Data Article

Impact of current ripples on the durability of proton exchange membrane fuel cells based on two ageing datasets

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A R T I C L E   I N F O

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A B S T R A C T

The dataset proposed two long term tests to evaluate the impact of the current ripples of the fuel cell durability. To be able to compare both degradations, the first ageing test is performed under steady-state conditions at constant current. This time series could be used as the durability reference. While the second long-term test is dedicated to degradation under rippled current with high frequency triangular perturbations, similar to the load imposed by a power converter. Thus, the second time series considers the actual degradation that could appear on an embedded system. Both tests are running on two fresh proton exchange membrane fuel cell (PEMFC) stacks composed of 5-cells during around 1000 h, to make degradation comparable. An in-lab test bench is used to monitor all the fluidic, thermal and electric parameters thanks to a National Instruments acquisition device and an in-lab designed Labview software. Some polarization curves and electrochemical impedance spectra (EIS) are performed periodically during both durability tests. Both datasets provide to study the performance degradation along time for steady-state and rippled solicitations. These datasets can be directly used to validate some prognostics approaches and estimate the remaining useful lifetime (RUL).

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### Specifications Table

| Subject                          | Energy Engineering and Power Technology |
|----------------------------------|----------------------------------------|
| Specific subject area            | Long-term ageing tests performed on two PEMFC stacks supplying constant DC current and rippled current based on 1kW-test bench |
| Type of data                     | Table                                  |
| How the data were acquired       | The datasets were acquired thanks to a 1kW in-lab test bench using National Instruments acquisition cards combined with a Labview software. The polarization curves were implemented on the software too. The electrochemical impedance spectra (EIS) have been performed through an in-lab plug in impedancemeter also based on National Instruments acquisition cards and a Labview software. |
| Data format                      | Raw                                    |
| Description of data collection   | All the electric, fluidic and thermal parameters were recorded with an acquisition frequency of 1 Hz. The EIS frequency range is comprised between 50 mHz and 10 kHz. Fuel cell 1: long-term test under steady state with a nominal current density of 0.7A/cm². Fuel cell 2: long-term test with high frequency triangular current ripples (±10% of the nominal current density @ 5 kHz). |
| Data source location             | Institution: FEMTO-ST Institute / FCLAB / Univ. Bourgogne Franche-Comté  
• City/Town/Region: Belfort  
• Country: France  
• Latitude and longitude (and GPS coordinates, if possible) for collected samples/data: 47.6428111 / 6.8456559 |
| Data accessibility               | Repository name: IEEE PHM Data Challenge  
Data identification number: doi:10.25666/DATAUBFC-2021-07-19  
Direct URL to data: https://mycore.core-cloud.net/index.php/s/Auus4Gts0vlij31  
Instructions for accessing these data: The dataset is store and registered on an OpenData portal named “DataOSU/Dat@UBFC” [1]. Please follow the direct URL or the DOI and Click Data access button on the top right of the webpage |

### Value of the Data

- Two datasets are available with two kinds of long-term tests (1000 h for each) performed on two fresh PEMFC stacks: constant current and rippled current ageing. Periodic characterizations are included in with polarization curves and EIS that are the two main techniques to study ad evaluate the degradation mechanisms of the PEMFCs. The degradation trends could be compared depending on the load profile.
- Researchers in fuel cell durability fields can benefit from these data. Besides, the datasets can be used to validate some prognostics approaches and evaluate the robustness and the accuracy of such forecasting models. The datasets could be used to build an effective model that can predict the evolution of degrading indicators and estimating the Remaining Useful Life (RUL) of the PEMFCs.
- These datasets could be used to study the fuel cell ageing phenomenon. Moreover, they could help to design a new ageing protocol with more dynamics to accelerate the ageing or to study the impact of the current ripples by using sinus or square current ripples instead of triangles.
- The datasets could be reused for prediction way to determine or estimate the RUL as in the PHM Data Challenge 2014 [2–4]. In this challenge, participants could train their
algorithm on the steady state time series or on the dynamic ones to forecast the end-of-life on the dedicated dataset but it is also possible to train the forecasting algorithm on the reference time series to estimate the remaining useful lifetime of the second ones. This is possible because it is the same stack, provide by the same manufacturer with the same specifications and coming from the same supply chain.

1. Data Description

Both datasets included the characterizations (polarization curves and EIS) are detailed in this section. The complete shared datasets are available on IEEE PHM Data Challenge repository. Two separated files have been created: one per long-term durability test.

(1) Dataset #1 - Steady-state conditions:

“FC1_Without_Ripples_Excel” fold is dedicated to the steady-state durability test. This folder contains 42 excel format files.

(a) Raw data

There are three excel data files for the durability test dataset #1 which was recording during the test period. The dataset #1 files are named according to the experiment time:

- “FC1_Ageing_part1.csv” recorded data from 0 to 497 h;
- “FC1_Ageing_part2.csv” recorded data from 497 to 1046 h;
- “FC1_Ageing_part3.csv” recorded data from 1046 to 1154 h.

With an acquisition frequency of 1 Hz.

Table 1 presents all the parameters gathered during the durability test; the explicit physical meaning of the parameters was introduced. The ageing time is recorded in the time column. The current is set and controlled by a TDI Dynaload active load. The inlet gas temperatures are set at 28 °C and 42 °C for Hydrogen and Air, respectively. The regulation is based on inlet values. The outlet temperature of the water cooling is considered the stack temperature and is maintained to 55 °C. The gas pressures are regulated in inlet and set at 1300 mbar absolute (= 1300 hPa). The stoichiometric values are 2 and 4 for Hydrogen and Air respectively. These parameters are linked to the inlet gas flows. The water-cooling flow is set at 2lpm and the relative humidities are set 0% and 50% for Hydrogen and Air, respectively.

(b) Electrochemical Impedance Spectra (EIS) measurements

The EIS are also measured for the steady-state durability test. It exists 31 files dedicated to EIS for different current densities:

| Table 1 | Ageing parameters gathered during experiments. |
|------------------------|---------------------------------------------|
| Index (as in datasets) | Physical meaning [Unit]                      |
| Time                   | Ageing time [h]                              |
| U1 to U5; Utot         | Single cells and stack voltage [V]           |
| I; J                   | Current [A]; Current density [A/cm²]         |
| T_inH₂; T_outH₂        | Inlet and outlet temperatures of H₂ [°C]     |
| T_inAir; T_outAir      | Inlet and outlet temperatures of Air [°C]    |
| T_inWat; T_outWat      | Inlet and outlet temperatures of water cooling [°C] |
| P_inH₂; P_outH₂        | Inlet and outlet pressures of H₂ [mbar]       |
| P_inAir; P_outAir      | Inlet and outlet pressures of Air [mbar]      |
| D_inH₂; D_outH₂        | Inlet and outlet flow rates of H₂ [slpm]      |
| D_inAir; D_outAir      | Inlet and outlet flow rates of Air [slpm]     |
| D_outWat               | Outlet flow rate of water cooling [lpm]       |
| HR_outAirFC            | Inlet air relative humidity – estimated [%]   |
• 0.70A/cm² for the EIS performed before the polarization curves named “FC1_EIS70A_prepolA_Txxx.csv” were “xxx” is corresponding to the ageing time (i.e. the EIS performed before the polarization curve after 991 h of running is recorded in the file named “FC1_EIS70A_prepolA_T991.csv”)

• 0.70; 0.45; 0.20 A/cm² for the EIS measured after the polarization curve named “FC1_EISyyA_postpola_Txxx.csv” were “xxx” is corresponding to the ageing time and “yy” stands for the current density (i.e. the EIS performed after the polarization curve after 991 h of running at a current density of 0.45 A/cm² is recorded in the file named “FC1_EIS45A_postpola_T991.csv”).

For the EIS measurements, the files contained only three columns where:
“frequency [Hz]” (column 1) represents the sweep frequency from 10 kHz to 50 mHz with 20 points per decade at high frequency (>10Hz) and 10 points per decade under the cutting frequency value (10Hz).
“r [ohm]” (column 2) represents the real part of the Nyquist plot.
“i [ohm]” (column 3) represents the imaginary part of the Nyquist plot.

(c) Polarization curves

The polarization curves are recorded in files named “FC1_Pola_Txxx.csv” were “xxx” is corresponding to the ageing time (i.e., the polarization curve performed after 48 h of running is recorded in the file named “FC1_Pola_T048.csv”). It exists 8 polarization files. For the polarization files, only the 5-cell voltages, the stack voltage, the current and the current density are recorded.

(2) Dataset #2 – Rippled current conditions

“FC2_With_Ripples_Excel” fold is dedicated to the rippled current durability test including triangular current ripples at a frequency of 5kHz with a magnitude of ±10% of the DC current. This folder contains 34 excel format files.

(a) Raw Data

There is two excel data files for the durability test dataset #2 which was recording during the test period. The dataset #1 files are named according to the experiment time:

• “FC2_Ageing_part1.csv” recorded data from 0 to 505h;
• “FC2_Ageing_part2.csv” recorded data from 505 to 1,020h;

with an acquisition frequency of 1Hz.

The parameters gathered during the durability test are the same as such recorded for the dataset #1 summed up in Table 1. The operating conditions are also the same.

(b) EIS measurements

The EIS are also measured for the steady-state durability test. It exists 24 files dedicated to EIS for different current densities: 0.70; 0.45; 0.20A/cm² for the EIS measured after the polarization curve named “FC2_EISyyA_postpola_Txxx.csv” were “xxx” is corresponding to the ageing time and “yy” stands for the current density (i.e. the EIS performed after the polarization curve after 666 h of running at a current density of 0.45A/cm² is recorded in the file named “FC2_EIS45A_postpola_T666.csv”).

For the EIS measurements, the files contained only three columns where:
“frequency [Hz]” (column 1) represents the sweep frequency from 10 kHz to 50 mHz with 20 points per decade at high frequency (>10Hz) and 10 points per decade under the cutting frequency value (10 Hz).
“r [ohm]” (column 2) represents the real part of the Nyquist plot.
“i [ohm]” (column 3) represents the imaginary part of the Nyquist plot.
(c) Polarization curves

The polarization curves are recorded in files named “FC2_Pola_Txxx.csv” were “xxx” is corresponding to the ageing time (i.e. the polarization curve performed after 515 h of running is recorded in the file named “FC2_Pola_T515.csv”). It exists 8 polarization files. For the polarization files, only the 5-cell voltages, the stack voltage, the current and the current density are recorded.

As for an example of some monitoring index that are gathered, consider Fig. 1. One can note the voltage drop as time grows, which depicts degradation phenomena within the stack. The voltage rejuvenations observed on Fig. 1 are linked to the polarization curves as these measurements do not consider the same operating conditions as due to the current sweep.

2. Experimental Design, Materials and Methods

(1) Experimental setup used
   (a) Test bench specifications

The test bench (Fig. 2) is designed for a 1 kW-PEMFC. All the fluidic, thermal and electrical parameters are monitored and recorded via National Instruments acquisition system. Thanks to the developed Labview software, the users can control and operate:

- stack temperature;
- air and hydrogen relative humidity 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;
Fig. 2. PEM fuel cell test bench used.

Table 2
Test bench specification range.

| Parameters            | Control range [Unit] |
|-----------------------|-----------------------|
| Cooling temperature   | 20–80 [°C]           |
| Cooling flow          | 0–10 [lpm]           |
| Gas temperature       | 20–80 [°C]           |
| Gas humidification    | 0–100 [%]            |
| Air flow              | 0–100 [slpm]         |
| H₂ flow               | 0–30 [slpm]          |
| Gas pressure          | 0–2 [bara]           |
| Load current          | 0–300 [A]            |

- current

Table 2 gives the maximal operating ranges that could be achieved for each parameter, on this test bench.

All these parameters can be monitored using an in-house interface developed with Labview. The gas humidification is obtained thanks two boilers located before the stack. Air and hydrogen cross their respective boilers before reaching the stack to get humidified. Some mass flows are used to measure the gas flow at the stack inlet and the pressure is also monitored and regulated using PID controllers. The stack temperature is maintained by using a heat exchanger that let pass through a certain iced water flow to the main wooled circuit to evacuate the heat generated. The current is controlled by a TDI Dynaload active load.

(b) Fuel cell stacks used for the durability tests

Both considered fuel cell stacks tested have a nominal power of 300W with a nominal current density of 0.7 A/cm². The PEMFC is assembled with commercial membranes, gas diffusion layers and bipolar plates to make a 5-cells short stack with an active area of 100 cm².

(2) Ageing tests performed
   (a) Durability tests – protocol
Two long-term tests were carried out and were described in this section (Fig. 3).

A first 5-cell stack was operated in steady-state profile under nominal operating conditions to be used as a reference test. A second 5-cell stack was operated under rippled current testing conditions, i.e., with high frequency triangular current ripples with ±10% of the nominal current density @ 5 kHz.

For both tests, characterizations were carried out once per week with the same experiment 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 EIS measurement (i.e., measuring the “Nyquist” plot of the fuel cell stack over a frequency range from 50 mHz to 10 kHz).

(b) FC1: Fuel cell operated in steady state conditions – reference part

The test untitled FC1 is performed under steady-state current at nominal and stationary operating conditions. Thus, the current density is fixed at 0.7 A/cm². This experiment could be used as a reference test. As all the parameters are at their nominal value, the degradation is optimized. Under these conditions the degradation is minimized.

A complete characterization of the PEMFC was realized once a week:

• Firstly, an EIS was performed at a current density of 0.70 A/cm² (nominal value), in order to evaluate the state of health of the PEMFC before the measurement of the polarization curve.
• Secondly, a polarization curve was performed: the stack and cells voltages were measured under a descending current ramp from 1 A/cm² to 0 A/cm² of 1000 s. To avoid a star-
Table 3
Resume of the characterizations.

| FC1 (Without ripple)                  | Characterizations (Polarization curve + EIS) | @ t = 0; 48; 185; 348; 515; 658; 823; 991h |
|---------------------------------------|---------------------------------------------|---------------------------------------------|
|                                       | 1. EIS performed before the polarization curve | @ J = 0.70A/cm²                           |
|                                       | 2. Polarization curve                        | Ramp: from 1 A/cm² to 0 A/cm² of 1000 s    |
|                                       | 3. EIS performed after the polarization curve | @ J = {0.70; 0.45; 0.20}A/cm²              |

| FC2 (With ripples)                    | Characterizations (Polarization curve + EIS) | @ t = 0; 35; 182; 343; 515; 666; 830; 1016 h |
|---------------------------------------|---------------------------------------------|---------------------------------------------|
|                                       | 1. Polarization curve                        | Ramp: from 1 A/cm² to 0 A/cm² of 1000 s    |
|                                       | 2. EIS performed after the polarization curve | @ J = {0.70; 0.45; 0.20}A/cm²              |

Fig. 4. Some polarization curves and EIS obtained over time.
vation a minimum gas flow is fixed corresponding to an equivalent current density of 0.20 A/cm².
• Then another EIS was performed. Measurements have been made in the following order: constant current of 0.70 A/cm², 0.45 A/cm², 0.20 A/cm². Between every measurement, a stabilization period of 15 min has been respected to guarantee the stability of parameters.
  (c) FC2: Fuel cell operated under rippled current

The second ageing test was performed under rippled current solicitations: a ripple current density of 0.70 A/cm² with 0.14 A/cm² oscillations at a frequency of 5 kHz was imposed to the PEMFC to emulate a DC/DC power converter effect when connected to the fuel cell. A complete characterization of the PEMFC was realized every week (around every 160 h) in the following order: first polarization curve and then EIS (with same current densities than in previous test). The characterizations were done at time: t = 0; 35; 182; 343; 515; 666; 830; 1016 h (Table 3).

(3) Characterizations scheduling

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 Fig. 4.

Ethics Statements

None

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Data Availability

IEEE PHM Data Challenge (Original data) (MyCore).

CRediT Author Statement

Elodie Pahon: Conceptualization, Writing – original draft, Visualization; Marie-Cécile Péra: Conceptualization, Writing – original draft, Visualization, Supervision, Project administration, Funding acquisition; David Bouquain: Conceptualization, Writing – original draft, Visualization, Supervision, Project administration; Daniel Hissel: Conceptualization, Writing – original draft, Visualization, Supervision, Project administration, Funding acquisition.

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