IEEE PHM 2014 Data Challenge

Outline, Experiments, Scoring of results, Winners

Contents

1 Overview

The IEEE Reliability Society, FCLAB research federation, FEMTO-ST Institute, and the Laboratory of excellence ACTION were proud to organize the IEEE PHM 2014 Data Challenge. The challenge was focused on the estimation of the remaining useful life (RUL) of a Proton Exchange Membrane Fuel Cell (PEMFC). Both Academic (from University) and Professional teams (from Industry) were encouraged to enter! The top scoring participants have been distinguished and invited to present at a special session of the 2014 IEEE International Conference on Prognostics and Health Management (`http://www.phmconf.org/`). To ensure equity during the competition, no member from FCLAB participated in the challenge.

1.1 Motivations and outline

Fuel Cell Systems (FCS) appear to be a promising energy conversion device to face some of the economic and environmental challenges of modern society. However, even if this technology is close to being competitive, it is not yet ready to be considered for large scale industrial deployment: FCS still must be optimized, particularly by increasing their limited lifespan. Indeed, Proton Exchange Membrane Fuel Cell systems (PEMFC) usually have a life span of around 2000 hours, whereas 6000 hours are required for some applications, including transportation... Enhancing FCS durability involves not only developing a better understanding of ageing phenomena but also requires the ability to emulate the behavior of the whole system to support the development of improvements to those systems. Prognostics and Health Management (PHM) of FCS is an emerging field of scientific and technological development that has the potential to provide and enable improvements in the life management, use and support of Fuel Cell Systems. This was the aim of our challenge: we expected participants to develop robust PHM methods to:

- assess the health state of a PEMFC FC (State of Health - SoH);
- predict its remaining useful life (RUL).

1.2 Challenge datasets

Challenge datasets are provided by FCLAB Research Federation (FR CNRS 3539, France, `http://eng.fclab.fr/`). Experiments were carried out on test facilities that enable normal or accelerated ageing of FCS stacks under constant and/or variable operating conditions, while controlling and gathering health monitoring data like power loads, temperatures, hydrogen and air stoichiometry rates, etc. The data sets provided for the challenge include both temporal and frequential data.

2 Experimental setup used for the challenge

2.1 Test bench

The test bench (Figure 1) is adapted for Fuel Cells with a power up to 1 kW (electrical power). Many physical parameters involved in the stack can be measured and controlled in order to master the FC operating conditions as accurately as possible (see Table 1):

- stack temperature, gas flows, air and hydrogen hygrometry rates;
- inlet and outlet flows (of hydrogen, air, and cooling water), inlet and outlet pressures (of hydrogen and air), temperatures (of incoming and outlet hydrogen, air, and cooling water),

single cell and stack voltages, current can be monitored using a home-made interface developed with Labview®.

The gas humidification is achieved through two independent boilers placed upstream of the stack. Air and hydrogen cross their respective boilers before reaching the stack. However, only the air boiler is heated in order to obtain the relative humidity desired. Meanwhile, the hydrogen boiler remains at the room temperature, given the operation of the dry anode gas. The temperature of the stack is controlled by a cooling water system. The current supplied by the battery is controlled by a TDI Dynaload active load.

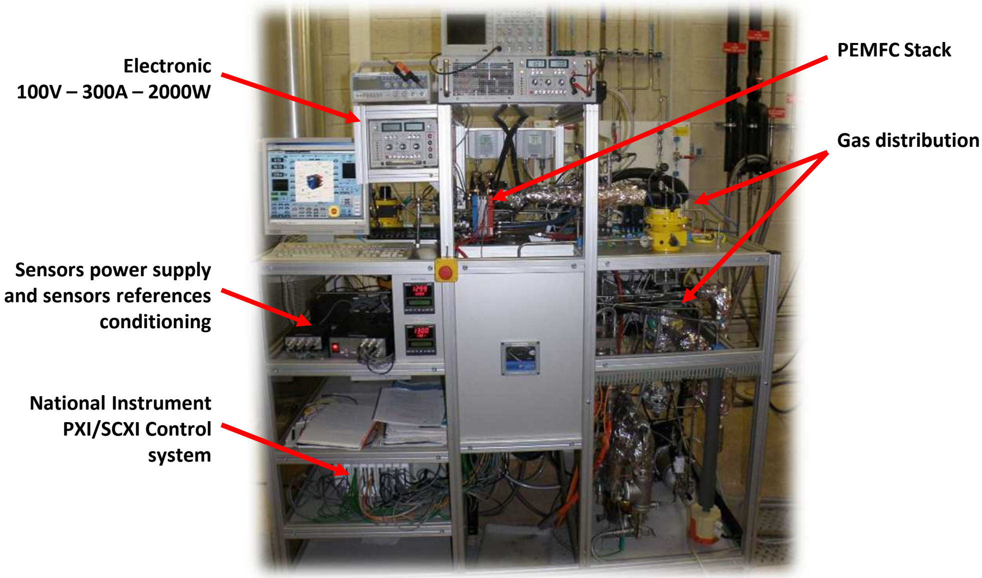

Figure 1: PEMFC Fuel Cell test bench @ FCLAB

Parameter	**Control range**
Cooling temperature	20 °C to 80 °C
Cooling flow	0 to 10 l/min
Gas temperature	20 °C to 80 °C
Gas humidification	0 to 100 % RH
Air flow	0 to 100 l/min
H2 flow	0 to 30 l/min
Gas pressure	0 to 2 bars
Fuel Cell current	0 to 300 A

Table 1: Range of physical parameters controlled

2.2 FC stacks used for the challenge

The considered fuel cell stacks tested were assembled at FCLAB. They are 5-cell stacks. Each cell has an active area of 100 cm^2. The PEM (Proton Exchange Membrane) FC (Fuel Cell) was here realized with commercial membranes, diffusion layers and machined flow distribution plates. The nominal current density of the cells is 0.70 A/cm^2. Their maximal current density is 1 A/cm^2.

3 Ageing tests performed for the challenge

3.1 Durability tests - protocol

Two long-term tests were carried out (Figure 2).

- A first stack was operated in stationary regime at roughly nominal operating conditions. This experiment serves actually as a reference test.
- A second stack was operated under dynamic current testing conditions, i.e. with high-frequency current ripples.

For both tests, characterizations were carried out once per week (around every 160 hours) according to an identical protocol: polarization curve test (i.e. measuring the static I/V curve of the fuel cell stack), global historic curves (i.e. evaluating the evolution over time of voltage levels), and Electrochemical Impedance Spectroscopy (EIS) measurement (i.e. measuring the "Nyquist" plot of the fuel cell stack over a frequency range from 50 mHz to 10 kHz).

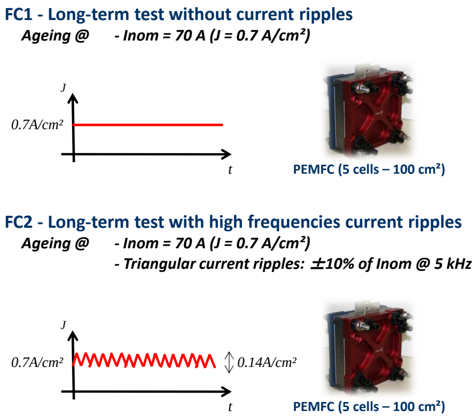

Figure 2: Durability tests performed for the challenge

3.1.1 FC1: Fuel Cell operated in stationary regime

The reference ageing test consisted in operating the FC stack in stationary conditions (a current of 70 A was imposed). A complete characterization of the FC was realized roughly every week: at time $t = 0; 48; 185; 348; 515; 658; 823; 991$ h (Table 2).

1. Firstly, an electrochemical impedance spectroscopy (EIS) was realized only at 0.70 A/cm^2, in order to evaluate the state of the FC before the measurement of the polarization curve (it can be mentionned that the measurement of the polarization curve can modify the internal state of the fuel cell stack, thus modifying the EIS results).
2. Secondly, polarization curve was realized: the stack and cells voltages were measured under a current ramp from 0 A/cm^2 to 1 A/cm^2 of 1000 s. In order to keep stoichiometric factors constant, the air and hydrogen flows were reduced accordingly until a current of 20 A. Below this value, the air and hydrogen flows are kept constant and equal to their values for a current of 20 A.
3. Then electrochemical impedance spectroscopy (EIS) was realized another time. Measurements have been made in the following order: constant current of 0.70 A/cm^2, 0.45 A/cm^2, 0.20 A/cm^2. Between every measure, a stabilization period of 15 minutes has been respected in order to guarantee the stability of parameters.

3.1.2 FC2: Fuel Cell operated under dynamic current

The second ageing test was performed under current dynamic solicitations: a ripple current of 70 A with 7 A oscillations at a frequency of 5 kHz was imposed to the FC in order to emulate the effect of connecting a power converter connected at the output of the FC stack. A complete characterization of the FC was realized every week (around every 160 hours) in the following order: first polarization curve and then electrochemical impedance spectroscopy (EIS) (with sames current density than in previous test). The characterizations were done at time: $t = 0; 35; 182; 343; 515; 666; 830; 1016$ h (Table 2).

FC1 (Without Ripple)	
Characterizations (Polarization + EIS)	@ $t = 0; 48; 185; 348; 515; 658; 823; 991$ h
1. EIS performed before polarization	@ $J = 0.70$ A/cm^2
2. Polarization curve	Ramp: from 0 A/cm^2 to 1 A/cm^2 of 1000 s
3. EIS performed after polarization	@ $J = \{0.70 ; 0.45 ; 0.20\}$ A/cm^2

FC2 (With Ripple)	
Characterizations (Polarization + EIS)	@ $t = 0; 35; 182; 343; 515; 666; 830; 1016$ h
1. Polarization curve	Ramp: from 0 A/cm^2 to 1 A/cm^2 of 1000 s
2. EIS performed after polarization	@ $J = \{0.70 ; 0.45 ; 0.20\}$ A/cm^2

Table 2: Resume of characterizations

3.2 Ageing data

Participants of the challenge were provided with ageing data that are briefly described here after.

3.2.1 Monitoring data

As stated before, test facilities enable normal or accelerated ageing of FCS stacks under constant and/or variable operating conditions, while controlling and gathering health monitoring data like power loads, temperatures, hydrogen and air stoichiometry rates, etc. These parameters are resumed in Table 3. As for an example of some monitoring index that was gathered, consider Figure 3. One can note the voltage drop as time grows, which depicts degradation phenomena within the stack.

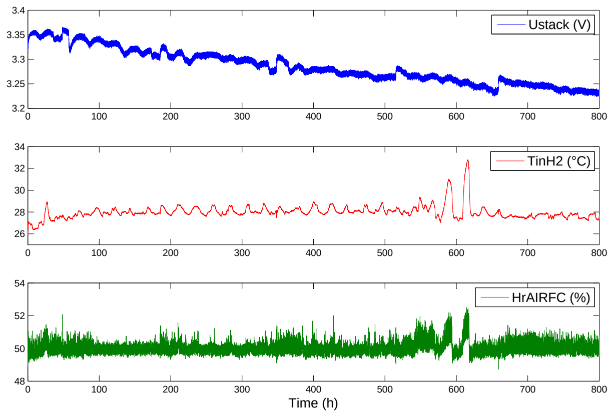

Figure 3: FC1 - example of monitoring index

3.2.2 Polarization curves and Electrochemical Impedance Spectroscopy

Data gathered during characterization phases also enable the observation of ageing phenomena. Indeed, polarization curves and Nyquist plots (obtained thanks to EIS) allow catching the static and dynamic behaviors of the stack. These curves give useful information regarding losses and internal physical parameters of the stack. As for some illustrations, consider Figure 4.

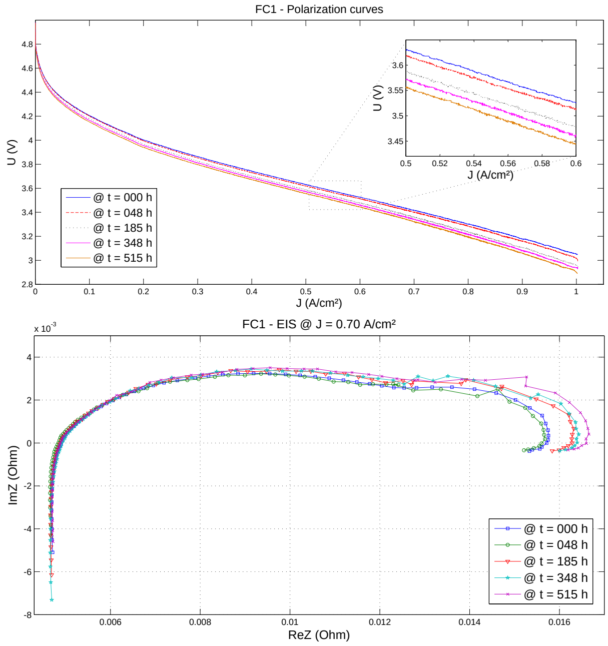

Figure 4: FC1 - some polarization curves and Nyquist plots obtained over time

Index *(as in datasets)*	**Physical meaning**
Time	Ageing time (h)
U1 to U5 ; Utot	Single cells and stack voltage (V)
I ; J	Current (A) and current density (A/cm^2)
TinH2 ; ToutH2	Inlet and Outlet temperatures of H2 (°C)
TinAIR ; ToutAIR	Inlet and Outlet temperatures of Air (°C)
TinWAT ; ToutWAT	Inlet and Outlet temp. of cooling Water (°C)
PinH2 ; PoutH2	Inlet and Outlet Pressure of H2 (mbara)
PinAIR ; PoutAIR	Inlet and Outlet Pressure of Air (mbara)
DinH2 ; DoutH2	Inlet and Outlet flow rate of H2 (l/mn)
DinAIR ; DoutAIR	Inlet and Outlet flow rate of Air (l/mn)
DWAT	Flow rate of cooling water (l/mn)
HrAIRFC	Inlet Hygrometry (Air) - estimated (%)

Table 3: Ageing parameters gathered during experiments

4 IEEE PHM 2014 Data Challenge

4.1 Data provided for the challenge

Two kinds of data were available for the challenge (section 3.2): polarization and EIS parameters as defined in Table 2, and ageing parameters as defined in Table 3. According to this, participants were provided with 2 sets of data (Figure 5)[1].

1. Data from experiment on FC1 (Fuel Cell operated in stationary regime) were fully given. This set of data was refereed as the "learning dataset".
2. Data from experiment on FC2 (Fuel Cell operated under dynamic current) were partially given: only data until time $t = 550$ h were available. This set of data was refereed as the "testing dataset"

Note that downloadable folders are labeled as follows: '`FC1_Without_Ripples.7z`' for the "learning dataset", '`FC2_With_Ripples.7z`' for the "testing dataset". The complete "testing dataset" (including hidden part) is also made publicly available: '`Full_FC2_With_Ripples.7z`'.

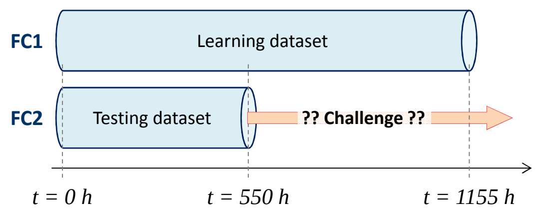

Figure 5: Illustration of learning and testing datasets

4.2 PHM challenge - Part 1: State of Health estimation

As mentioned before, Nyquist plots (obtained thanks to EIS) allow catching the dynamic behavior of a stack and give useful information regarding its internal physical parameters. According to that, the State of Health estimation has been addressed in the challenge by considering frequential domain.

Participants were expected to predict the real and imaginary parts of the impedance of FC2 (ReZ ; ImZ) for a defined current density ($J = 0.70$ A/cm^2) at different instants (@ $t =$ 666; 830; 1016 h). In other words, the aim of this part of the challenge was to approximate physical characteristics of the stack upon time. Estimates to be provided by participants are resumed in Table 4.

$J = 0.70$ A/cm^2	@ $t = 666$ h	@ $t = 830$ h	@ $t = 1016$ h
Frequency $Fr = 50$ mHz	?? ReZ ; ImZ (Ohm) ??		
Frequency $Fr = 789$ mHz			
Frequency $Fr = 5.18$ Hz			
Frequency $Fr = 505$ Hz			

Table 4: Challenge Part 1: SoH estimation - estimates to be provided by participants

[1] Organization of data is described in Appendix A.1

4.3 PHM challenge - Part 2: Remaining Useful Life (RUL) prediction

As being a promising energy converter, a Fuel Cell system is expected to furnish a certain amount of electrical power for a given period of time. According to that, mission achievement can be defined as the ability of a FC to ensure sufficient power at any time. Due to degradation phenomena, this ability drops however, and this is what was proposed to be predicted.
Remaining Useful Life (RUL) was defined for the challenge, as the time before a certain amount of power losses is reached. More precisely, various power drops were considered: 3.5 %, 4 %, 4.5 %, 5 %, 5.5 % of initial power (P_{init}). Here again, the challenge was focused on FC2: participants were expected to predict the remaining time before those power losses are obtained (assuming that predictions are made @ $t_{pred} = 550$ h). Estimates to be provided by participants are resumed in Table 5.

t_{pred} = 550 h	RUL estimates
Failure threshold: 3.5 % of P_{init}	
Failure threshold: 4.0 % of P_{init}	
Failure threshold: 4.5 % of P_{init}	?? $\widehat{RUL}$??
Failure threshold: 5.0 % of P_{init}	
Failure threshold: 5.5 % of P_{init}	

Table 5: Challenge Part 2: RUL prediction - estimates to be provided by participants

4.4 Scoring of results

Applicants were **not** required to participate to both parts of the challenge: they were able to either submit results on SoH estimation or on RUL prediction (or both). The two parts of the challenge were thereby scored independently: winners for each parts of the challenge were designed.

4.4.1 Scoring of SoH estimation

Teams have been scored based on their estimates that have been converted into euclidean distance to actual values. Consider following notations.

- $Fr \in \{50 \text{ mHz}; 789 \text{ mHz}; 5.18 \text{ Hz}; 505 \text{ Hz}\}$: frequency of estimates as defined in Table 4;
- $t \in \{666; 830; 1016 \text{ h}\}$: instant of estimate as defined in Table 4;
- $ActSoH_{Fr/t} = \{ReZ_{Fr/t}; ImZ_{Fr/t}\}$: actual SoH characteristics to be predicted;
- $\widehat{SoH}_{Fr/t} = \{\widehat{ReZ}_{Fr/t}; \widehat{ImZ}_{Fr/t}\}$: estimated SoH characteristics (by a participant).

According to that, the euclidean distance on a single estimate is defined by:

$$ED_{Fr/t} = \sqrt{\left(ReZ_{Fr/t} - \widehat{ReZ}_{Fr/t}\right)^2 + \left(ImZ_{Fr/t} - \widehat{ImZ}_{Fr/t}\right)^2} \quad (1)$$

Estimates were not considered in the same manner as times grows. Thereby, the error of estimates for each times t was defined as:

$$Err_t = \frac{1}{t - 550} \sum_{Fr} (ED_{Fr/t}) \quad (2)$$

and the final score of all SoH estimates was defined as being the mean of all Err_t:

$$\boxed{Score_{SoH} = \frac{1}{3}\sum_t (Err_t)} \tag{3}$$

Obviously, $Score_{SoH}$ was expected to be as low as possible.

4.4.2 Scoring of RUL prediction

Teams have been scored based on their RUL results that have been converted into percent errors of predictions. Consider following notations.

- $FT \in \{3.5; 4.0; 4.5; 5.0; 5.5\ \%\}$: failure threshold defined in Table 5;
- $ActRUL_{FT}$: actual RUL before FT is reached to be predicted;
- $\widehat{RUL}_{FT}$: estimated RUL before FT is reached (by a participant).

According to that, the percent error on a RUL estimate was defined by:

$$\%Er_{FT} = 100 \times \frac{ActRUL_{FT} - \widehat{RUL}_{FT}}{ActRUL_{FT}} \tag{4}$$

Underestimates and overestimates were not considered in the same manner: good performance of estimates relates to early predictions of RUL (i.e. cases where $\%Er_{FT} > 0$), with deduction to early removal, and more severe deductions for RUL estimates that exceed actual RUL (i.e. cases where $\%Er_{FT} < 0$). The score of accuracy of a RUL estimate was thereby defined as follows:

$$A_{FT} = \begin{cases} exp^{-ln(0.5).(\%Er_{FT}/5)} & \text{if } \%Er_{FT} \leq 0 \\ exp^{+ln(0.5).(\%Er_{FT}/20)} & \text{if } \%Er_{FT} > 0 \end{cases} \tag{5}$$

Figure 6 depicts the evolution of this scoring function. The final score of all RUL estimates was defined as being the mean of all A_{FT}:

$$\boxed{Score_{RUL} = \frac{1}{5}\sum_{FT} (A_{FT})} \tag{6}$$

Obviously, $Score_{RUL}$ was expected to be as greater as possible ($max = 1$).

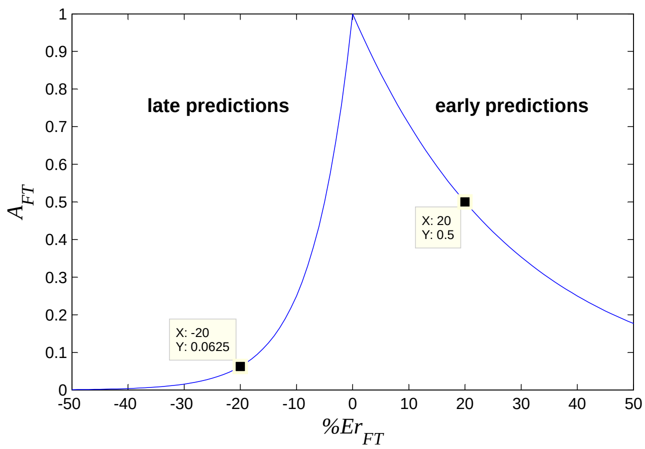

Figure 6: Scoring function of a RUL estimate according to its percent error

5 Actual SOHs and RULs, and top-scoring participants

5.1 Actual SOHs to be estimated

@ t_{pred} = 666 h	ReZ (Ohm)	ImZ (Ohm)
$Fr = 50$ mHz	0.01661200	-0.00032995
$Fr = 789$ mHz	0.01705200	+0.00106490
$Fr = 5.18$ Hz	0.01371100	+0.00313550
$Fr = 505$ Hz	0.00500670	+0.00049070
@ t_{pred} = 830 h	ReZ (Ohm)	ImZ (Ohm)
$Fr = 50$ mHz	0.01769600	-0.00034782
$Fr = 789$ mHz	0.01812300	+0.00132880
$Fr = 5.18$ Hz	0.01413400	+0.00353000
$Fr = 505$ Hz	0.00499880	+0.00055520
@ t_{pred} = 1016 h	ReZ (Ohm)	ImZ (Ohm)
$Fr = 50$ mHz	0.01888100	-0.00028024
$Fr = 789$ mHz	0.01915200	+0.00151630
$Fr = 5.18$ Hz	0.01475700	+0.00389130
$Fr = 505$ Hz	0.00498770	+0.00057563

Table 6: Challenge Part 1: SOH estimation - actual values ($J = 0.70$ A/cm^2)

5.2 Actual RULs to be predicted

t_{pred} = 550 h	RUL estimates
Failure threshold: 3.5 % of P_{init}	021.4442 h
Failure threshold: 4.0 % of P_{init}	194.1917 h
Failure threshold: 4.5 % of P_{init}	209.7127 h
Failure threshold: 5.0 % of P_{init}	384.3280 h
Failure threshold: 5.5 % of P_{init}	386.7023 h

Table 7: Challenge Part 2: RUL prediction - actual values

5.3 Top-scoring participants

- SOH estimation

– WINNER FROM UNIVERSITY (Top scoring participant)
  - Depart. of Mechanical & Aerospace Engineering, Seoul National University, Korea
  - Contact: Youn Byeng Dong (Professor) - `bdyoun@snu.ac.kr`
  - $Score_{SoH} = 5.3177e^{-6}$

– WINNER FROM INDUSTRY
  - EMBRAER, São José do Campos, Brazil
  - Contact: Ivo Medeiros (R&D Engineer) - `ivo.medeiros@embraer.com.br`
  - $Score_{SoH} = 7.8932e^{-6}$

- RUL prediction

– WINNER FROM UNIVERSITY (Top scoring participant)
  - Depart. of Mechatronic & Dynamic, University of Paderborn, Germany
  - Contact: James K. Kimotho (Scientist) - `jkimotho@campus.uni-paderborn.de`
  - $Score_{RUL} = 0.7760$

– WINNER FROM INDUSTRY
  - IBM Almaden Research Center, San Jose, CA, USA
  - Contact: Axel Hochstein (Dr., Research Staff) - `ahochst@us.ibm.com`
  - $Score_{RUL} = 0.3592$

6 Acknowledgment and contact point

Datasets are being made publicly available. Publications making use of these databases are requested to explicitly mention in an acknowledgment paragraph that data were provided by FCLAB Federation, FR CNRS 3539, France.

For any request please contact the local organizing committee (Rafael Gouriveau, Mickaël Hilairet, Daniel Hissel, Samir Jemeï, Marine Jouin, Elodie Lechartier, Simon Morando, Elodie Pahon, Marie-Cécile Péra, Noureddine Zerhouni) at:
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`http://www.labex-action.fr/en`

A Appendix

A.1 ASCII files

Both learning and test datasets are given in "7z" compressed folders (`FC1_Without_Ripples`) and (`FC2_With_Ripples`). Each one contains monitoring and characterization ASCII files:

- "`FC#_EIS##A_prepola_T###.csv`": EIS data before polarization as depicted in Table 2;
- "`FC#_EIS##A_postpola_T###.csv`": EIS data after polarization as depicted in Table 2;
- "`FC#_Pola_T###.csv`": data from polarization curves as depicted in Table 2;
- "`FC#_Ageing_part#.csv`": monitoring data as depicted in Table 3.

EIS data. In each ASCII file, data are arranged as follows ("Col." states for "Column").
- Col. 1: Frequency, expressed in Hz;
- Col. 2: ReZ, expressed in Ohm;
- Col. 3: ImZ, expressed in Ohm.

Polarization data. In each ASCII file, data are arranged as follows ("Col." states for "Column").
- Col. 1-5: cells voltages, expressed in V;
- Col. 6: stack voltage, expressed in V;
- Col. 7: current, expressed in A;
- Col. 8: current density, expressed in A/cm^2.

Monitoring data. In each ASCII file, data are arranged as follows ("Col." states for "Column").
- Col. 1: time (t), expressed in h;
- Col. 2-6: cells voltages ($U1/5$), expressed in V;
- Col. 7: stack voltage ($Utot$), expressed in V;
- Col. 8: current density (J), expressed in A/cm^2;
- Col. 9: current (I), expressed in A;
- Col. 10-11: inlet/outlet temp. of H2 ($TinH2$, $ToutH2$), expressed in °C;
- Col. 12-13: inlet/outlet temp. of Air ($TinAIR$, $ToutAIR$), expressed in °C;
- Col. 14-15: inlet/outlet temp. of cooling water ($TinWAT$, $ToutWAT$), expressed in °C;
- Col. 16-17: inlet/outlet pressure of Air ($PinAIR$, $PoutAIR$), expressed in mbara;
- Col. 18-19: outlet/inlet pressure of H2 ($PoutH2$, $PinH2$), expressed in mbara;
- Col. 20-21: inlet/outlet flow rate of H2 ($DinH2$, $DoutH2$), expressed in l/mn;
- Col. 22-23: inlet/outlet flow rate of Air ($DinAIR$, $DoutAIR$), expressed in l/mn;
- Col. 24: flow rate of cooling water ($DWAT$), expressed in l/mn;
- Col. 25: inlet hygrometry of Air ($HrAIRFC$), estimated %.