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International Conference on  
**Battery and Fuel Cell  
Technology**



CPD

# THE QUESTION OF FUEL CELL DURABILITY “DYNAMIC MULTIFRACTALITY IN STACK VOLTAGE SIGNAL AS AN INDICATOR OF PEMFC SoH”

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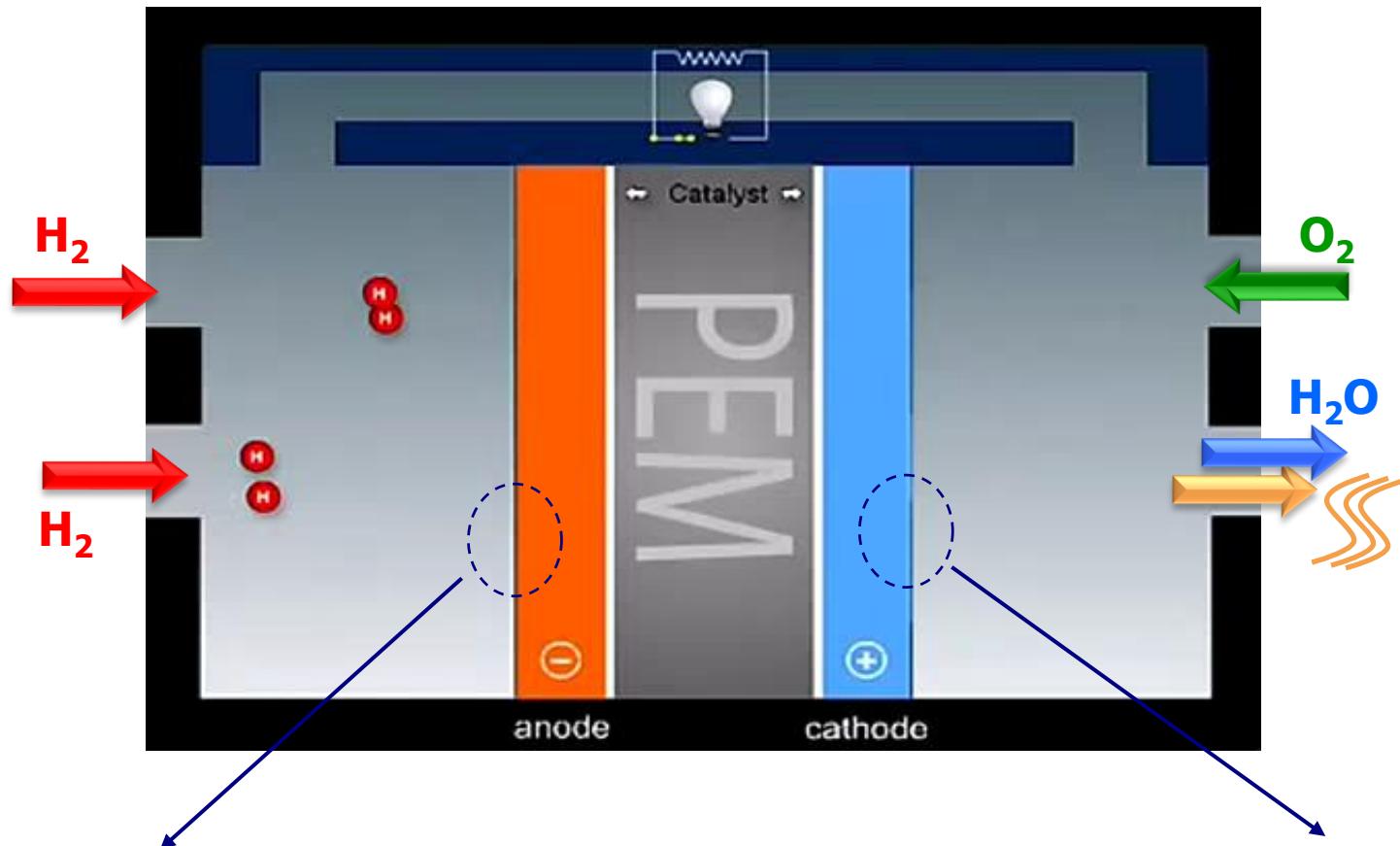
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# 1. Polymer Electrolyte Membrane (PEM) Fuel Cells

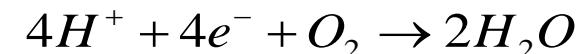
## – How do PEM Fuel Cells work? –



**Hydrogen oxydation**



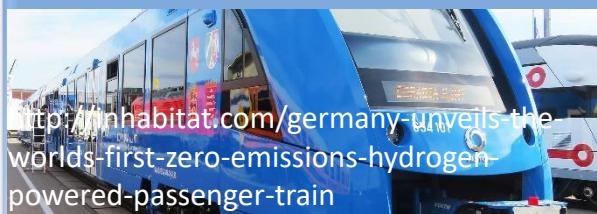
**Oxygen reduction**



**Overall reaction:  $H_2 + \frac{1}{2} O_2 \rightarrow H_2O + \text{Current} + \text{Heat}$**

# 1. Polymer Electrolyte Membrane (PEM) Fuel Cells – Applications –

<http://inhabitat.com/tag/hydrogen-fuel-cell/>



## Transport



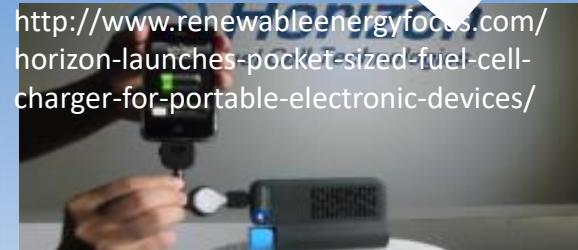
<http://fuelcelltoday.com/news-archive/2013/september/panasonic-and-viessmann-to-launch-fuel-cell-system-in-germany>



<http://www.afhypac.org/>



<http://www.renewableenergyfocus.com/horizon-launches-pocket-sized-fuel-cell-charger-for-portable-electronic-devices/>



## Portable

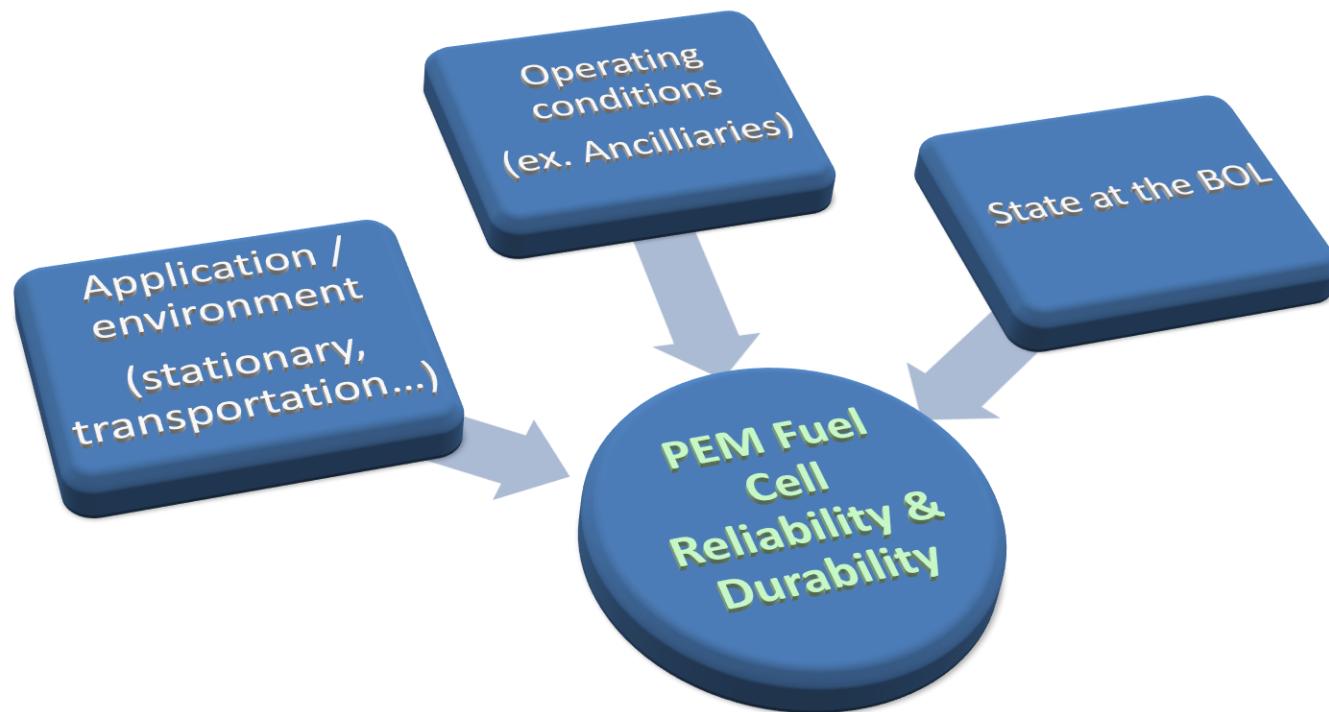


[http://batteryuniversity.com/learn/article/fuel\\_cell\\_technology](http://batteryuniversity.com/learn/article/fuel_cell_technology)

# 1. Polymer Electrolyte Membrane (PEM) Fuel Cells

## – Reliability & Durability –

- **Durability** – the ability of the PEM Fuel Cells to resist to permanent changes in performance over time. Durability is restricted by degradation mechanisms.
- **Reliability** – the ability of the PEM Fuel Cells to deliver the required power, under stated conditions, for a period of time.



**Objective:** Development of PEM Fuel Cells faults diagnosis tool using its stack voltage only

☞ Non-intrusive, without Fuel Cells excitation and low cost tool

## 2. Synopsis of the investigated PEM Fuel Cells

### Two experimented PEMFC

*Table 1. Summary of the tested PEMFC characteristics*

Characteristics	PEMFC <sub>Automotive</sub>	PEMFC <sub>μCHP</sub>
Number of cells	8	12
Electrode active surface	220 cm <sup>2</sup>	?250 cm <sup>2</sup>
Gas distributor plates	Metallic plates	



*The experimented 8 cell PEMFC (operated with pure H<sub>2</sub>)*

*Manufacturer : CEA  
LITEN Grenoble-France*

*Experiments done in the frame of the ANR DIAPASON2 project*

*Table 2. Summary of the nominal operating conditions*

Operating conditions	PEMFC <sub>Automotive</sub>	PEMFC <sub>μCHP</sub>
Coolant flow: deionized water	2 l/min	3 l/min
Anode stoichiometry (H <sub>2</sub> )	1.5	1.3
Cathode stoichiometry (air)	2	2
Absolute pressure for H <sub>2</sub> inlet	150 kPa	11 kPa
Absolute pressure for air inlet	150 kPa	5 kPa
Maximal anode - cathode pressure gap	30 kPa	20 kPa?
Temperature at cooling circuit outlet	80°C	70°C
Anode relative humidity (80°C)	50 %	50%
Cathode relative humidity (80°C)	50 %	50%
Load current	110 A	80A
Current density	0.5 A.cm <sup>-2</sup>	

### Design for automotive application

*The experimented 12 cell PEMFC (operated with mixture gas of 75% H<sub>2</sub> and 25% CO<sub>2</sub>).*

*Manufacturer : Inhouse Engineering GmbH-H-Germany*

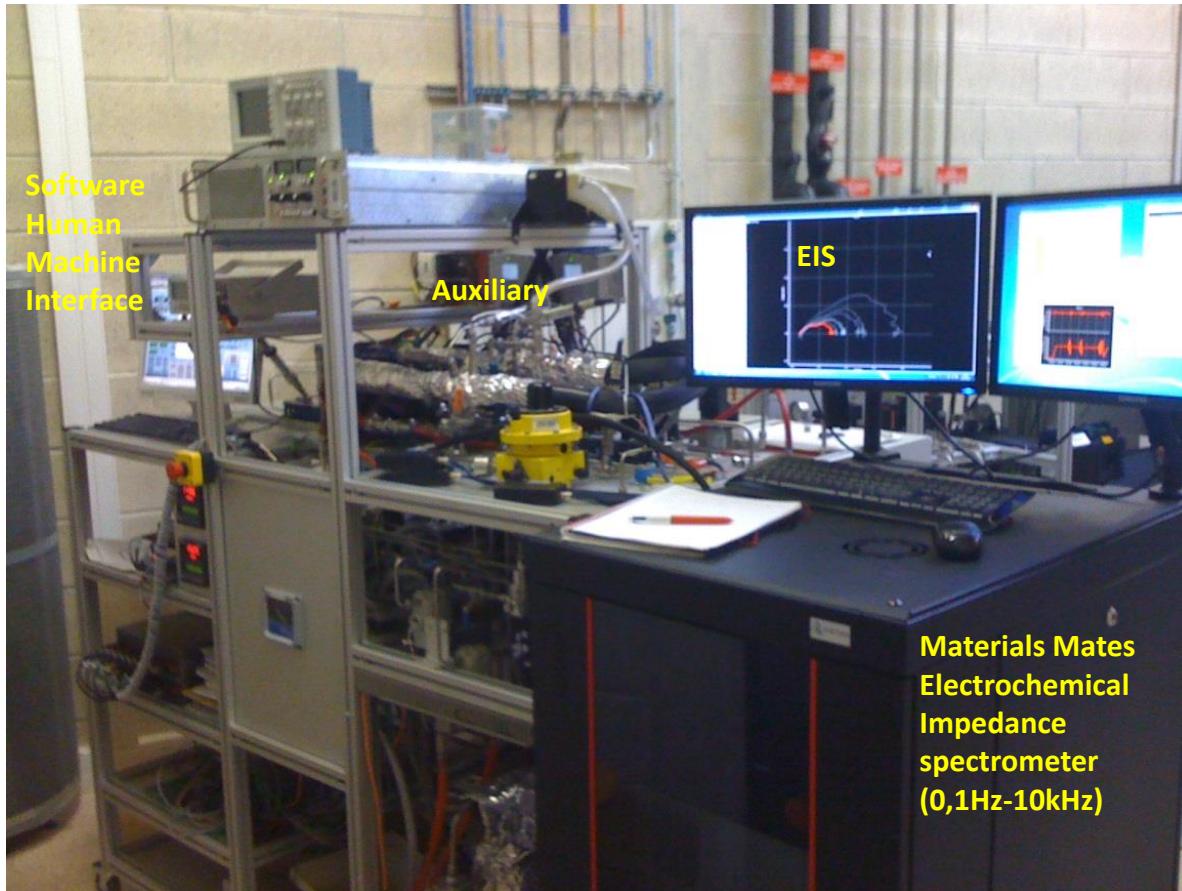
*Experiments done in the frame of micro-cogeneration project.*



### Design for μCHP application

### 3. Experimental process

- Test bench of the fuel cells test platform in Belfort - France



Acquired data:

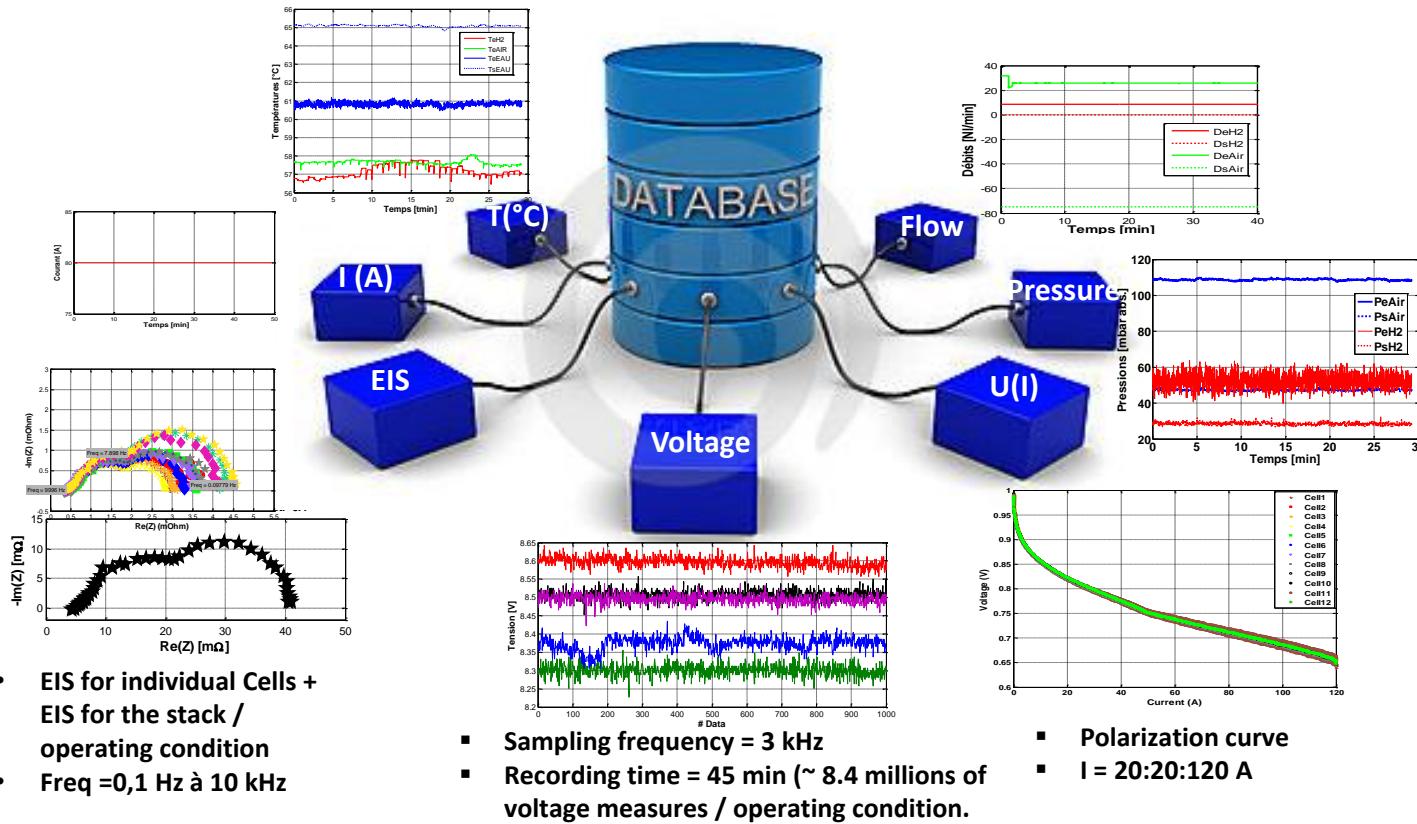
- Stack voltage
- Individual cell voltage
- Current
- Power
- Gas pressures
- Gas flows
- Temperatures
- Hygrometry rates
- Impedance spectra (stack & cells)

### 3. Experimental process

- The various fault scenarios have been introduced by changing different parameter values from the nominal ones :
  - cathode stoichiometry rate '**FSC**' – anode stoichiometry rate '**FSA**' – gas pressure '**P**' –
  - cooling circuit temperature '**T**' – Relative humidity level '**RH**' – carbon monoxide '**CO**' poisoning –

Parameters value	Ref		DFSC		DFSA		DP		DT		DH		DCO	
	PEMFC Automotive	PEMFC $\mu$ CHP	PEMFC Automotive	PEMFC $\mu$ CHP	PEMFC Automotive	PEMFC $\mu$ CHP	PEMFC Automotive	PEMFC $\mu$ CHP	PEMFC Automotive	PEMFC $\mu$ CHP	PEMFC Automotive	PEMFC $\mu$ CHP	PEMFC Automotive	PEMFC $\mu$ CHP
<b>FSC</b>	2	2	<u>1.3</u>	<u>2.6</u> <u>1.6</u>	2	2	2	2	2	2	2	2	2	2
<b>FSA</b>	1.5	1.3	1.5	1.3	<u>1.3</u>	<u>1.5</u> <u>1.2</u>	1.5	1.3	1.5	1.3	1.5	1.3	1.5	1.3
<b>P(bars.abs)</b>	1.5	0.1	1.5	0.1	1.5	0.1	<u>1.3</u>	<u>ND</u>	1.5	0.1	1.5	0.1	1.5	0.1
<b>T(°C)</b>	80	70	80	70	80	70	80	70	<u>75</u>	<u>72</u> <u>65</u>	80	70	80	70
<b>RH (%)</b>	50	50	50	50	50	50	50	50	50	<u>ND</u>	<u>46</u> <u>54</u>	50	50	50
<b>Presence of CO (ppm)</b>	0	0	0	0	0	0	0	0	0	0	0	0	<u>10</u>	<u>ND</u>

### 3. Experimental process



## 4. Dynamic multifractality in the voltage signal

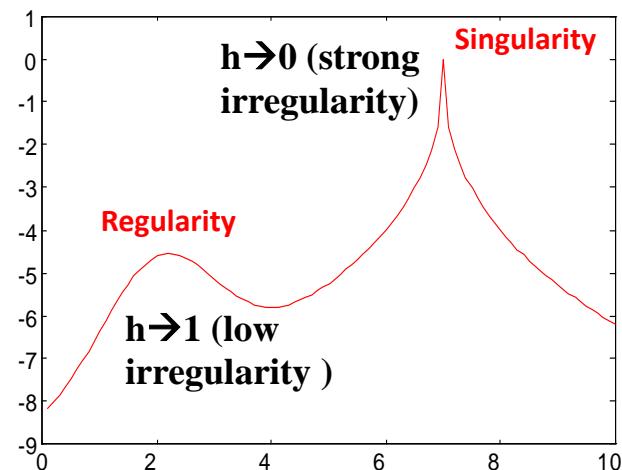
### – Method tools –

**Proposed method = pointwise singularity analysis of the PEMFC voltage signal**



To extract a latent information from the morphology of the stack voltage signal

- ☞ Pointwise regularity of the signal is measured by Hölder exponent « h ».
- ☞ The whole of the singularity strengths is represented by the singularity spectrum (SS).



Analysis method:

Discrete wavelets + multifractal formalism

# 4. Dynamic multifractality in the voltage signal

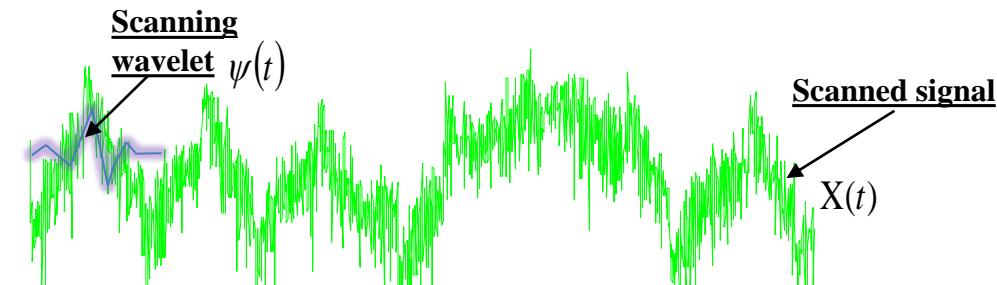
## – Method tools –

### ➤ Discrete wavelet transform

**Wavelet function:**  $\psi_{j,k}(t) = \frac{1}{2^j} \psi\left(\frac{t - 2^j k}{2^j}\right), j \in \mathbb{Z} \text{ and } k \in \mathbb{Z}$

$j \rightarrow$  multiresolution parameter.  $k \rightarrow$  time location.

**Wavelet coefficients:**  $d_X(j, k) = \int_R X(t) 2^{-j} \psi(2^{-j} t - k) dt$

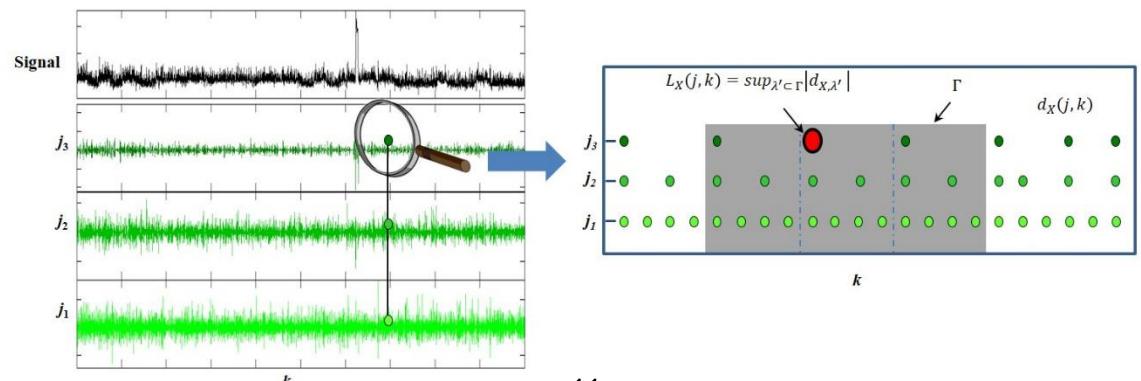


### ➤ Leader coefficients

**Diadic interval:**  $\lambda = [k \cdot 2^j, (k + 1) \cdot 2^j]$

**Diadic cube:**  $\Gamma = 3\lambda = \lambda_{j,k-1} \cup \lambda_{j,k} \cup \lambda_{j,k+1}$

**Leader coefficients:**  $L_X(j, k) = \sup_{\lambda' \subset \Gamma} |d_{X, \lambda'}|$



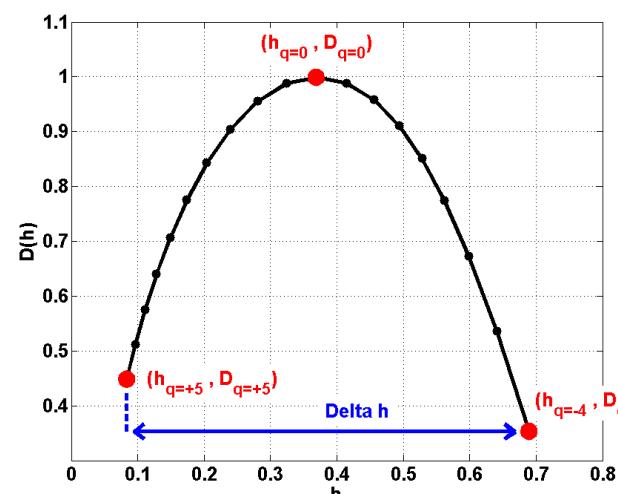
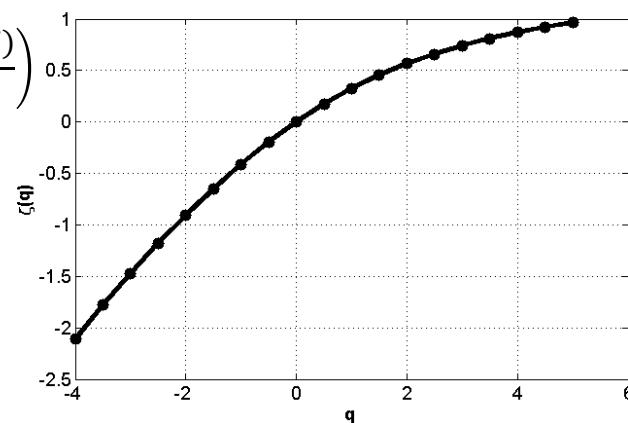
### ➤ Multifractal formalism

**Structure function:**  $S_L(q, j) = \frac{1}{n_j} \sum_{k=1}^{n_j} |L_X(j, k)|^q$

**Scale function:**  $\xi_L(q) = \liminf_{j \rightarrow 0} \left( \frac{\log_2 S_L(q, j)}{j} \right)$

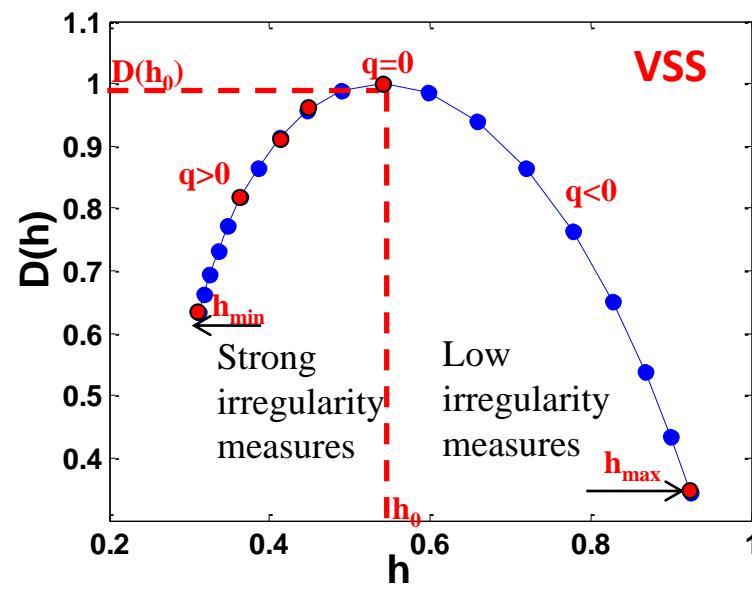
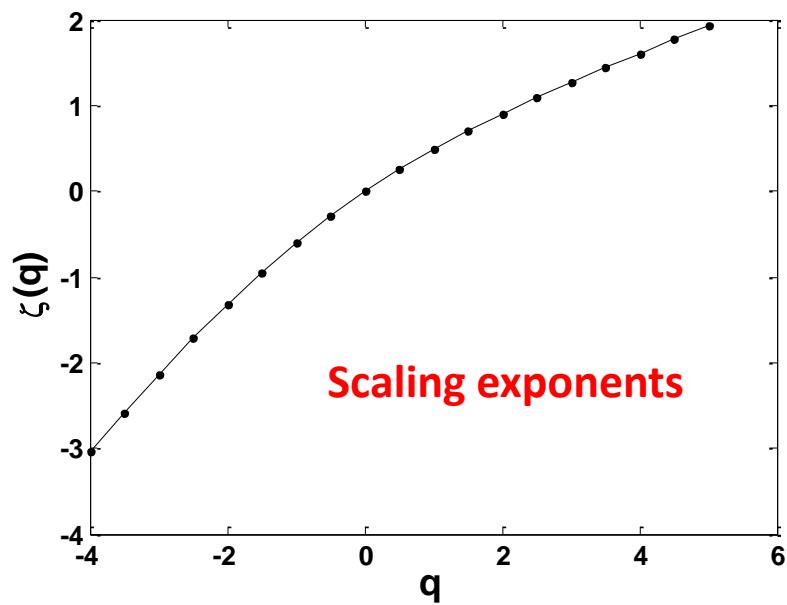
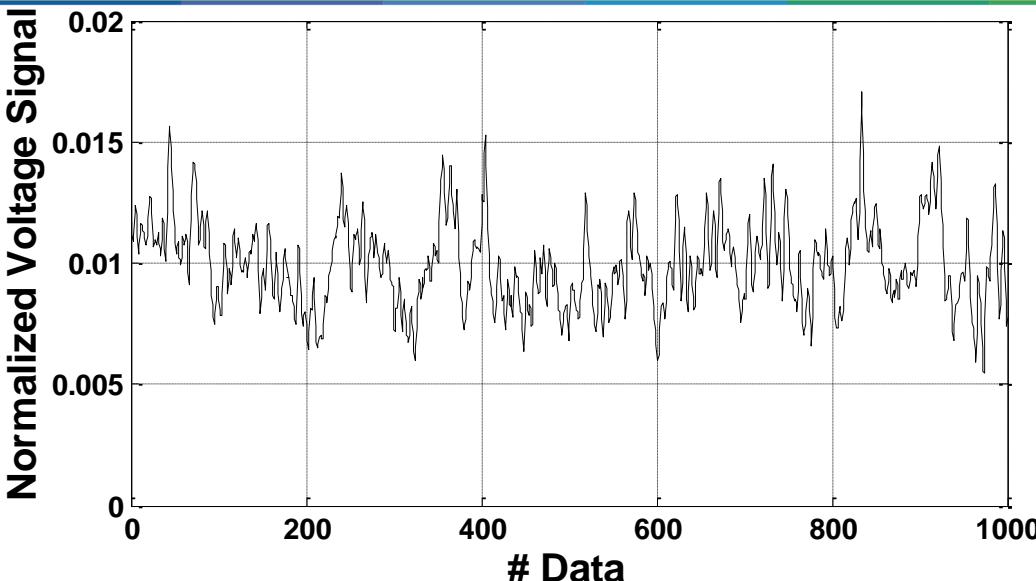
**Singularity spectrum (SS):**

$$D_q(h) = \inf_{q \neq 0} (1 + qh - \xi_L(q))$$



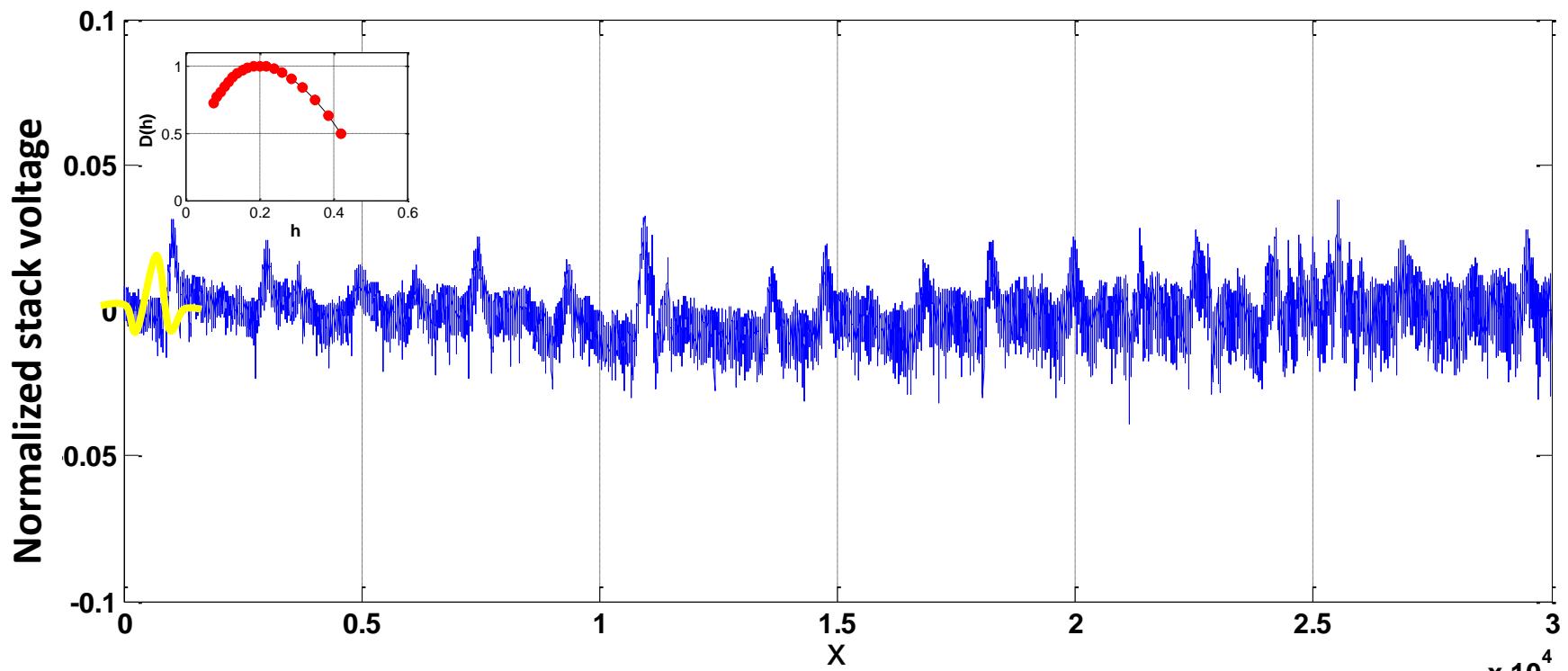
## 4. Dynamic multifractality in the voltage signal

– Voltage Singularity Spectrum (VSS) –



## 4. Dynamic multifractality in the voltage signal

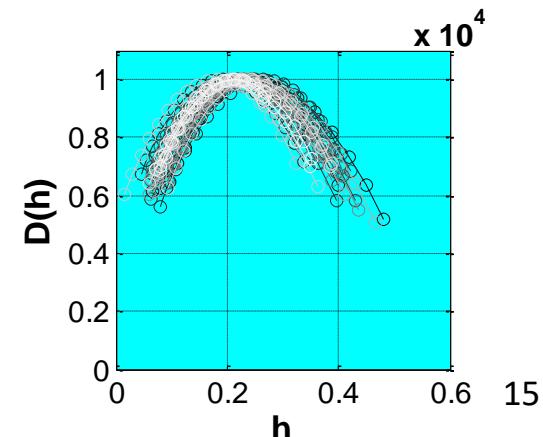
– Voltage Singularity Spectrum as a non intrusive tool for PEM Fuel Cells Diagnosis –



Test duration = 1 hour

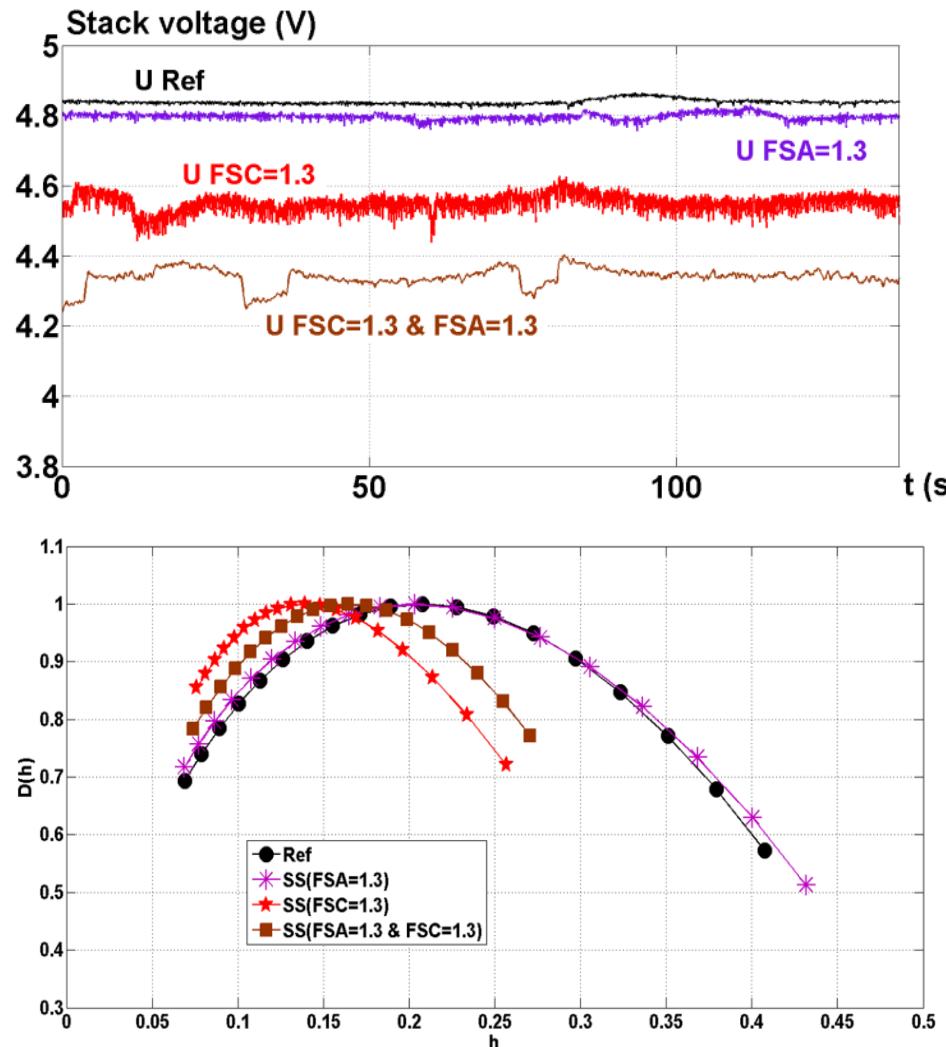
Signal duration / spectrum  $\approx 0.33$  s (windows of 1000 points).

VSS number / experimentation  $\approx 1090$  VSS.



## 4. Dynamic multifractality in the voltage signal

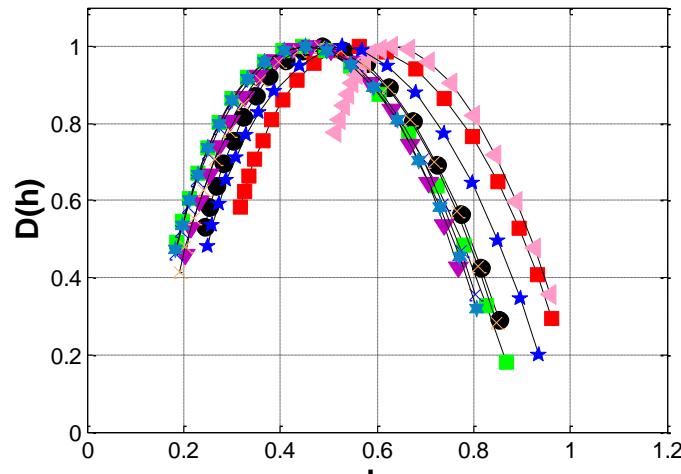
– Voltage Singularity Spectrum as a non intrusive tool for PEM Fuel Cells Diagnosis –



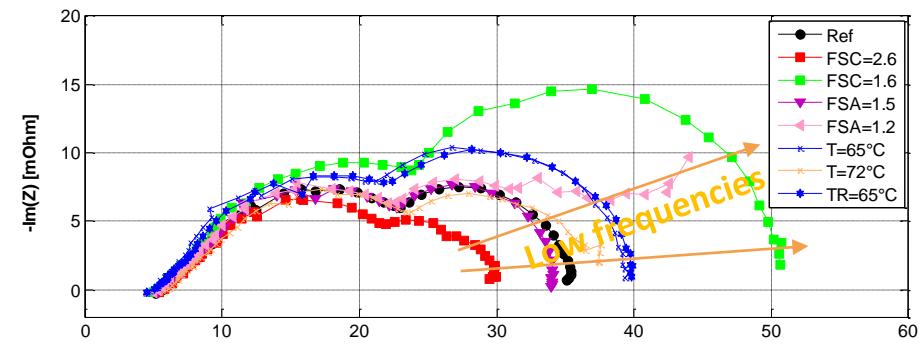
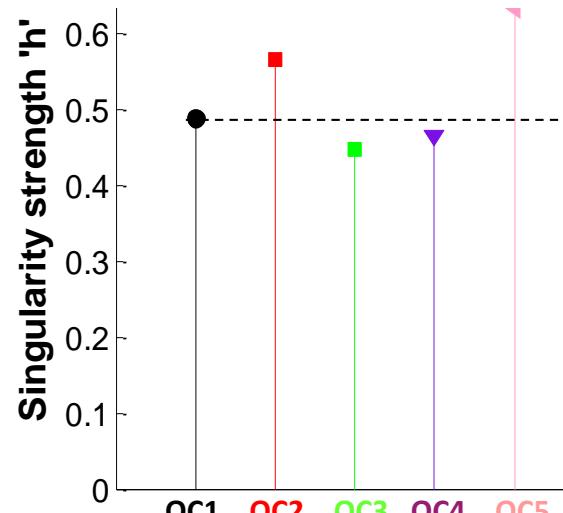
- These results highlight a **dynamic multifractality** in the voltage signal produced by the stack at different operating conditions.

# 4. Dynamic multifractality in the voltage signal

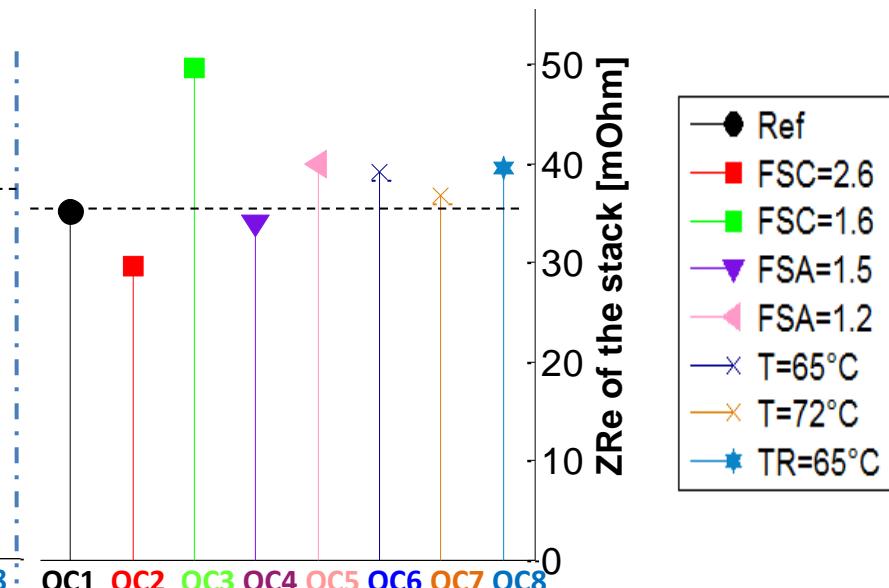
– Voltage Singularity Spectrum as a non intrusive tool for PEM Fuel Cells Diagnosis –



Typical curves of singularity spectrum obtained at various 'OC'.



Typical curves of electrochemical impedance spectrum obtained at various 'OC'.



High polarization resistance → Strong irregularity of the voltage signal ( $h \searrow$ )

Low polarization resistance → Low irregularity of the voltage signal ( $h \nearrow$ )

# 4. Dynamic multifractality in the voltage signal

## – Classification of the singularity spectrum pattern features –

**Supervised learning method: k-Nearest Neighboor 'KNN' method**

**Number of class= 10.**

**Training set= 200 observations.**

**Test set = 100 new observations.**

**Number of singularity features = 6.**

**Good classification rate = 89,61%**

**Ref : nominal conditions**

**DFSC : cathode flow failure ( $O_2$  starvation)**

**DFSA : anode flow failure ( $H_2$  starvation)**

**DP : gases pressure failure (low gases pressure)**

**DT : cooling circuit temperature failure (low  $T^\circ$ )**

**DCO : carbon monoxide poisoning ( $H_2 + CO$ )**



**PEMFC** Automotive

Class	$C_0$	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	$C_6$	$C_7$	$C_8$	$C_9$
Ref	<u>87.5</u>	0	0	<u>12.5</u>	0	0	0	0	0	0
DFSC	0	<u>100</u>	0	0	0	0	0	0	0	0
DFSA	0	0	<u>100</u>	0	0	0	0	0	0	0
DP	<u>50</u>	0	0	<u>50</u>	0	0	0	0	0	0
DT	0	0	0	0	<u>100</u>	0	0	0	0	0
DCO	0	0	0	0	0	<u>100</u>	0	0	0	0
DFSC & DP	0	0	0	0	0	0	<u>100</u>	0	0	0
DFSA & DP	0	0	0	0	0	0	0	<u>71.43</u>	<u>28.57</u>	0
DFSC & DFSA	0	0	0	0	0	0	0	0	<u>100</u>	0
DFSC & DFSA & DP	0	0	0	0	0	0	0	0	0	<u>100</u>

$C_0 \equiv \widehat{Ref}$ ,  $C_1 \equiv \widehat{DFSC}$ ,  $C_2 \equiv \widehat{DFSA}$ ,  $C_3 \equiv \widehat{DP}$ ,  $C_4 \equiv \widehat{DT}$ ,  $C_5 \equiv \widehat{DCO}$ ,  $C_6 \equiv \widehat{DFCS \& DP}$ ,

$C_7 \equiv \widehat{DFSA \& DP}$ ,  $C_8 \equiv \widehat{DFSC \& DFSA}$ ,  $C_9 \equiv \widehat{DFSC \& DFSA \& DP}$

# 4. Dynamic multifractality in the voltage signal

## – Classification of the singularity spectrum pattern features –

Supervised learning method: k-Nearest Neighbor ‘KNN’ method

Number of class = 9

Training set = 180 observations.

Test set = 90 new observations.

Number of singularity features = 6.

Ref : nominal conditions

$DFSC^{\uparrow}$ : cathode flow failure ( $O_2$  over-supply)

$DFSC_{\downarrow}$  : cathode flow failure ( $O_2$  starvation)

$DFSA^{\uparrow}$  : anode flow failure ( $H_2$  over-supply)

$DFSA_{\downarrow}$  : anode flow failure ( $H_2$  starvation)

$DT^{\uparrow}$  : cooling circuit temperature failure (high  $T^{\circ}$ )

$DT_{\downarrow}$  : cooling circuit temperature failure (low  $T^{\circ}$ )

$DRH^{\uparrow}$ : dew temperature failure (high  $dT^{\circ}$ )

$DRH_{\downarrow}$ : dew temperature failure (low  $dT^{\circ}$ )



PEMFC<sub>μCHP</sub>

Good classification rate = 95.55%

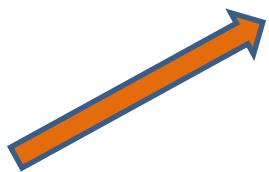
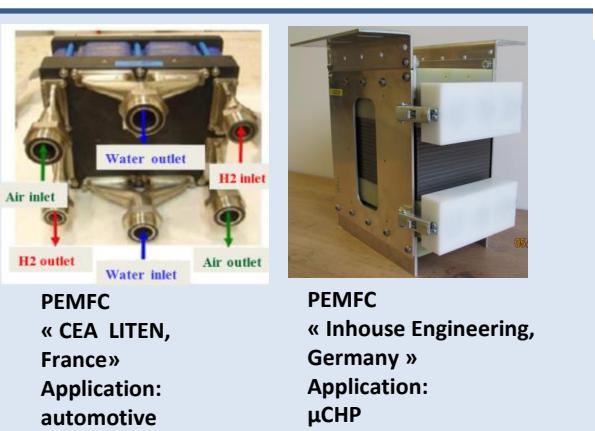
Class	$C_0$	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	$C_6$	$C_7$	$C_8$
Ref	<b>100</b>	0	0	0	0	0	0	0	0
$DFSC^{\uparrow}$	0	<b>100</b>	0	0	0	0	0	0	0
$DFSC_{\downarrow}$	0	0	<b>100</b>	0	0	0	0	0	0
$DFSA^{\uparrow}$	0	0	0	<b>90</b>	0	<b>10</b>	0	0	0
$DFSA_{\downarrow}$	0	0	0	0	<b>90</b>	0	0	0	<b>10</b>
$DT^{\uparrow}$	0	0	0	<b>20</b>	0	<b>80</b>	0	0	0
$DT_{\downarrow}$	0	0	0	0	0	0	<b>100</b>	0	0
$DRH^{\uparrow}$	0	0	0	0	0	0	0	<b>100</b>	0
$DRH_{\downarrow}$	0	0	0	0	0	0	0	0	<b>100</b>

$$C_0 \equiv \widehat{Ref}, C_1 \equiv \widehat{DFSC^{\uparrow}}, C_2 \equiv \widehat{DFSC_{\downarrow}}, C_3 \equiv \widehat{DFSA^{\uparrow}}, C_4 \equiv \widehat{DFSA_{\downarrow}}, C_5 \equiv \widehat{DT^{\uparrow}}, C_6 \equiv \widehat{DT_{\downarrow}},$$

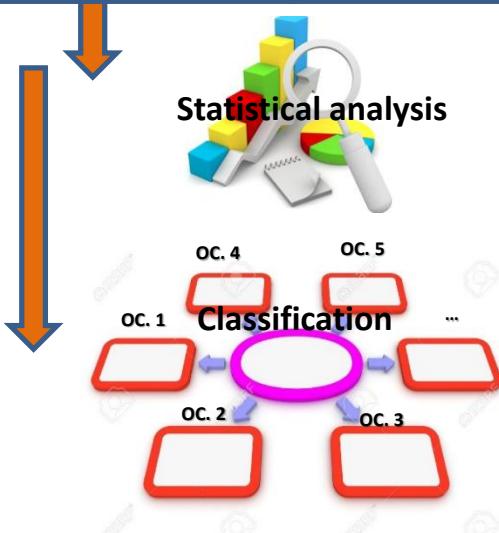
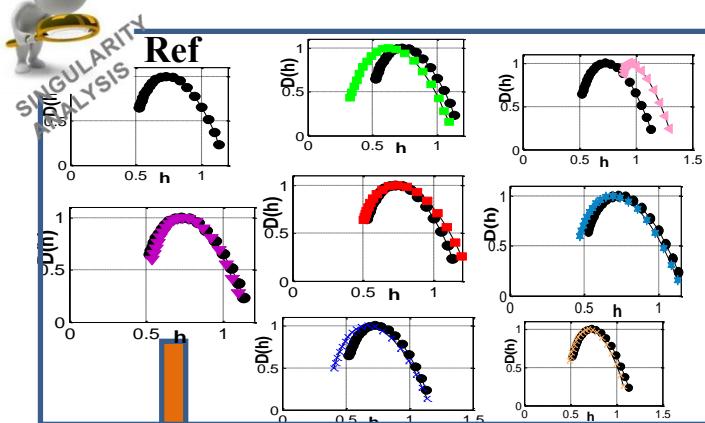
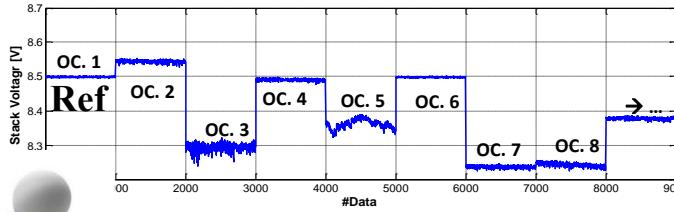
$$C_7 \equiv \widehat{DRH^{\uparrow}}, C_8 \equiv \widehat{DRH_{\downarrow}}$$

# 4. Dynamic multifractality in the voltage signal

## – Portability of the developed diagnosis tool –



Stack voltage signal for various operating conditions 'OC'



## RESULTS

Good classification rate

PEMFC<sub>Automotive</sub> / PEMFC <sub>$\mu\text{CHP}$</sub>

89.61 %      95.55%

OC studied

PEMFC<sub>Automotive</sub> / PEMFC <sub>$\mu\text{CHP}$</sub>

Ref	✓
DFSC	✓
DFSA	✗
DP	✓
DFSC&DP	✓
DFSA&DP	✓
DFSC&DSFA	✓
DFSC&DFSA&DP	✓

## 5. Conclusion & Future Works

- ☞ The singularity analysis based on wavelet leaders (mathematical microscope) highlights significant insights about the time dynamics of the fuel cell voltage during the considered operating conditions (fault scenarios).
- ☞ The computed singularity features describe the fuel cell time dynamics efficiently. These parameters offer good performance indicators on its SoH.
- ☞ The good classification rates obtained on the two experimented fuel cell (PEMFC<sub>Automotive</sub> and PEMFC<sub>μCHP</sub>) confirm the relevance of the developed diagnosis tool.
- ☞ The dynamic multifractality of the stack voltage can be considered as a pertinent non-intrusive tool for the monitoring of the fuel cell SoH.

In the near future:

- ☞ On-line implementation of the diagnosis tool.

THE QUESTION OF THE FUEL CELL DURABILITY  
“DYNAMIC MULTIFRACTALITY IN STACK VOLTAGE SIGNAL  
AS AN INDICATOR OF PEMFC SoH”

THANK YOU FOR YOUR ATTENTION

**D. Benouiuou<sup>1, 2, 4\*</sup>, D. Candusso<sup>1, 2, 4</sup>, F. Harel<sup>3, 4</sup>, P. Picard<sup>4,5</sup>**

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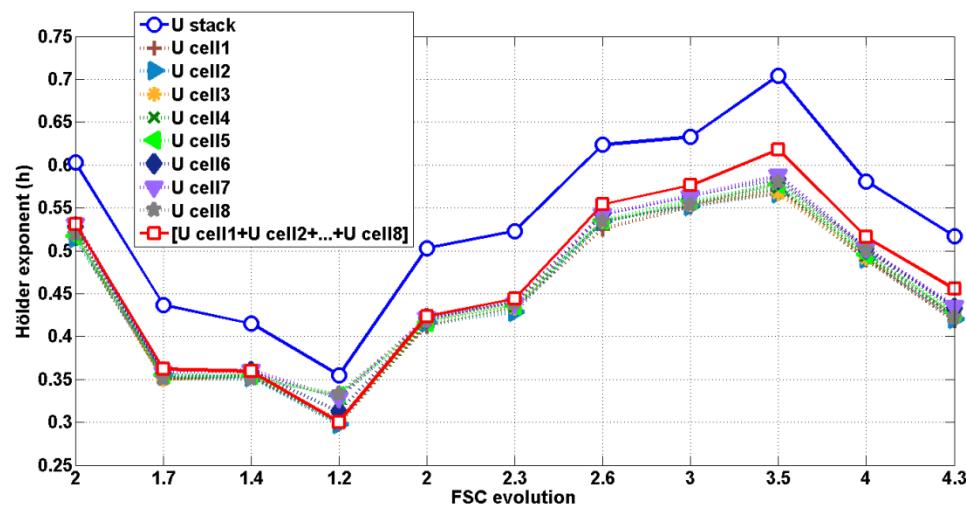
<sup>2</sup> IFSTTAR / COSYS / SATIE, UMR CNRS 8029, France.

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# Legendre transform

$$(x, y) \rightarrow (p, u)$$

