energies

Article

Internet-distributed Hardware-in-the-loop Simulation Platform for Plug-in Fuel Cell Hybrid Vehicles (Supplementary Material)

Yi Zhang [1], Qiang Guo [2] and Jie Song [1,*]

[1] School of Vehicle Engineering, Chongqing University of Technology, Chongqing, 400054, China;
[2] School of Electrical and Electronic Engineering, Chongqing University of Technology, Chongqing, 400054, China
* Correspondence: zagyi81@cqut.edu.cn; Tel.: +86-17623209206

S1. Experiments for ΔSOH_{fc} of PEM fuel cell (FIL)

There are two reasons for the degradation of the fuel cell. One is the startup operation, while the other is the operation under constant power. Thus, repeated experiments are set out to estimate the fuel cell's degradation rate ΔSOHfc under different working conditions.

1.1. Experiments for ΔSOH_{fc} caused by startup operations

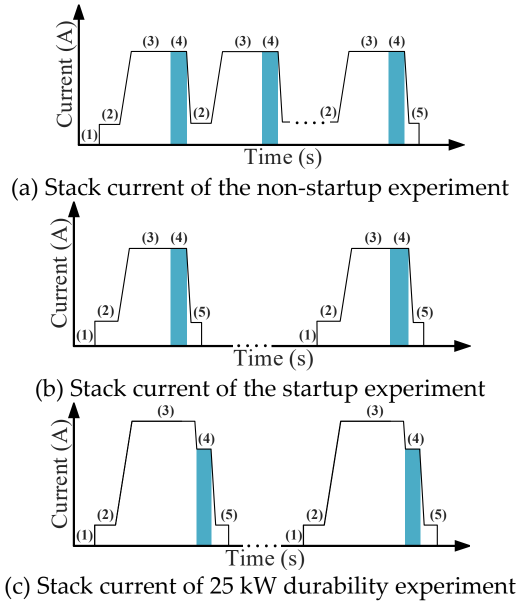


Figure S1. Load profile of durability experiment.

The experiment process for start-stop working conditions contains two experiments. One has no repeating start-stop working conditions in Figure S1 (a), while the other does in Figure S1 (b). The difference in the degradation of recorded V_{ref} between them is the effect of the start-stop working condition.

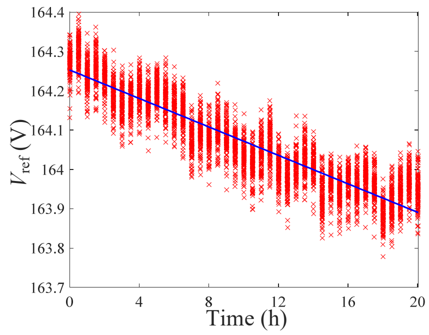
The process for the non-startup experiment (as shown in Figure S1 (a)) is as follows.

(1) Startup the stack;
Repeat (2) — (4) for 40 cycles {

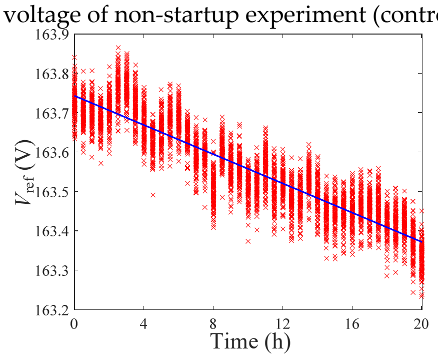
(2) Idling for 90 s;
(3) Working at I_{ref} for 30 min;
(4) At the last 120 s of (3), record V_{ref} once per second;
}
(5) Idling for 30 s, then shut down the stack.

The process for the start-stop experiment (as shown in Figure S1 (b)) is as follows.

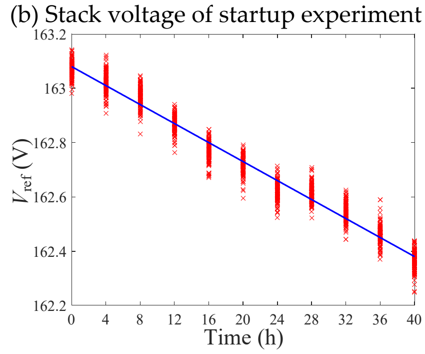
Repeat (1) — (5) for 40 cycles {
(1) Startup the stack;
(2) Idling for 90 s;
(3) Working at I_{ref} for 30 min;
(4) At the last 120 s of (3), record V_{ref} once per second;
(5) Idling for 30 s, and then shut down the stack for 1 h;
}



(a) Stack voltage of non-startup experiment (control group)



(b) Stack voltage of startup experiment



(c) Stack voltage of 25 kW durability experiment

Figure S2. Data sample of durability experiment.

Some data examples in Figure S2 for these experimental results are described above. The reference voltage data could not be used directly because of the noise in the stack voltage. Thus, linear regression is employed to calculate the average falling rate.

Based on the experiment results in Figure S2 (a) and (b), the effect of startup on stack degradation is evaluated as follows:

$$\Delta V_{\text{start}} = (\Delta V_2 - \Delta V_1) / 40 \tag{S1}$$

where ΔV_{start} is the difference of V_{ref} between Figure S2 (a) and (b), which is resulted from one startup operation, ΔV_1 is the variation of V_{ref} in Figure S2 (a), ΔV_2 is the variation of V_{ref} in Figure S2 (b). Combining Equations (3) and (S1), the effect of each startup on the fuel cell's health ($\Delta SOH_{\text{fc\_start}}$=6.93e-6) is obtained as follows.

$$\Delta SOH_{\text{fc\_start}} = \frac{\Delta V_{\text{start}}}{0.2 \times V_{\text{BOL}}} \times 100\% \tag{S2}$$

1.2. Experiments for ΔSOH_{fc} under constant power operations

The impact of the constant power working condition on fuel cell health could be studied. Taking 25kW as an example, the experiment process under constant output power (as shown in Figure S1 (c)) is as follows.

Repeat (1) — (5) for 10 cycles {
(1) Startup the stack;
(2) Idling for 90 s;
(3) Constant power working at 25 kW for 4 h;
(4) Working at I_{ref} for 120 s, meanwhile recording V_{ref} once per second;
(5) Idling for 30 s, and then shut down the stack for 1 h;
}

By subtracting the startup's effect from the result of the constant power experiment, the falling rate of the reference voltage (ΔV_{pwr} (V/h)), resulting from a specific constant power working condition, is obtained.

$$\Delta V_{\text{pwr}} = \Delta V'_{\text{pwr}} - \tfrac{1}{4} \times \Delta V_{\text{startup}} \tag{S3}$$

where $\Delta V'_{\text{pwr}}$ (V/h) is the variation of V_{ref} during the constant power experiment in Figure S2 (c). ΔVstartup is divided by 4 in Equation (S3) because it is assumed that a startup's effect is evenly allocated among the four working hours in one cycle (one startup). With Equations (3) and (S3), the variation of fuel cell health under specific power is as follows.

$$\Delta SOH_{\text{fc\_pwr}} = \frac{\Delta V_{\text{pwr}}}{0.2 \times V_{\text{BOL}}} \times 100\% \tag{S4}$$

At last, by repeating the experiment in Figure S1 (c) under different output power, a curve map of ΔSOH_{fc} is established in Figure 14 of Section 3.4.

S2. Experiments for ΔSOH_{bat} of LiFePO4 battery (BIL)

Because The output power (P_{bat}) and the battery SOC (SOC_{bat}) affect the battery degradation rate together, the variation in internal resistance (ΔR_{in}) is recorded under different P_{bat} and SOC_{bat} during degradation experiments to obtain a 2-D contour map of ΔSOH_{bat}.

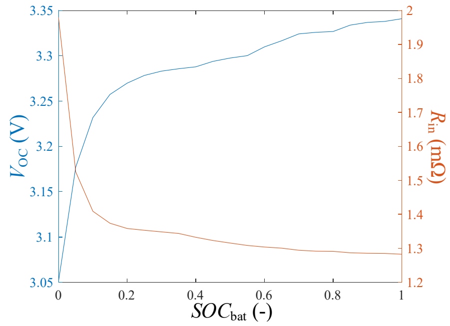


Figure S3. Open circuit voltage and internal resistance.

Before the experiment for ΔSOH_{bat}, the relation between the open-circuit voltage (V_{OC}) and SOC_{bat} should be calibrated, as shown in Figure S3, because it is the threshold value of the charging process. Then, the experiment for ΔSOH_{bat} could be illustrated by taking the working condition of P_{bat} = 450 W and SOC_{bat} = 75% as an example:

(1) Record the internal resistance at 100% SOCbat before the experiment as R1;
Second, repeat (2) — (5) for 500 cycles {
(2) Charge the battery to the voltage corresponding to 75% SOCbat (Figure S3) with 1 C constant current, and then charge with constant voltage until the current drops to 0.05C;
(3) Hold the battery still for 10 min;
(4) Discharge with 450 W constant power for 2.13 min (0.016 kWh, which is 10% of the total discharging energy in the battery with 100% SOCbat);
(5) Hold the battery still for 10 min;
}
(6) Charge SOCbat back to 100%. After holding still for 1 h, record the internal resistance after the experiment as R2.

With Equation (4), the variation of SOH_{bat} is defined as follows:

$$\Delta SOH_{bat} = \frac{R_1 - R_2}{cycles \times R_{BOL} \times E_{bat}} \times 100\% \tag{S5}$$

where *cycles* is the number of cycles, R_1 and R_2 are the internal resistance value recorded in the experiment, and E_{bat} (0.016 kWh) is the charging/discharging capacity in energy terms.

By repeating the previous experiment under different working conditions (P_{bat} and SOC_{bat}), the 2-D contour map of ΔSOH_{bat} is established in Figure 16.