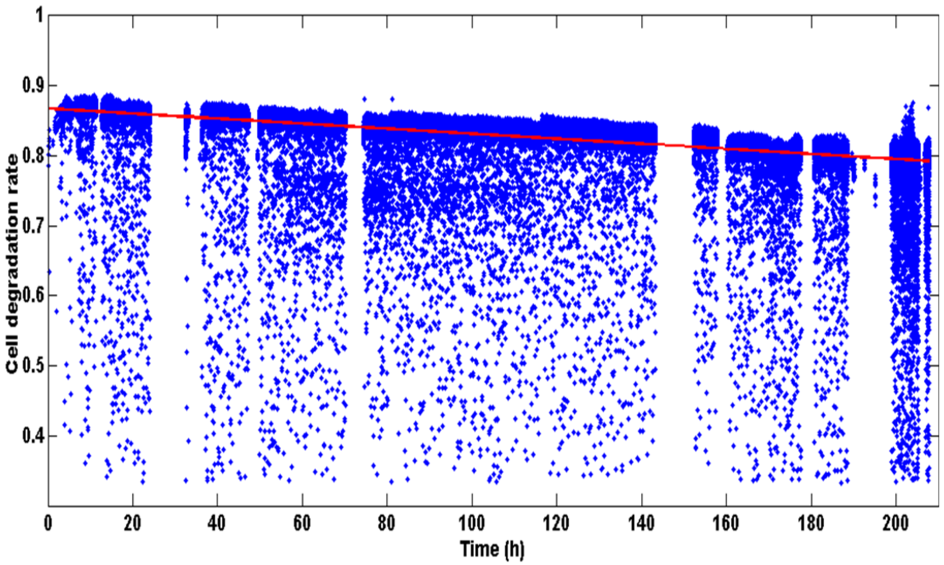


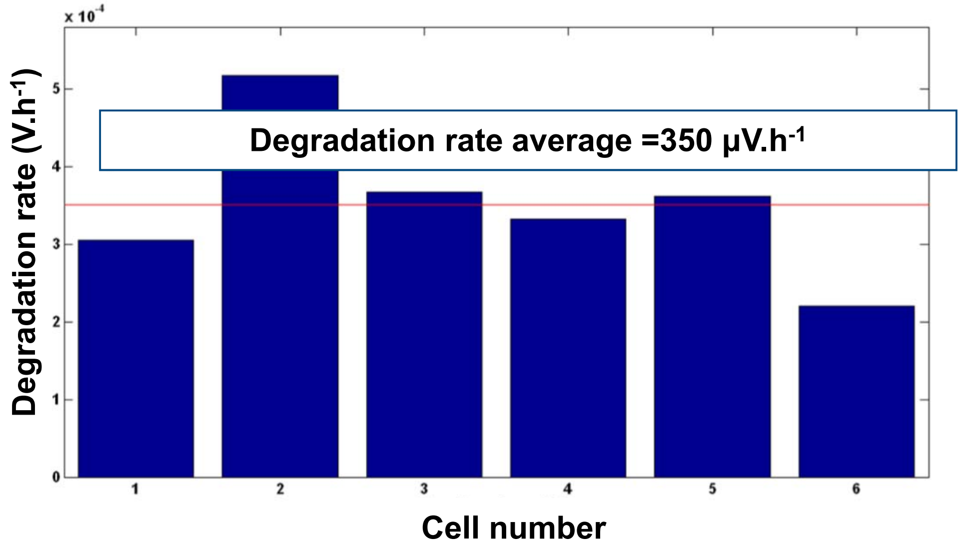
Examples of interactions system / stack

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

- **Consequences on ageing (2)**
  - 200 hours of test (instead of 1000 h)
  - Very high degradation rate
  - Accelerated OCV degradation







Examples of interactions system / stack

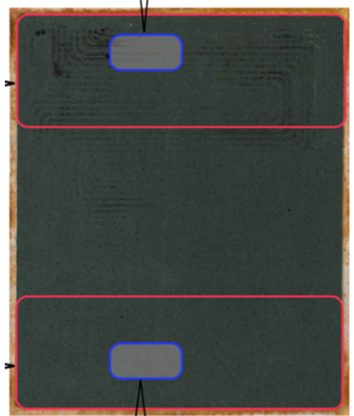
– Impact of compressor failure – oxidant circuit

▪ Consequences on ageing (3) – Post Mortem analysis

- Visual analysis
- TEM-FEG analysis

Sample 1

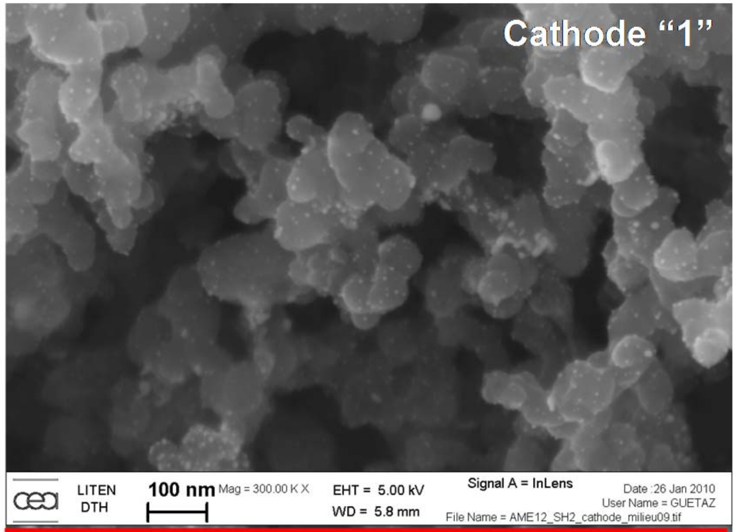
- Air Inlet
- High current density in starvation operation

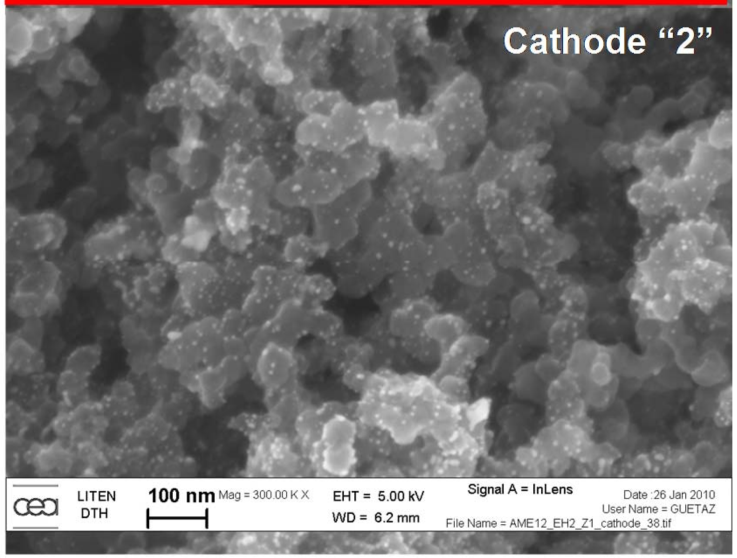


- Metallic bipolar plate corrosion
- Marks of seals caused by hot temperature
- Platinum particles in the membrane at sample “1” (air inlet, high current density in starvation operation)
- Active layer structure difference between sample “1” and sample “2”

Sample 2

- Air Outlet
- No current density in starvation operation

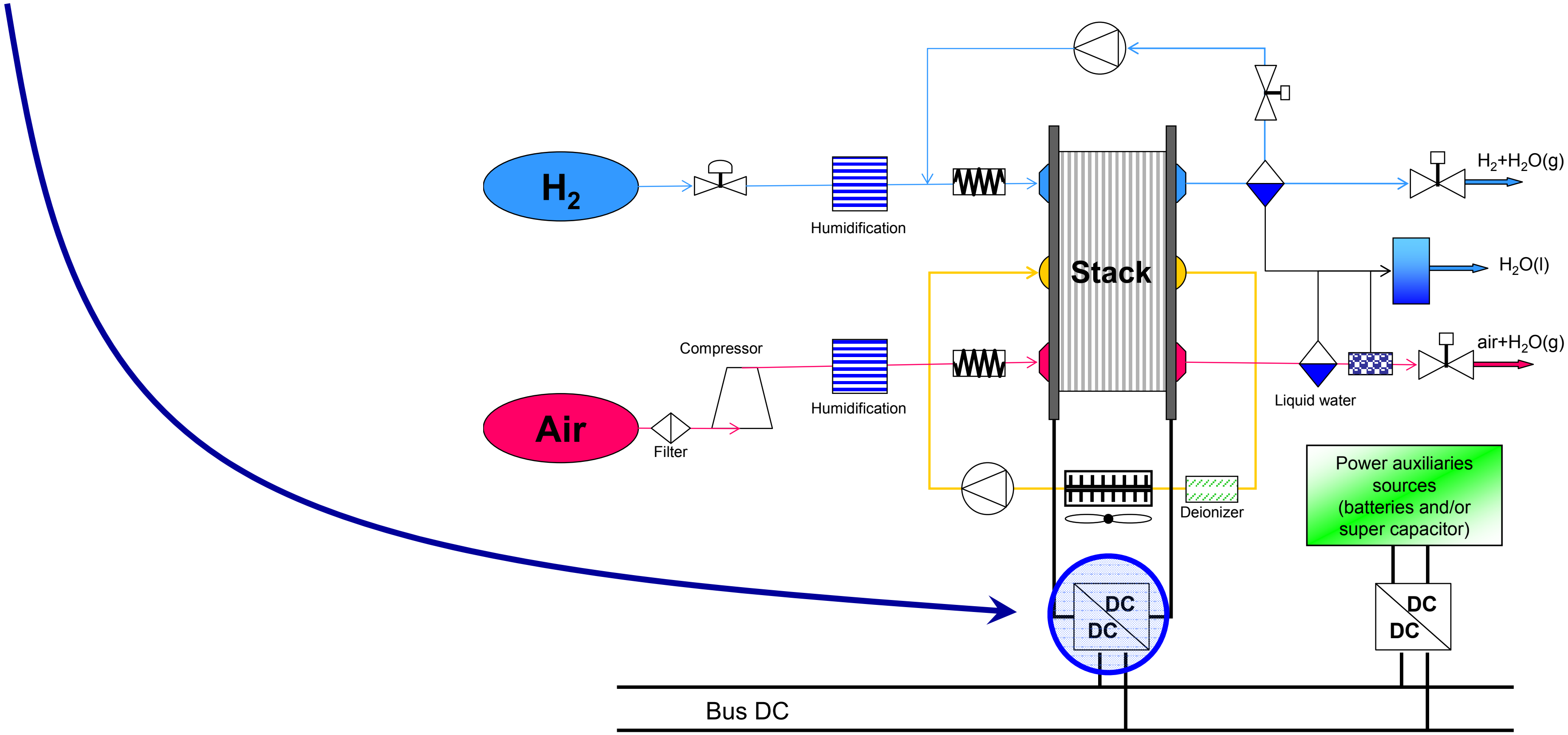




Examples of interactions system / stack

– 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)

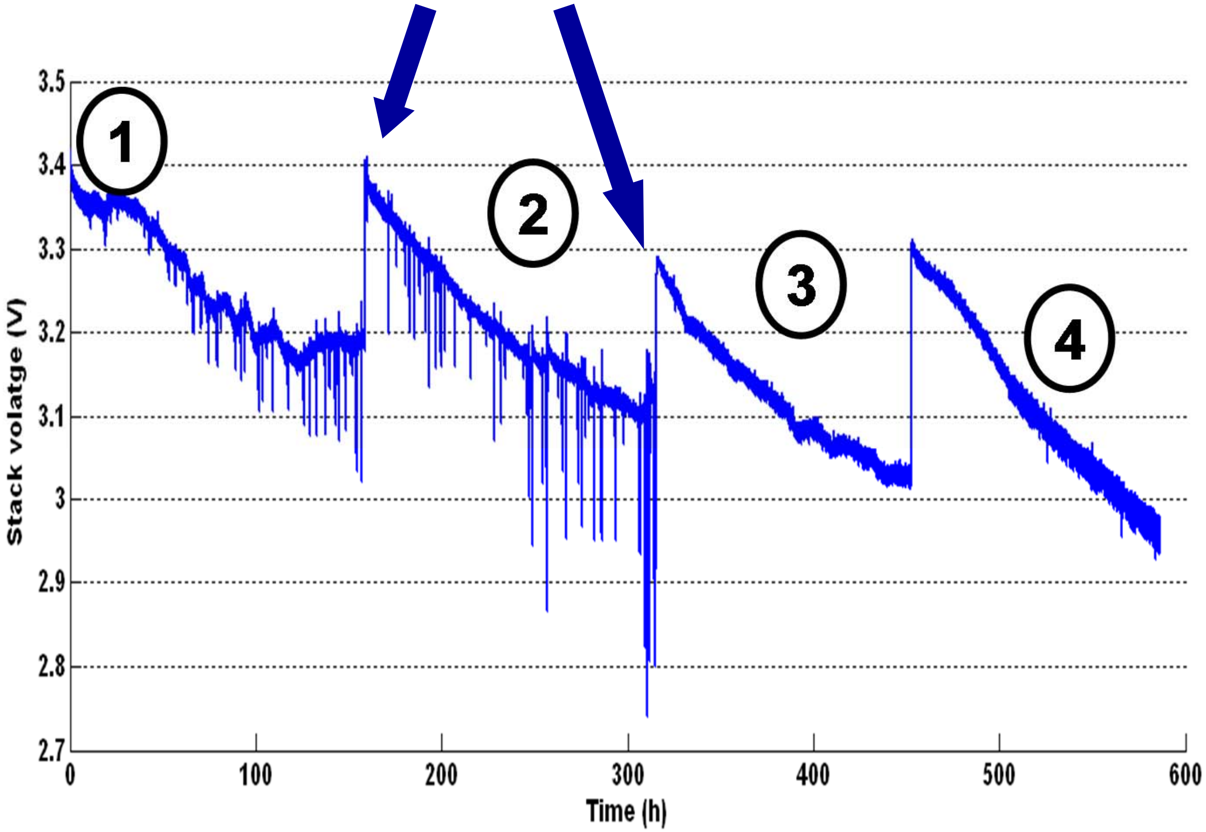
Ageing test nominal conditions	
Cooling temperature	348 K
Relative humidity	50%
Gas pressure	1.5 bars
Hydrogen stoichiometry	1.5
Oxygen stoichiometry	2
Nominal current density	110 A (0.5 $A.cm^{-2}$)
Ripple current frequency	5 kHz
Ripple current amplitude	20%

Examples of interactions system / stack

– Impact of the converter – current ripple

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

Characterization
- ripple is stopped
- polarization curve
- EIS



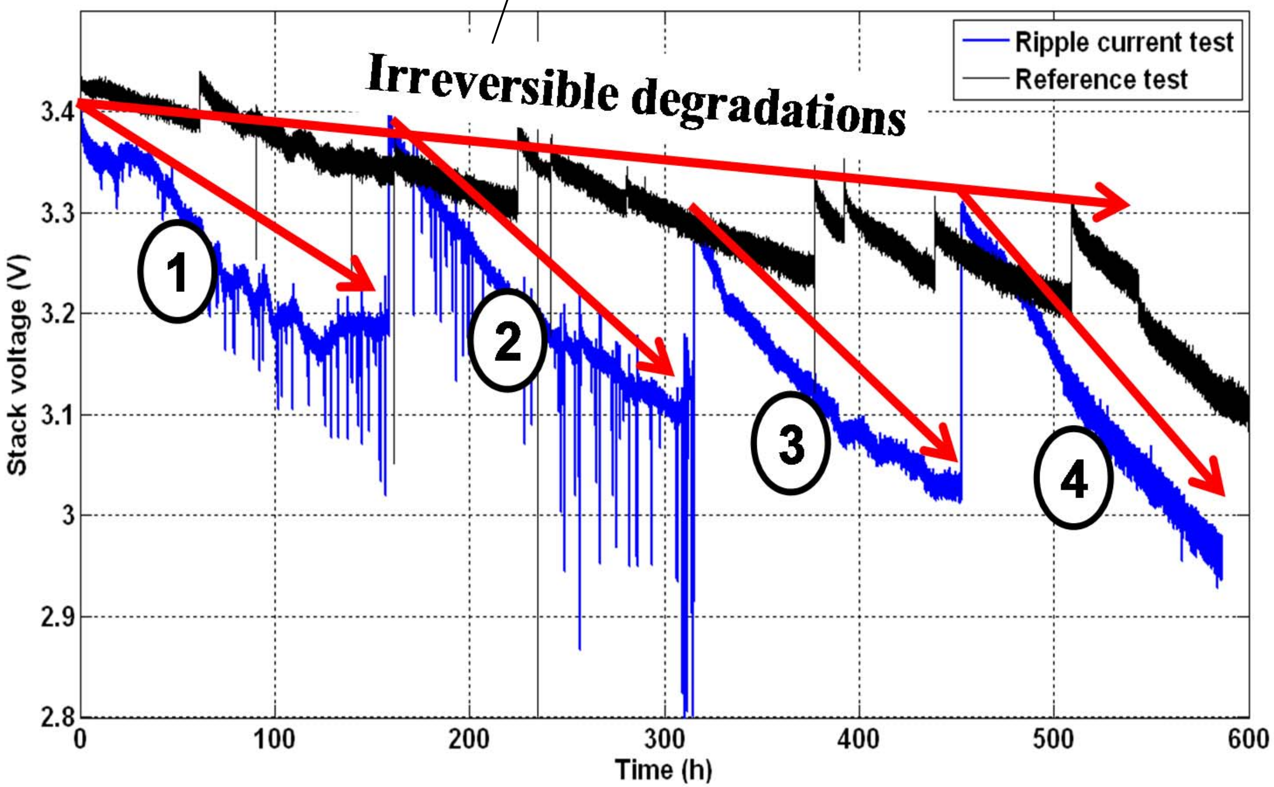
Examples of interactions system / stack

– **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

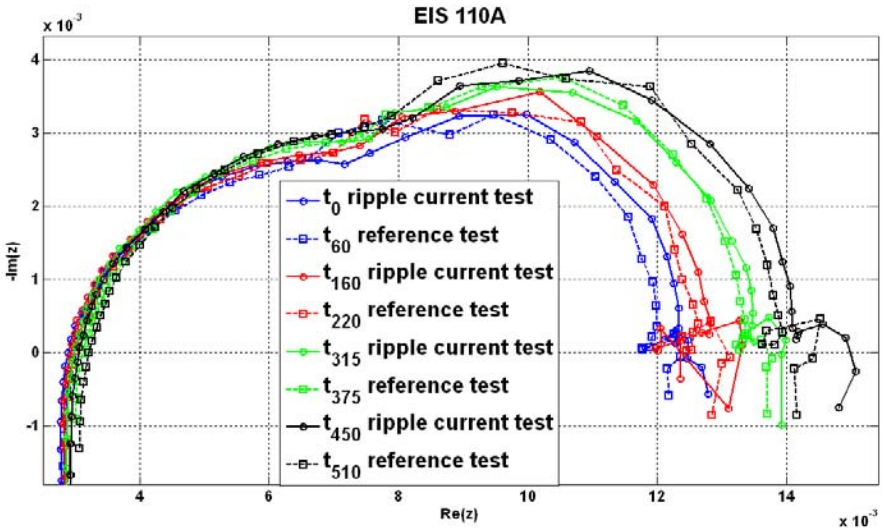
Irreversible degradation: 44 µV.h^{-1}

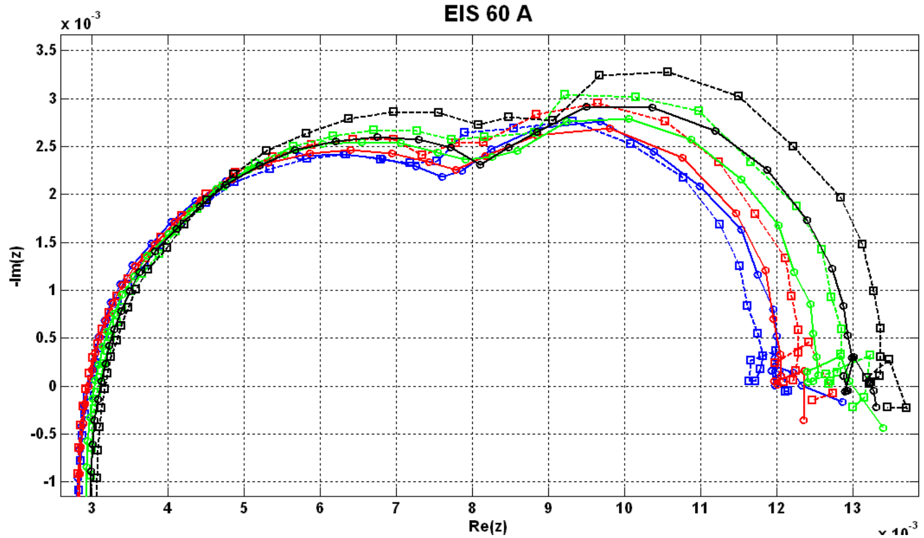


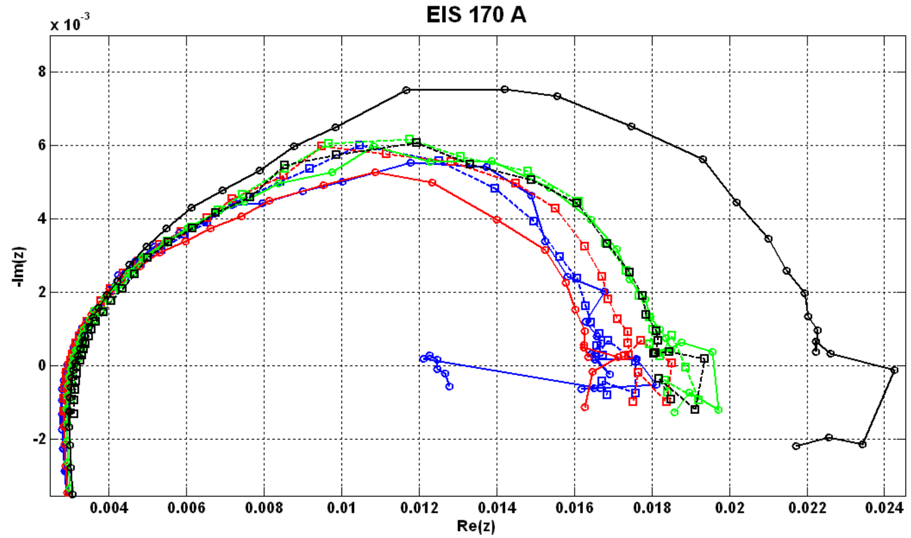
Examples of interactions system / stack

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

- **EIS comparison**
  - EIS at 3 different currents
  - No major difference between the two tests (with and without ripple)



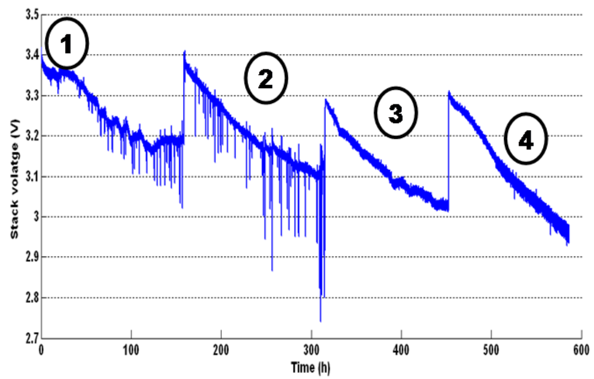




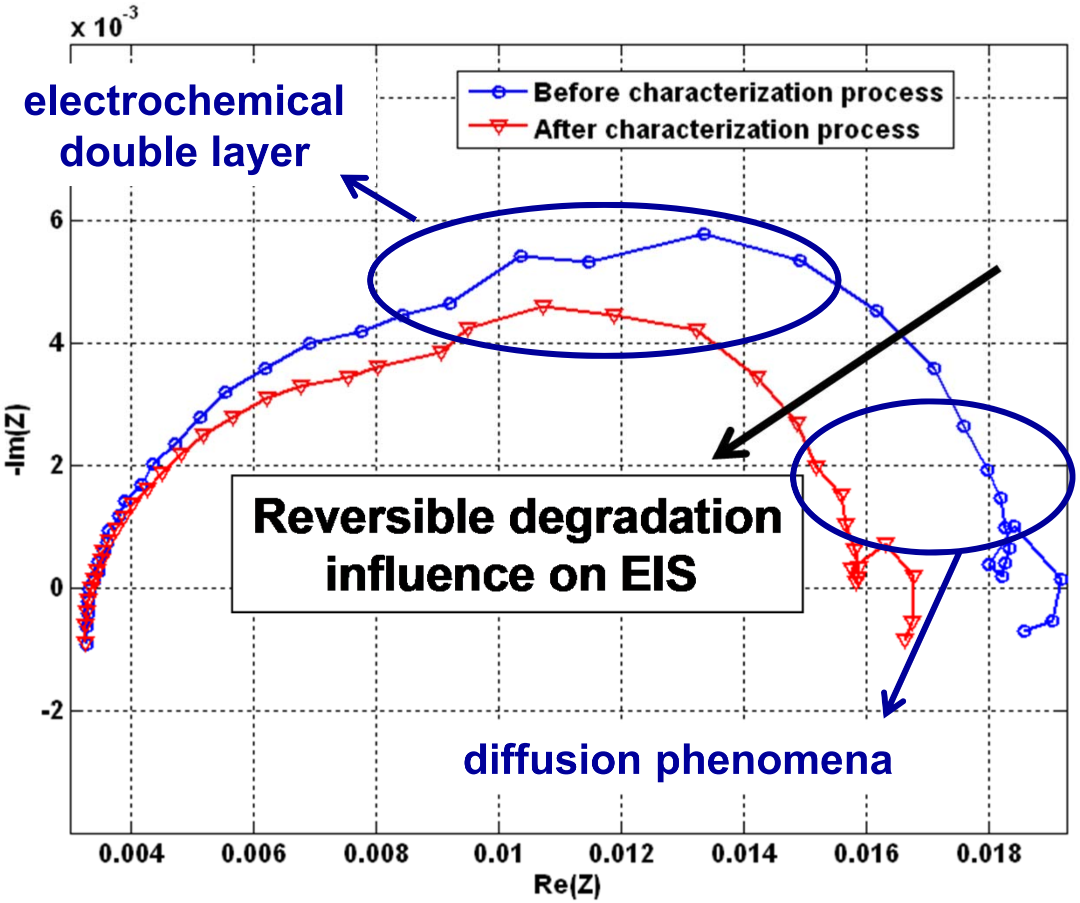
Examples of interactions system / stack

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

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



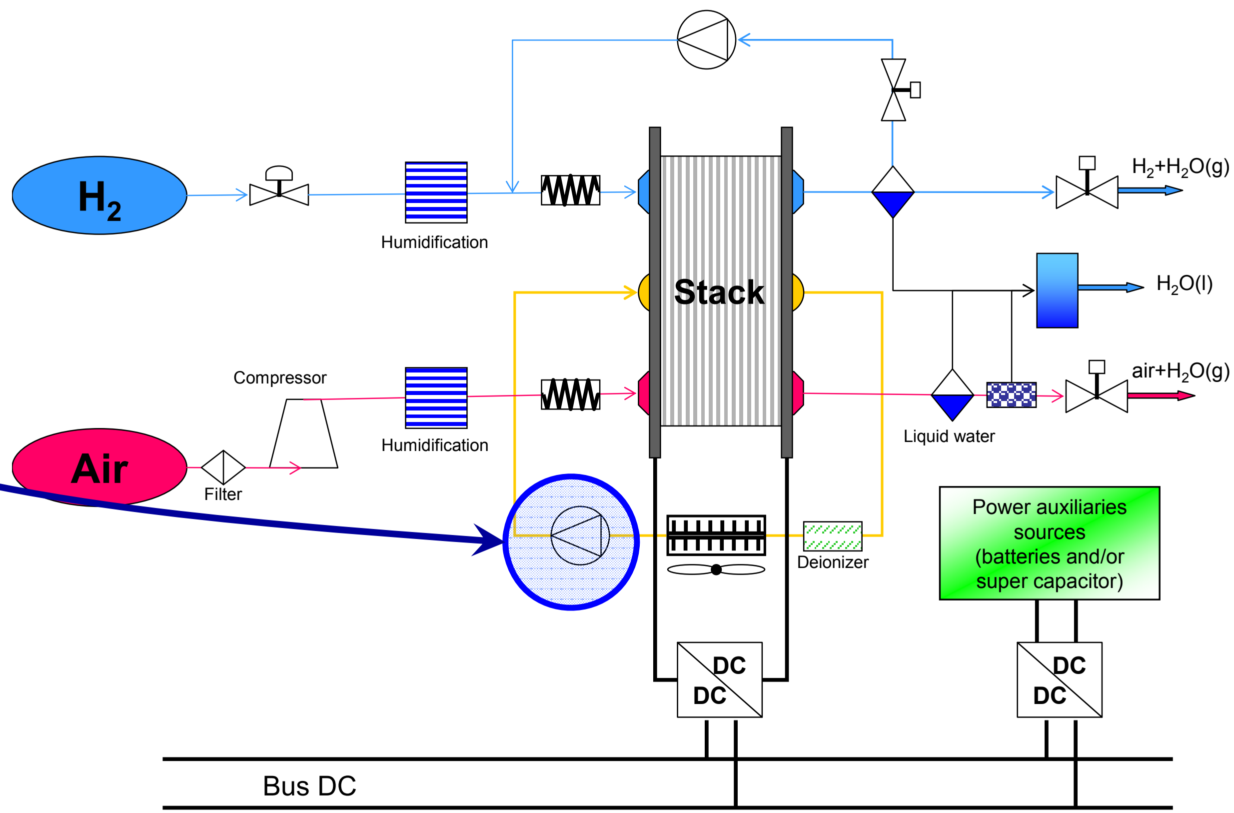
Reversible degradation
=
Water management on the active layer



Examples of interactions system / stack

– Impact of the cooling circuit

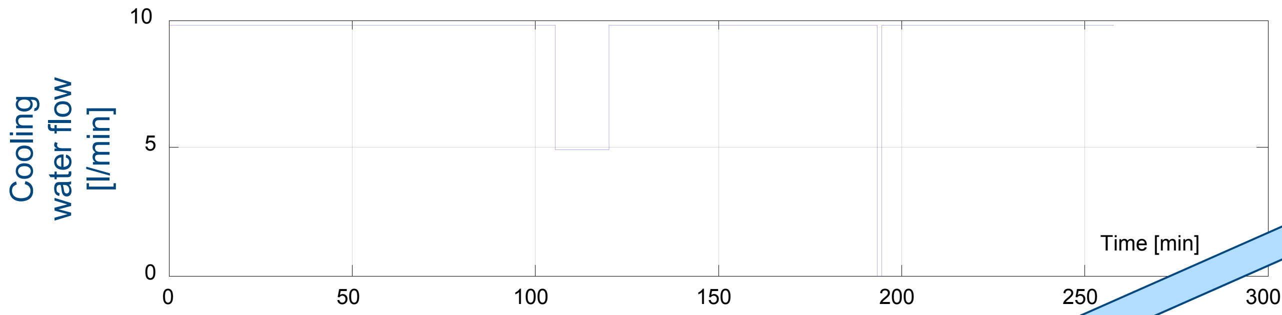
- **Cooling circuit**
  - Failure ⇨ Impact on performances / lifespan of the FC stack



Examples of interactions system / stack

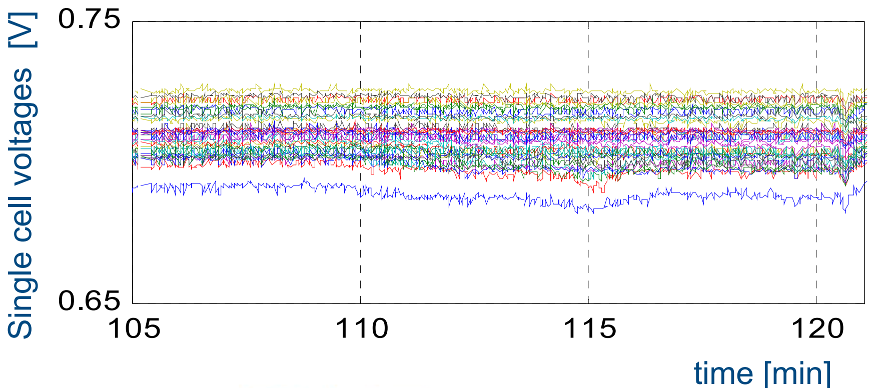
– Impact of the cooling circuit

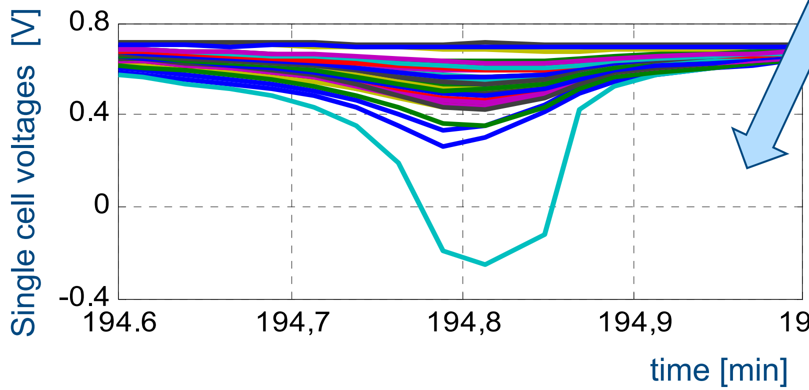
- **Experimental characterization**
  - 40-cell stack
  - Nominal operating conditions (80°C, HR=50%, SFA=1.5, SFC=2, I=110A)
  - Evolution of cooling water (deionized) flow (from 9,8l/min – nominal)



Limited evolution over 10 minutes for ½ of cooling flow

Very rapid drop of cell voltage in case of stopping the cooling flow





Health monitoring and ageing

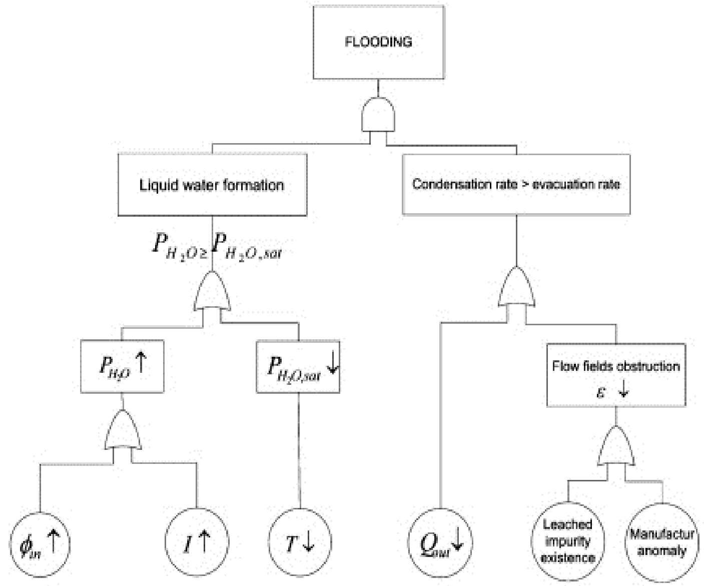
– Health monitoring

▪ 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)

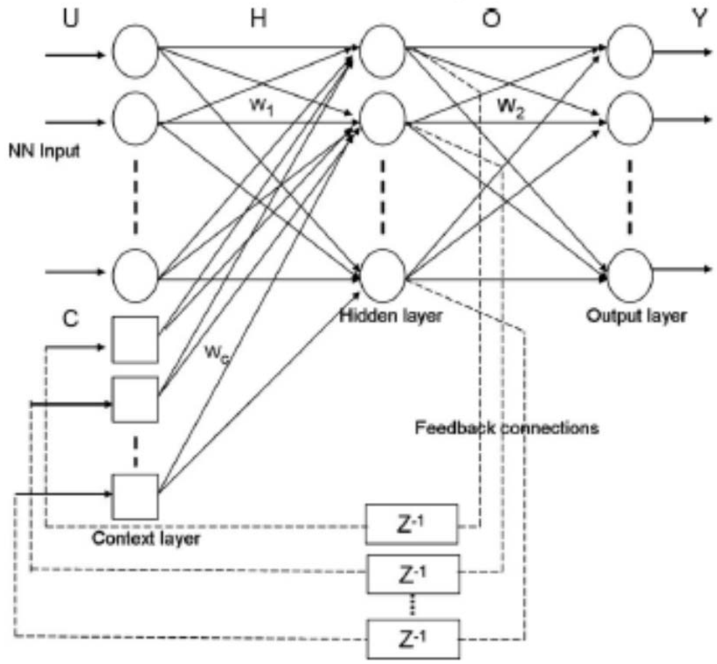
- Step 2: feature selection
  - Thanks to a fault tree analysis
    - current I
    - dew point temperature T_{dwpt} (inlet relative humidity)
    - stack temperature T
    - air inlet flow rate Q

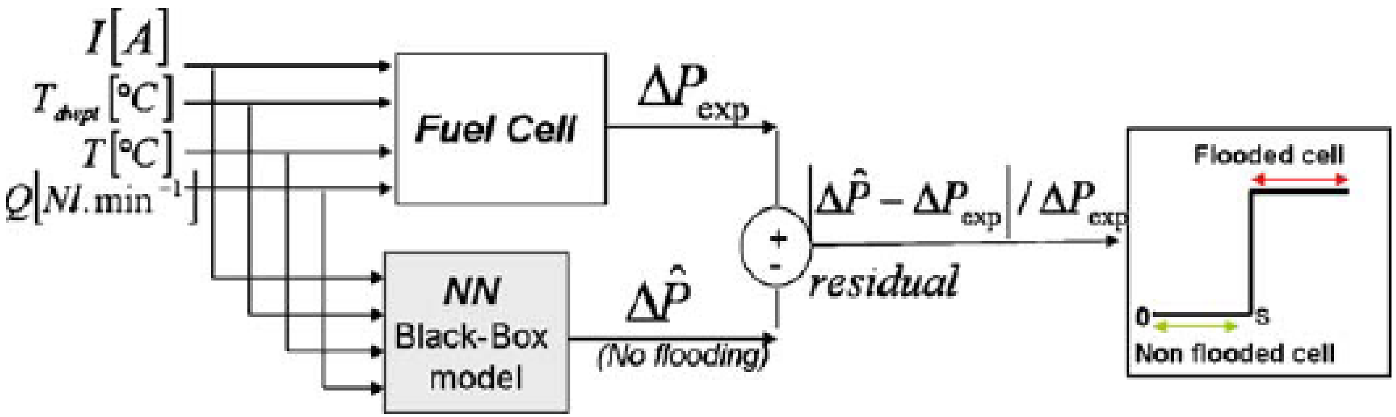


Health monitoring and ageing

– **Health monitoring**

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

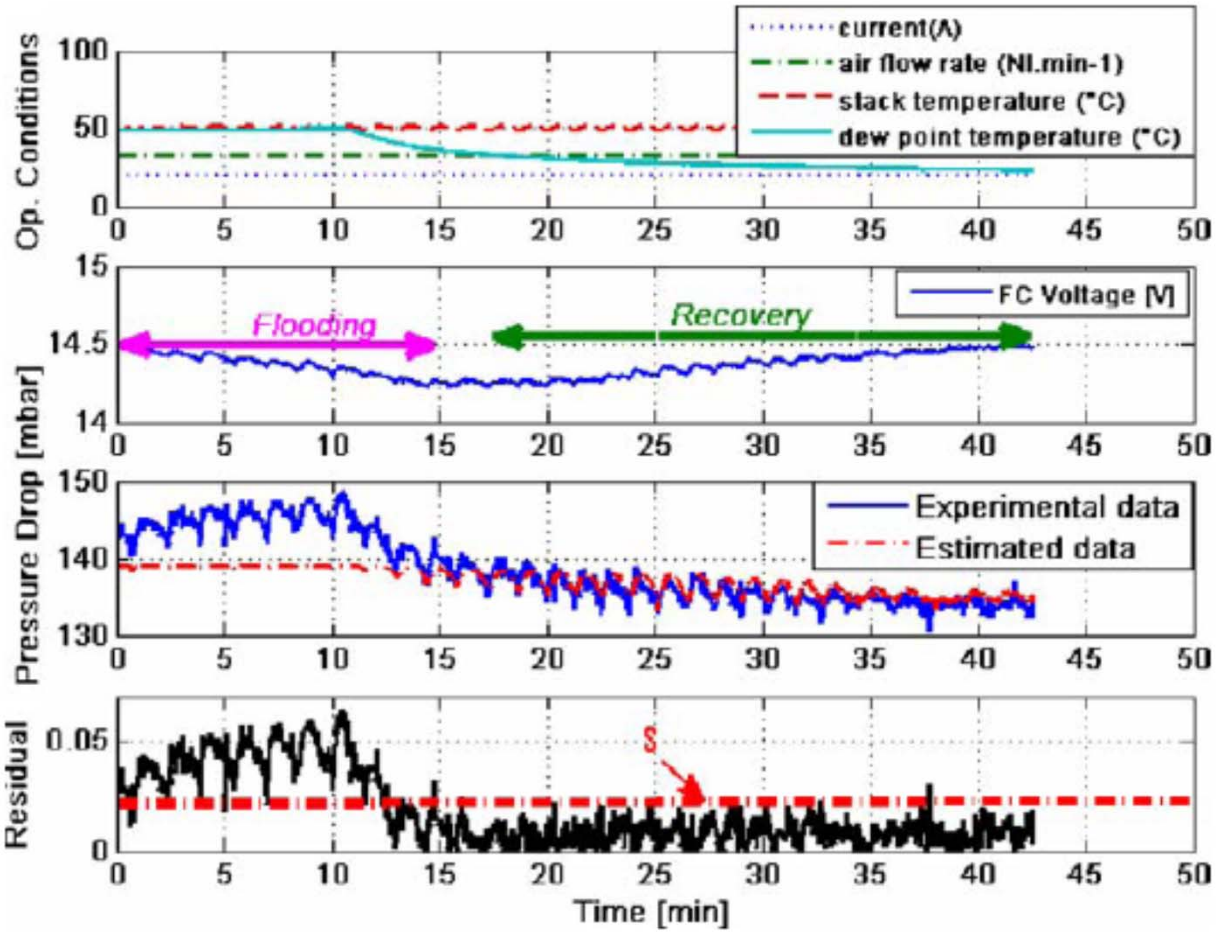




Health monitoring and ageing

– **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?

Data sample → State of Life Estimator → Begin of Life (BoL) / Ageing under conditions 1 / Ageing under conditions 2

Feature selection: hyper-parameters from Nyquist plot

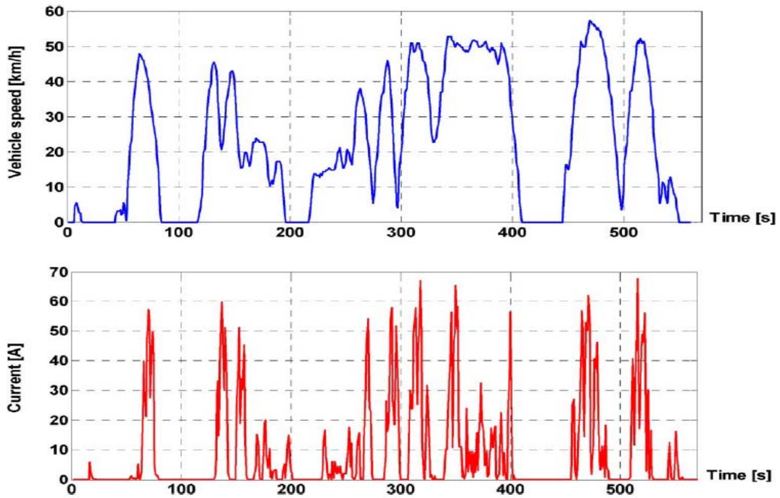
"Estimator" learned with Fuzzy Clustering
No system model involved

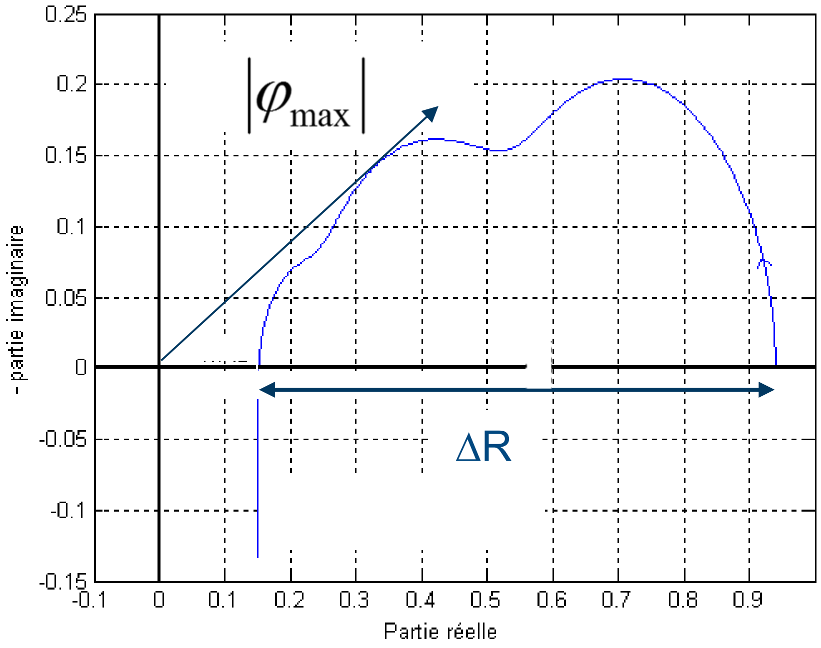
Health monitoring and ageing

– 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)





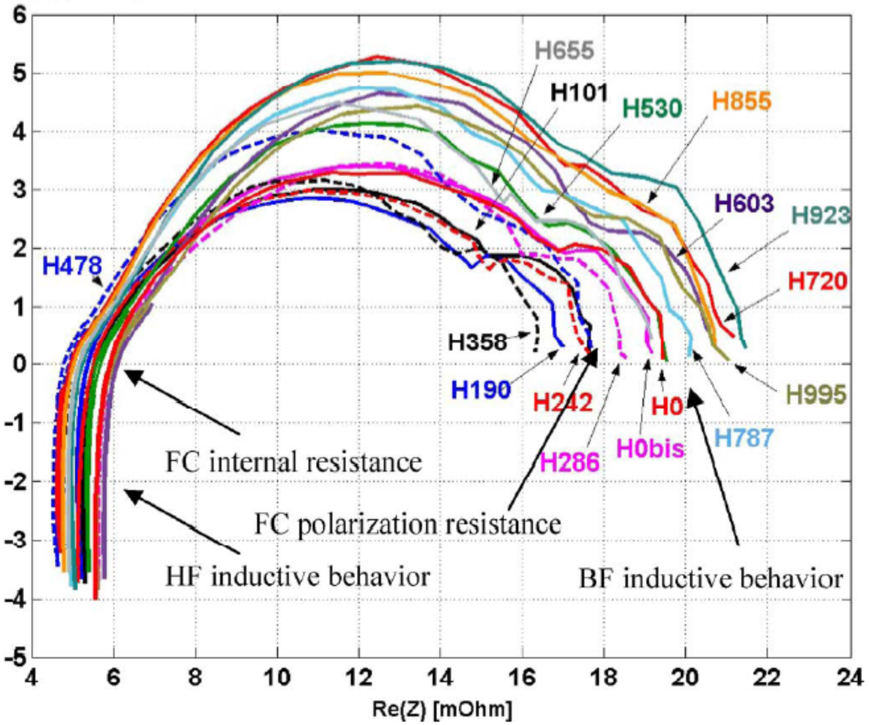
Health monitoring and ageing

– Ageing estimation – condition monitoring

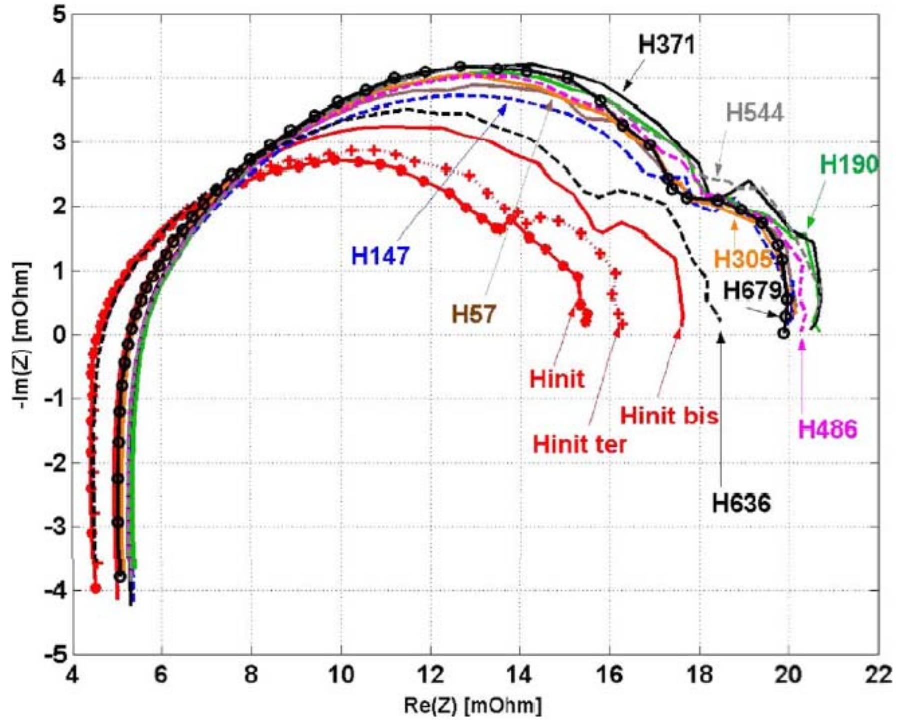
▪ Estimation of the age of a stack (3)

- Nyquist plot from both experiments

Stack 1 : **constant current 50 A**



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

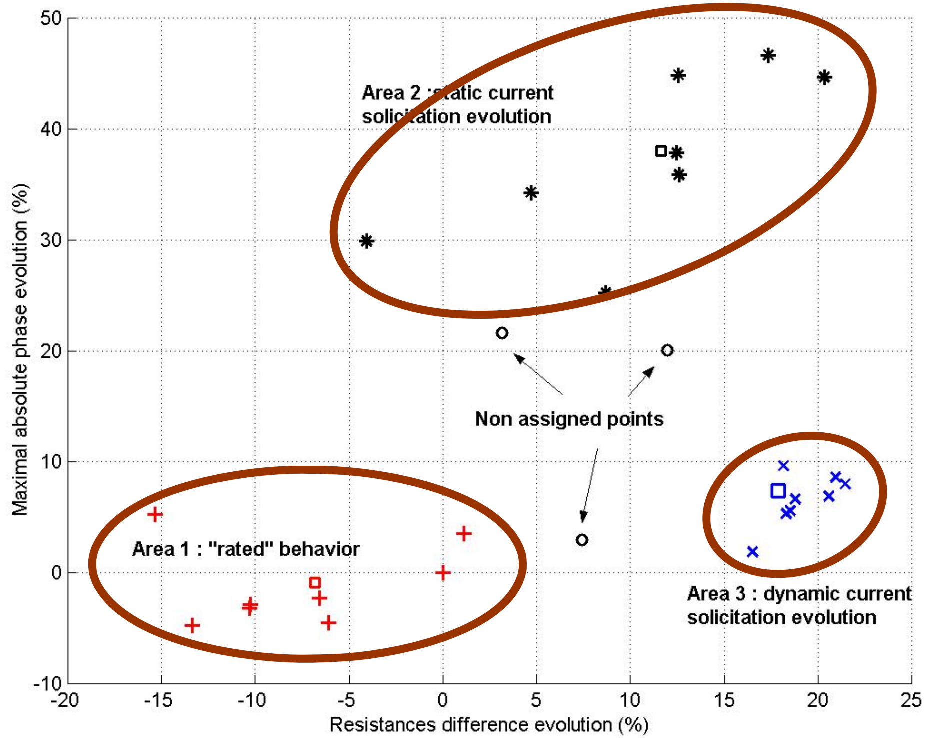


Health monitoring and ageing

– 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)

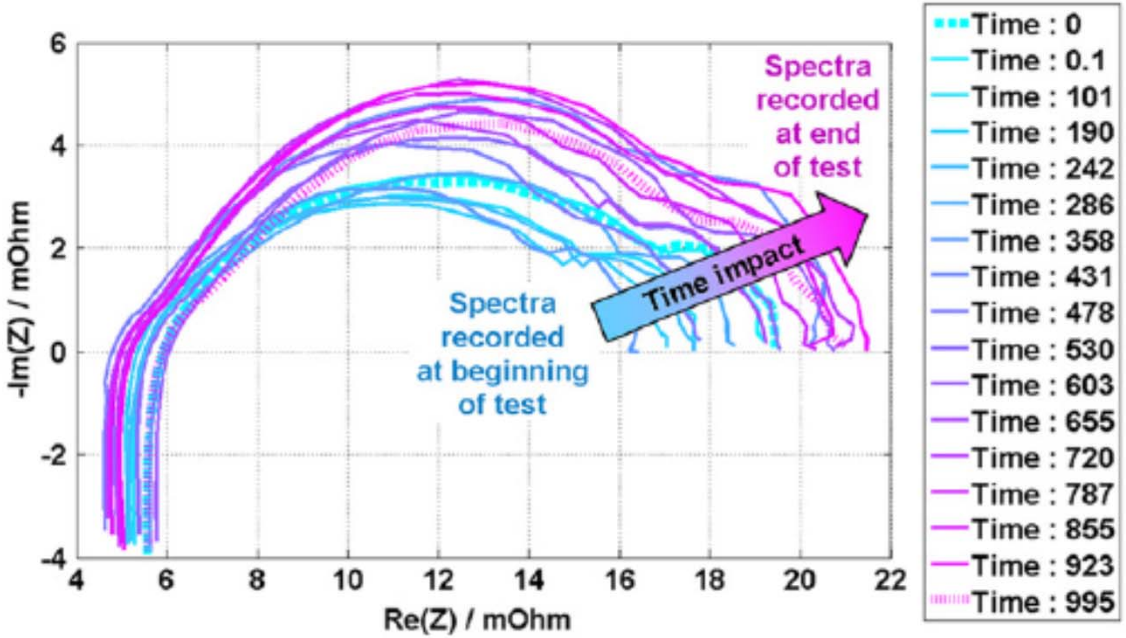


Health monitoring and ageing

– 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

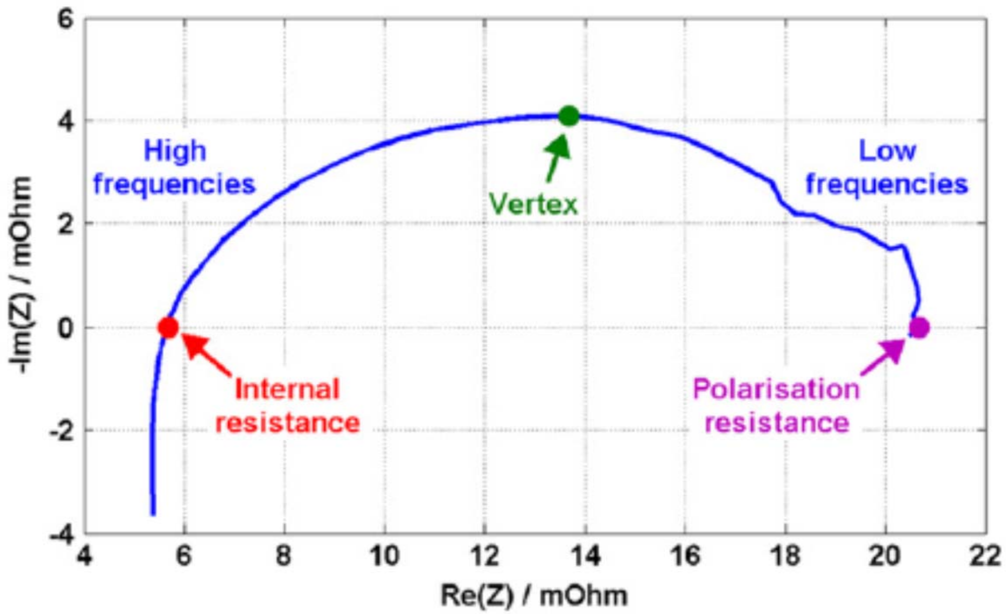


Health monitoring and ageing

– 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

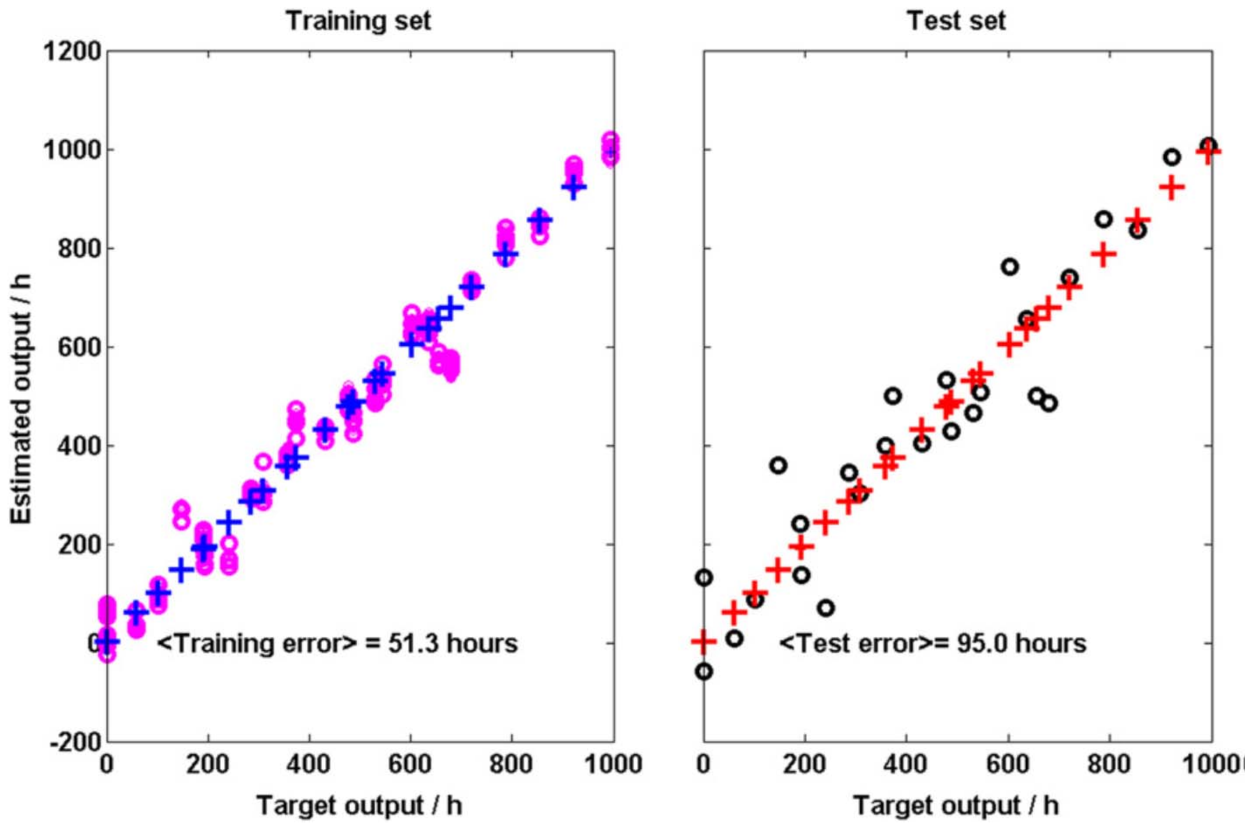


Health monitoring and ageing

– **Ageing estimation – past operating time estimation**

  - **Estimation of fuel cell operating time (3)**

    - Example of results



PHM of Fuel Cell System – A state of the art

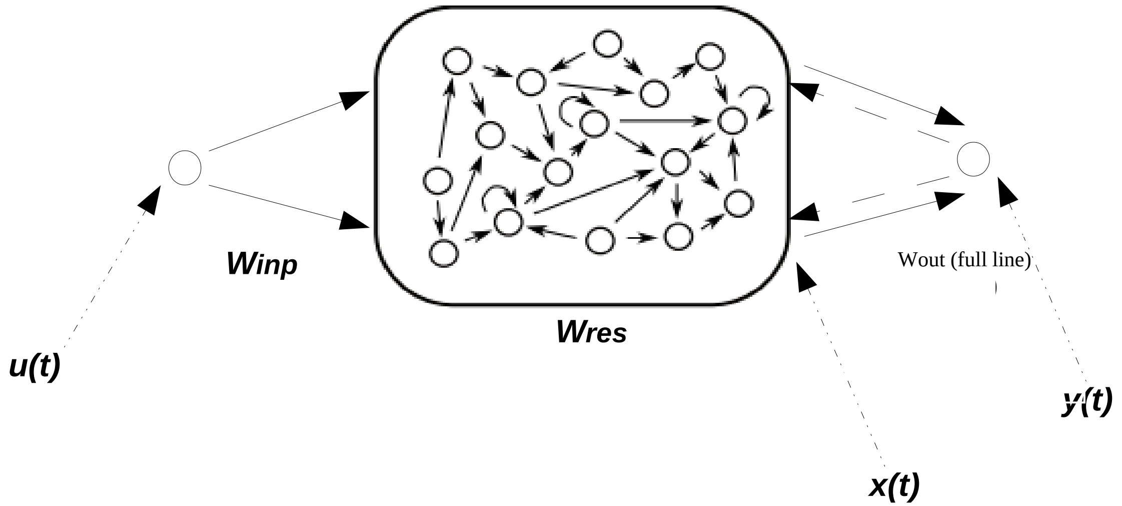
Part 5 – Ongoing works: prognostics of Fuel Cell Systems

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



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

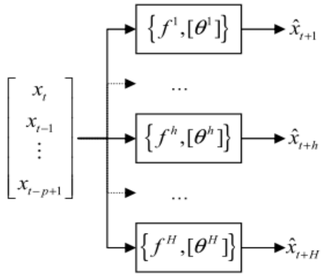
$$y(n) = W_{out}.x(n) + W_{feed}.y(n-1))$$
$$y(n) = f(W_{out}.x(n))$$

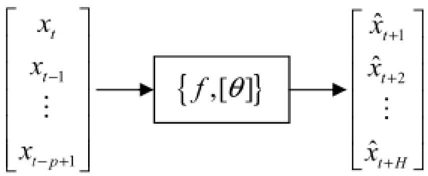
- **Outline**
  - Avoid algorithmic complexity ⇨ structural complexity
  - Learning phase in a single step: linear optimization (minimize MSE)

Data-driven prognostics of PEMFC

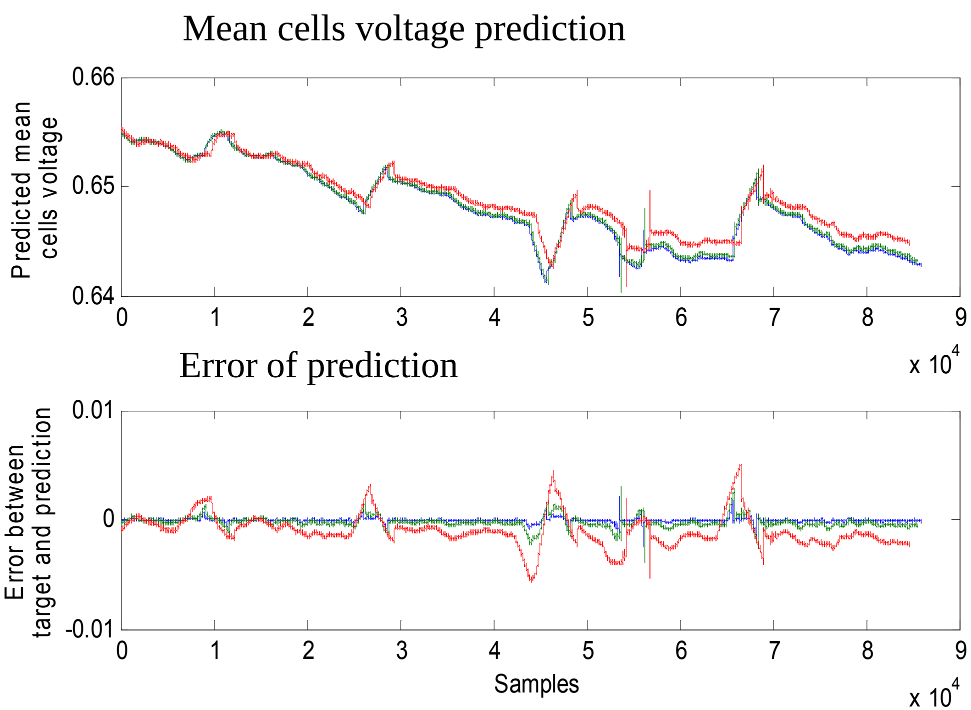
– **Echo State Networks for prognostics of FEMFC**

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

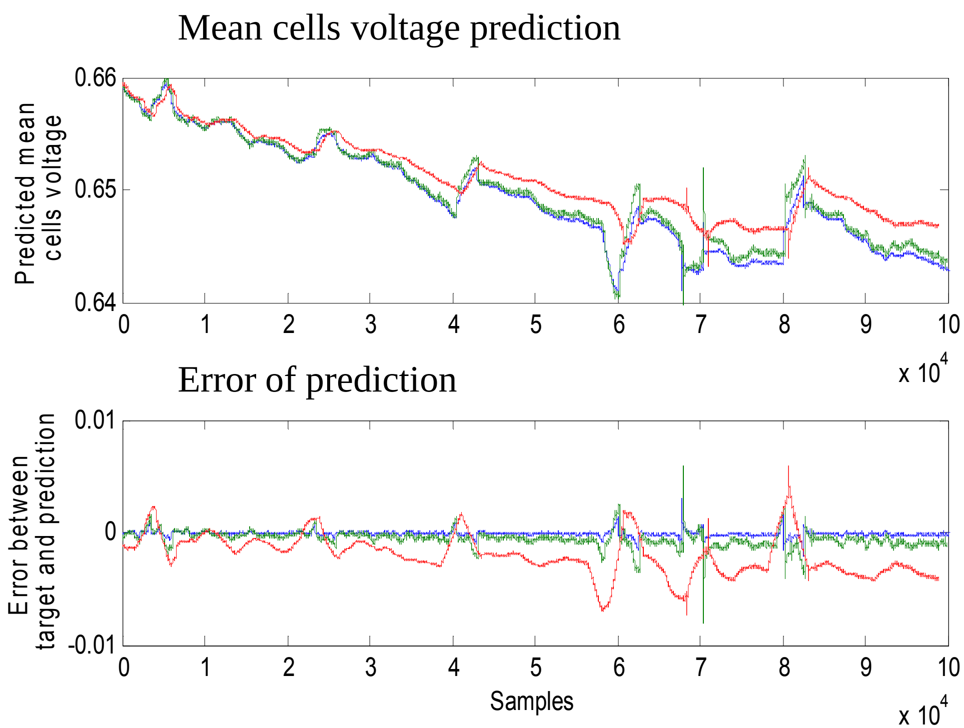




Direct approach



Parallel approach

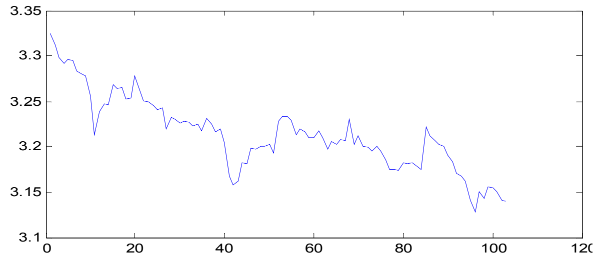


in blue: h=500, in green: h=1000, in red: for h=2500 samples

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**



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

Hybrid prognostics of PEMFC

– Matching empirical degradation models

- **Formulation**
  - Hidden state model ⇨ Degradation state – **3 empirical models**

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

  - Observation model ⇨ Available measurements

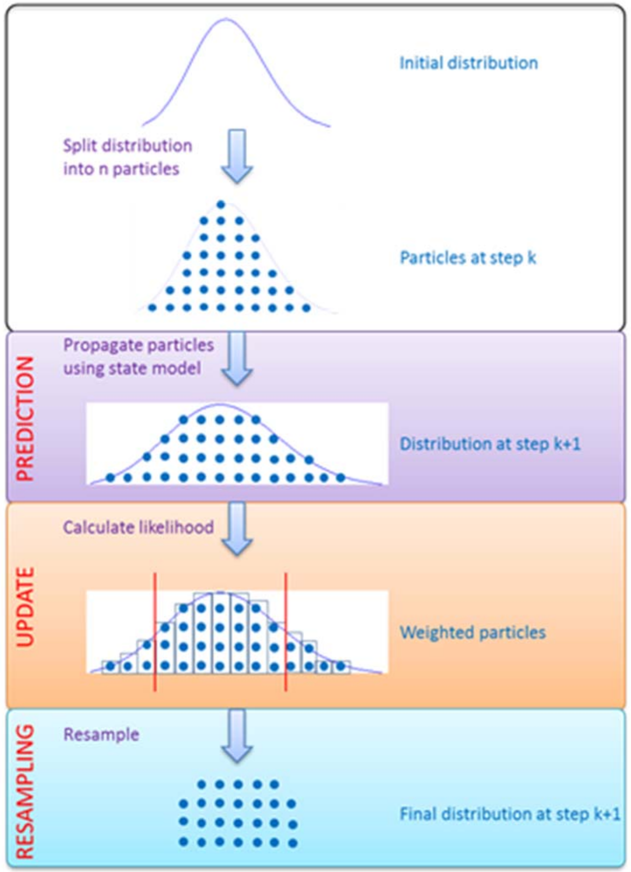
$$z_k = h\left(x_k, \mu_k\right)$$

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

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

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

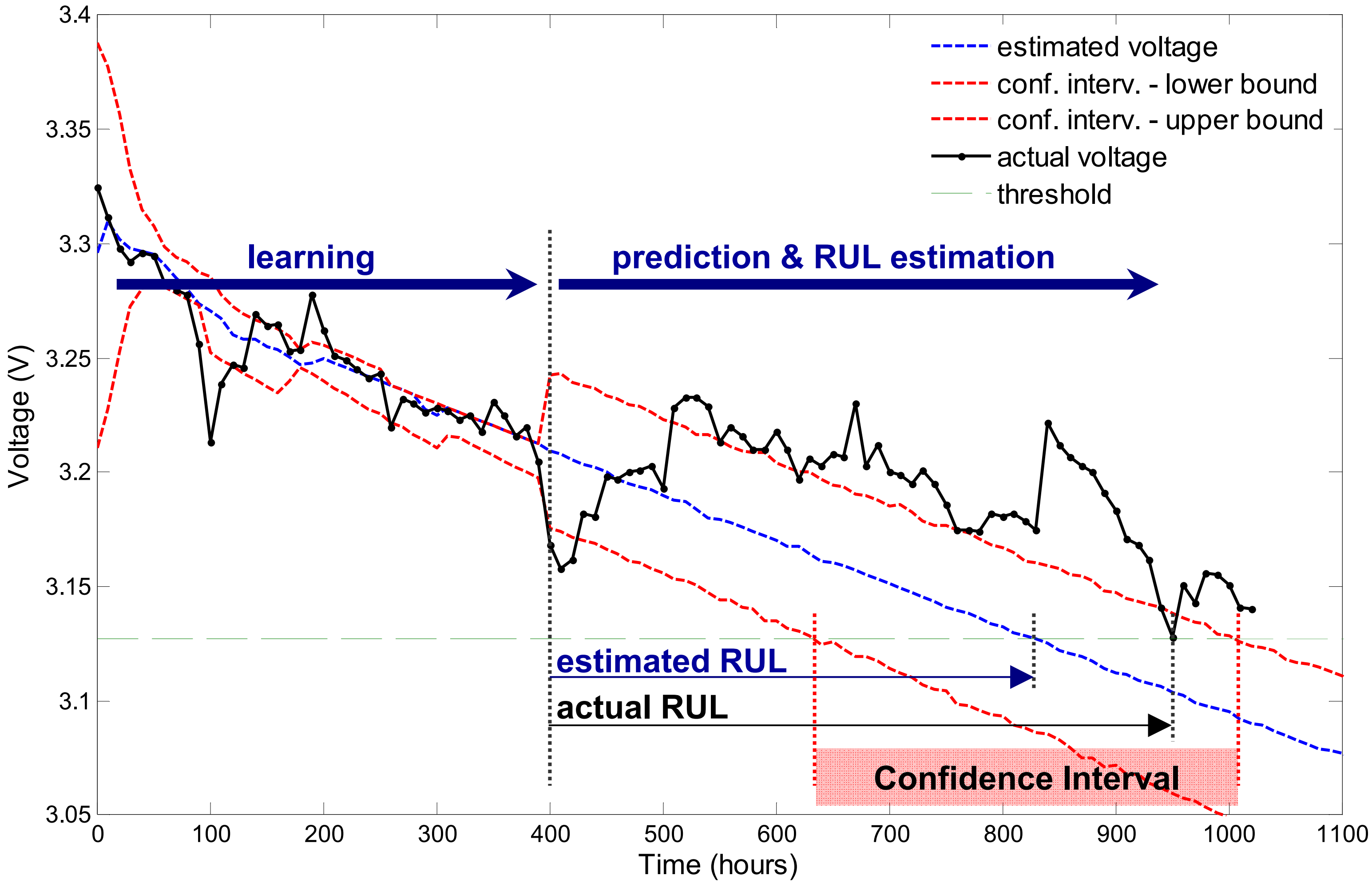
  - **Solving: particle filter**



Hybrid prognostics of PEMFC

– **Example of results**

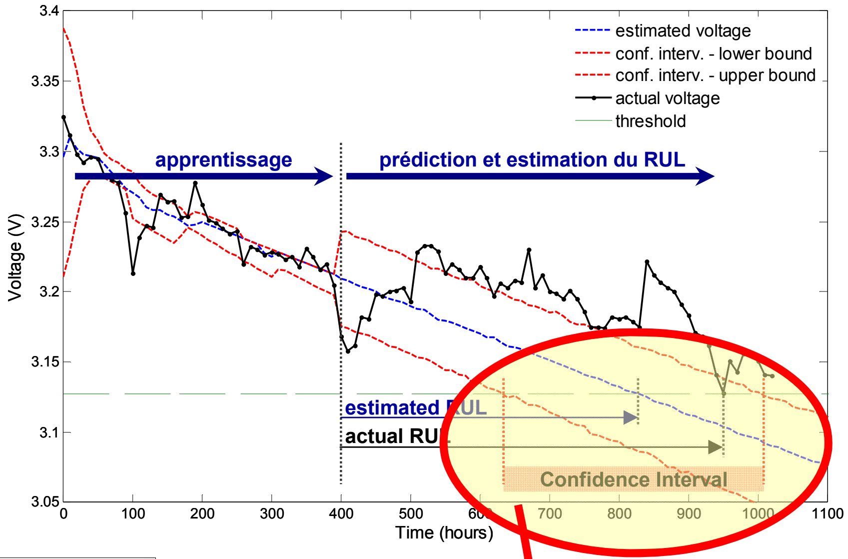
- **Estimations at t = 400 h**

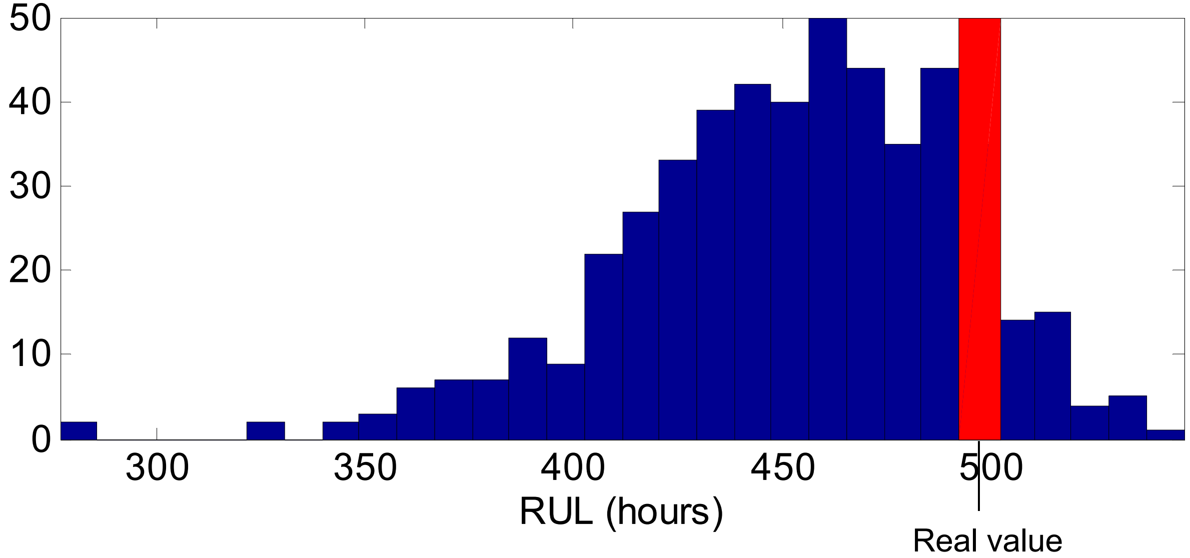


Hybrid prognostics of PEMFC

– Example of results

- **Prognostics at t = 400 h**

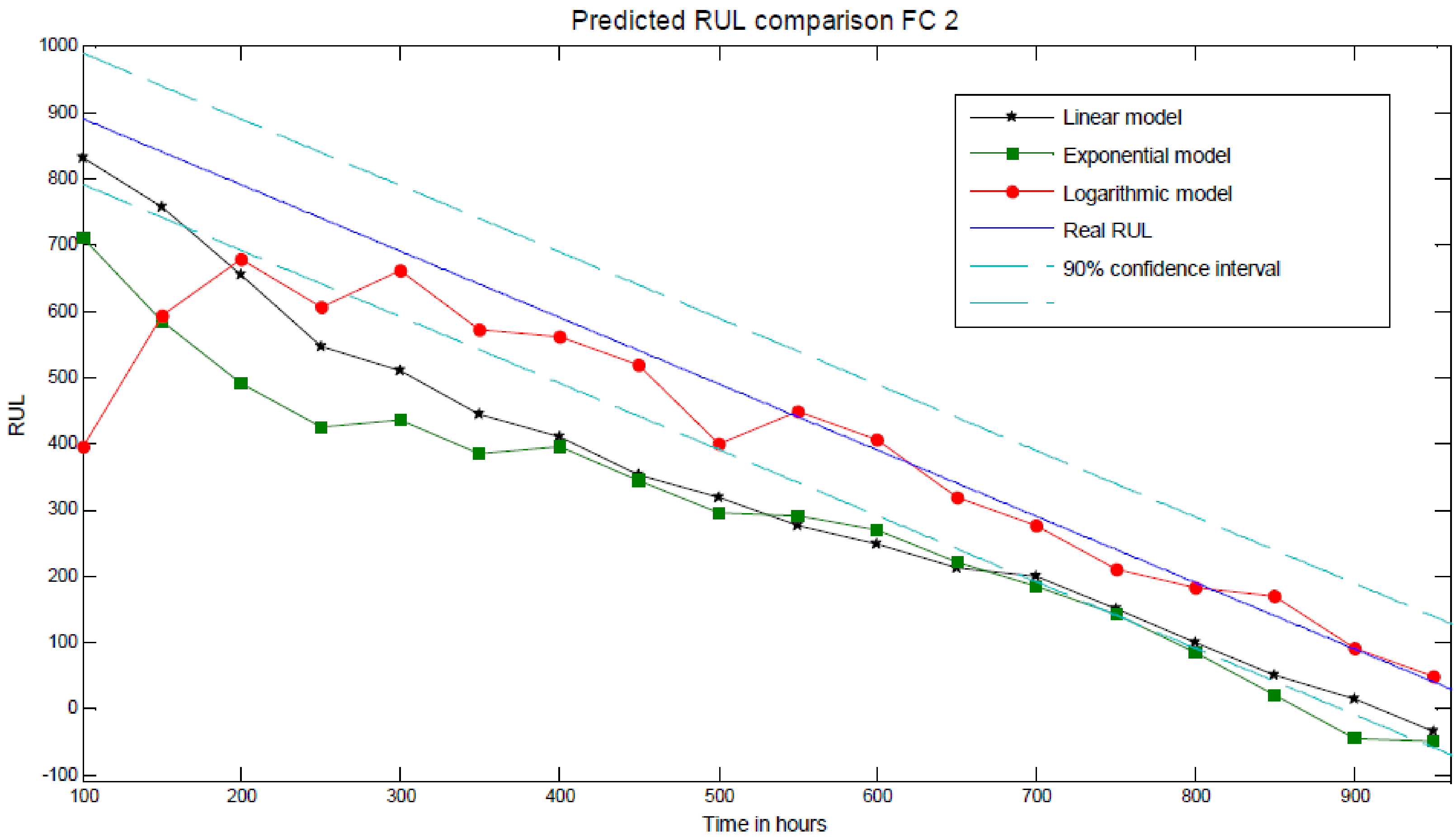




Hybrid prognostics of PEMFC

– Example of results

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



PHM of Fuel Cell Systems – A state of the art

Concluding remarks

Concluding remarks

– The interest of H2 technology

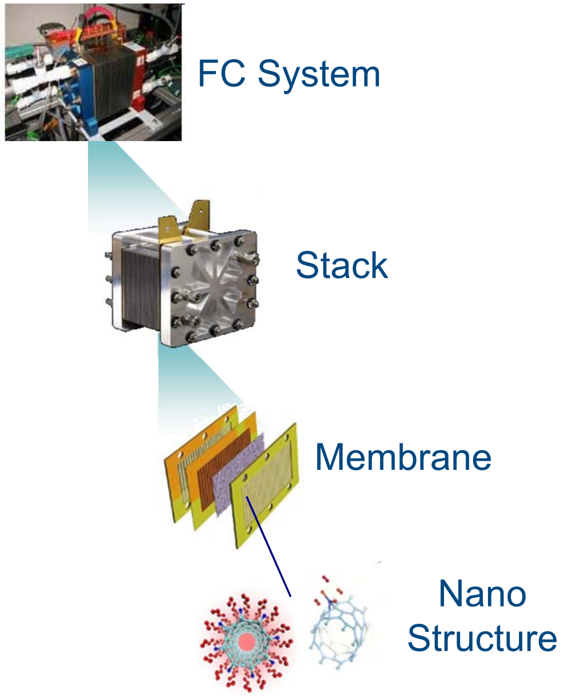
- **FC are promising energy converters**
  - High efficiency & low noise level
  - Possible heat recovery (especially for high temperature FC – SOFC)
  - Possibly no dependency to fossil fuels
  - Energy density is directly linked to the size & weight of the fuel tanks
  - Still issues on system-level
    - 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 ?

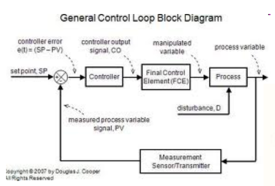
- Observe ageing
- Model the behavior
- Assess current health state
- Predict future health states
- Test, optimize and validate the approaches
- Prepare industrial transfer

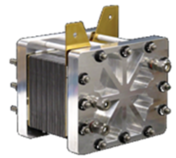
Concluding remarks

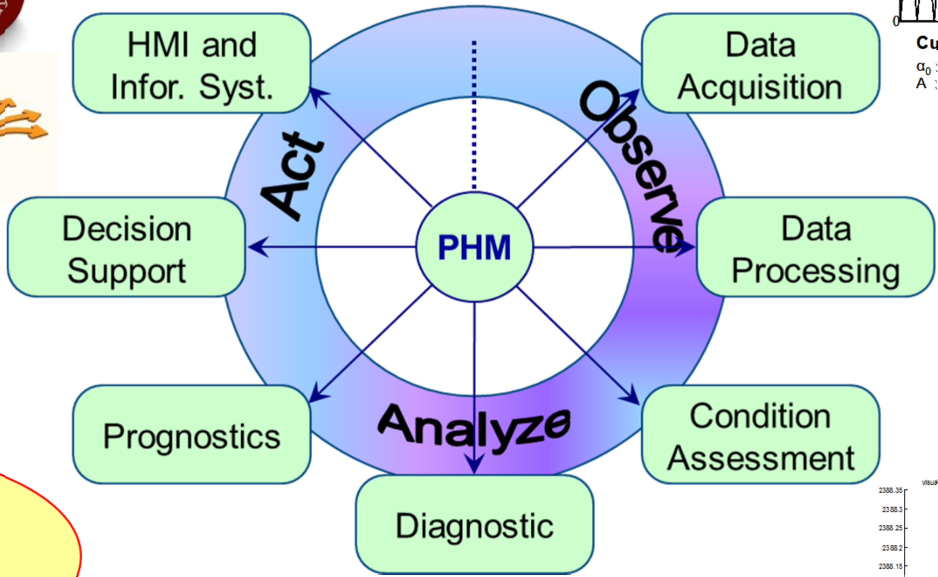
– **Already on-going works**

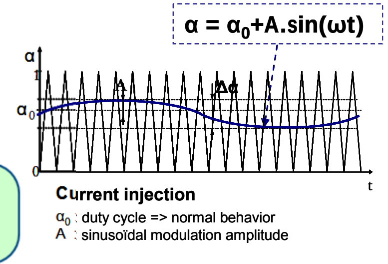
- taxonomy of failures
- wearing mechanism analysis…

- residual-based control…

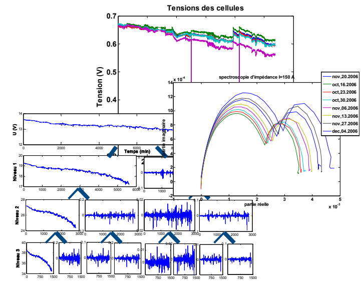




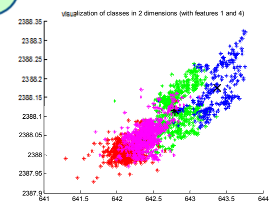




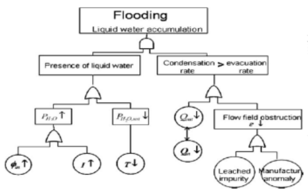
- T°, I, V
- EIS…

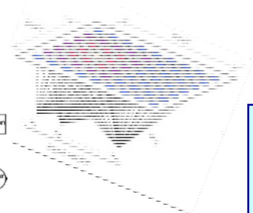


- polarization curves
- Nyquist diagrams…



Not well addressed



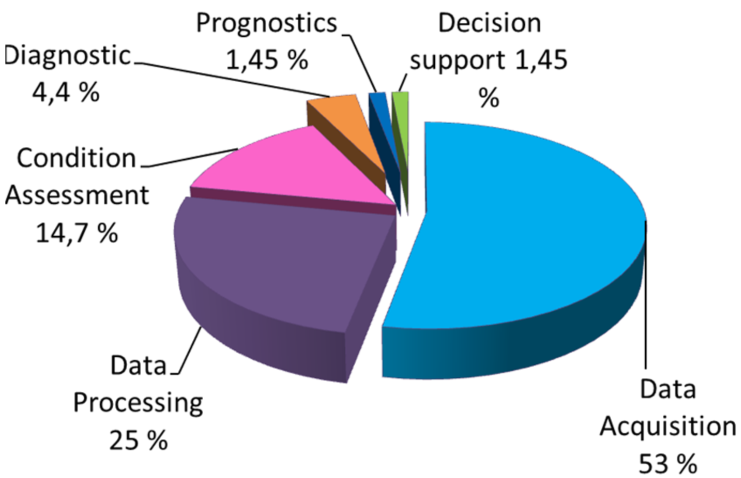


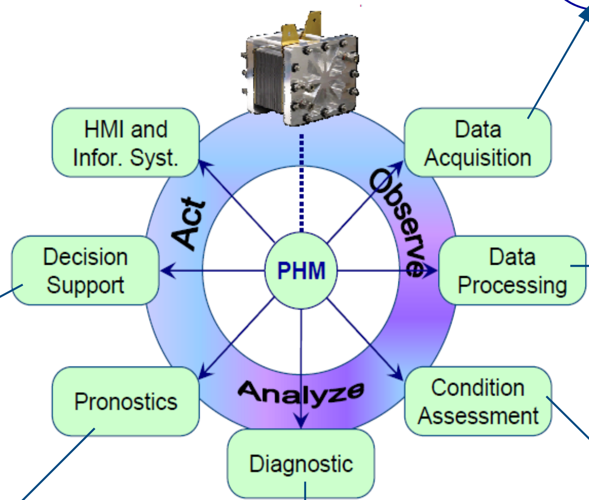
- fault tree analysis
- ANN models, wavelet analysis…

Concluding remarks

– **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**

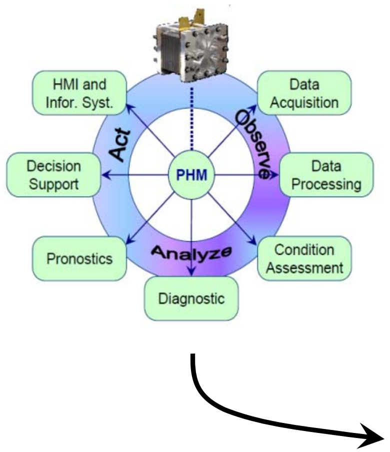
(3 works)

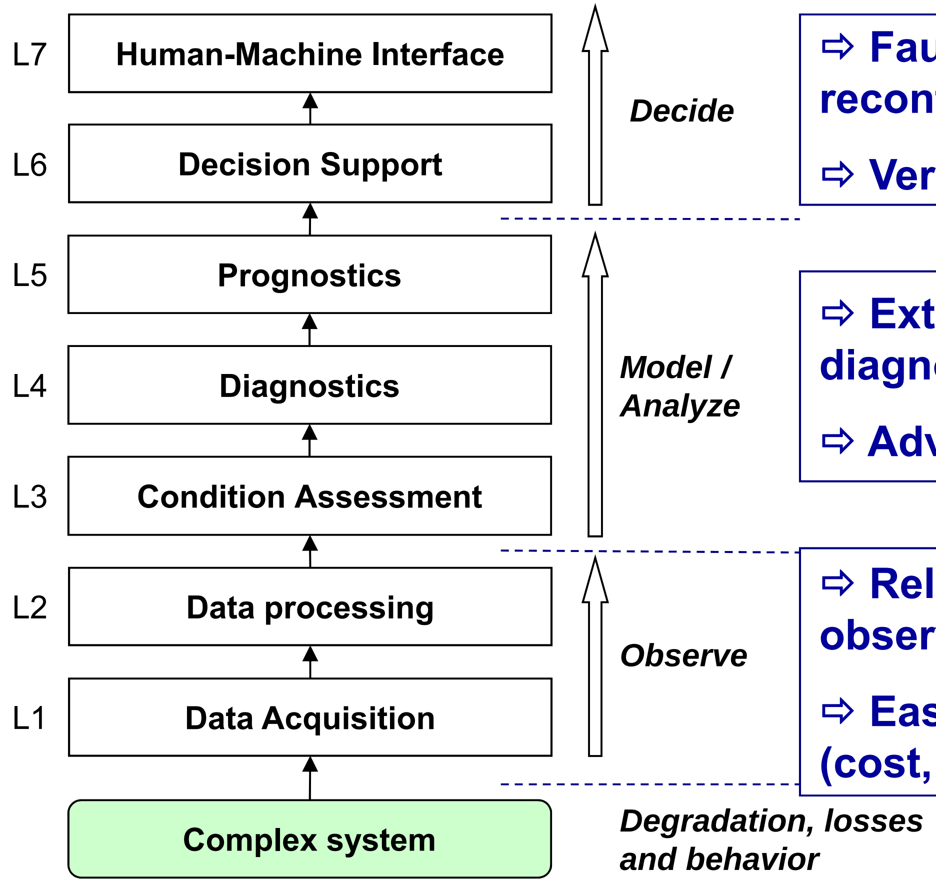
- **Residues (data - model)**
- **ANN, Fuzzy logic (clust.)**
- **Pattern recognition algorithm**
- **Parameters representation**

(10 works)

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.)**

PHM of Fuel Cell System – A state of the art

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