Degraded mode operation of multi-stack fuel cell systems

Neigél Marx1,2, David Camilo Toquica Cárdenas1, Loïc Boulon1, Frédéric Gustin2, Daniel Hissel2

1Institut de Recherche sur l’Hydrogène, Université du Québec à Trois-Rivières, Trois-Rivières, QC, Canada
2FCLAB, FR CNRS 3539, FEMTO-ST/Energy UMR CNRS 6174, University of Franche-Comte, Belfort, France
✉ E-mail: neigél.marx@uqtr.ca

Abstract: Multi-stack fuel cell (MFC) systems provide higher performances and reliability than single-stack fuel cell systems through higher flexibility. The aim of this study is to investigate the degraded mode operation of MFC systems upon the loss of one of its stack. The different power allocation strategies impact the behaviour of the MFC system. Fuel consumption results obtained through simulation using a driving cycle acquired on a test vehicle are used to compare the chosen allocation strategies. The simulations have been conducted in a Matlab-Simulink environment. The results show that with a simple reconfiguration of the system the multi-stack system can still complete the driving cycle. The fuel consumption results during normal and degraded mode operation are compared and show acceptable efficiency loss during degraded mode operation.

Nomenclature

Roman symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>free convection heat transfer surface ((m^2))</td>
</tr>
<tr>
<td>(A_1)</td>
<td>forced convection heat transfer surface ((m^2))</td>
</tr>
<tr>
<td>(b_{11})</td>
<td>experimentally identified parameter</td>
</tr>
<tr>
<td>(b_{12})</td>
<td>experimentally identified parameter</td>
</tr>
<tr>
<td>(C_d)</td>
<td>drag coefficient for the fan blades</td>
</tr>
<tr>
<td>(C_{FC})</td>
<td>thermal capacity of the fuel cell stack ((J K^{-1}))</td>
</tr>
<tr>
<td>(E)</td>
<td>electromotive force of the DC motor (V)</td>
</tr>
<tr>
<td>(e_0)</td>
<td>width of the fan blades (m)</td>
</tr>
<tr>
<td>(E_c)</td>
<td>activation energy of the reaction (66 kJ mol(^{-1}))</td>
</tr>
<tr>
<td>(E_n)</td>
<td>Nemst potential (V)</td>
</tr>
<tr>
<td>(F)</td>
<td>faraday constant (96485 A mol(^{-1}))</td>
</tr>
<tr>
<td>(h)</td>
<td>average heat transfer coefficient (W K(^{-1}) m(^{-2}))</td>
</tr>
<tr>
<td>(\Delta H)</td>
<td>enthalpy of the reaction (W)</td>
</tr>
<tr>
<td>(I_{conv})</td>
<td>current provided to the DC bus by the converter (A)</td>
</tr>
<tr>
<td>(I_{FAN})</td>
<td>current provided to the DC motor (A)</td>
</tr>
<tr>
<td>(I_{loss})</td>
<td>current representing the power loss in the converter (A)</td>
</tr>
<tr>
<td>(j)</td>
<td>current density (A m(^{-2}))</td>
</tr>
<tr>
<td>(j_0)</td>
<td>exchange current density (A m(^{-2}))</td>
</tr>
<tr>
<td>(j_{FAN})</td>
<td>inertia of the fan axis + fan blades system (kg m(^2))</td>
</tr>
<tr>
<td>(j_L)</td>
<td>current density limit (A m(^{-2}))</td>
</tr>
<tr>
<td>(j_{loss})</td>
<td>internal and fuel cross-over equivalent current density (A m(^{-2}))</td>
</tr>
<tr>
<td>(K)</td>
<td>gain of the differential equation (18) ((\Omega))</td>
</tr>
<tr>
<td>(K_1)</td>
<td>fitting coefficient</td>
</tr>
<tr>
<td>(K_2)</td>
<td>fitting coefficient (A cm(^{-2}))</td>
</tr>
<tr>
<td>(K_3)</td>
<td>fitting coefficient (V K(^{-1}))</td>
</tr>
<tr>
<td>(K_4)</td>
<td>fitting coefficient ((\Omega) cm(^2))</td>
</tr>
<tr>
<td>(K_5)</td>
<td>fitting coefficient (K)</td>
</tr>
<tr>
<td>(k_{aero})</td>
<td>mechanic-aerolic conversion coefficient for the fan blades</td>
</tr>
<tr>
<td>(K_{purge})</td>
<td>state of purging valve</td>
</tr>
<tr>
<td>(L_{conv})</td>
<td>inductance of the converter (H)</td>
</tr>
<tr>
<td>(L_{FAN})</td>
<td>internal inductance of the DC motor (H)</td>
</tr>
<tr>
<td>(N_0)</td>
<td>number of blades</td>
</tr>
<tr>
<td>(N_{cell})</td>
<td>number of cells</td>
</tr>
<tr>
<td>(P_0)</td>
<td>standard pressure (Pa)</td>
</tr>
<tr>
<td>(P_{air})</td>
<td>air pressure in the cathodic chamber (Pa)</td>
</tr>
<tr>
<td>(P_{air,in})</td>
<td>oxygen pressure in the cathodic chamber (Pa)</td>
</tr>
<tr>
<td>(P_{H2})</td>
<td>hydrogen pressure in the anodic chamber (Pa)</td>
</tr>
<tr>
<td>(P_{H2,in})</td>
<td>pressure of the hydrogen flowing from the tank (Pa)</td>
</tr>
<tr>
<td>(P_{H2,out})</td>
<td>pressure at the hydrogen outlet (Pa)</td>
</tr>
<tr>
<td>(P_{air,in})</td>
<td>air flow at the cathode inlet (m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(P_{air,fan})</td>
<td>air flow expelled from (V_{fan}) by the fan (m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(P_{air,out})</td>
<td>air flow at the cathode outlet (m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(P_{H2,conv})</td>
<td>convective heat transfer rate (m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(q_{H2,conv})</td>
<td>hydrogen flow consumed by the electrochemical reaction (m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(q_{H2,loss})</td>
<td>hydrogen flow evacuated by the purge (m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(q_{H2,react})</td>
<td>hydrogen consumed by the fuel cell (reaction and purge) (m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(q_{O2,conv})</td>
<td>oxygen flow consumed by the electrochemical reaction (m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(q_{H2,fl})</td>
<td>Hydrogen flow flowing from the hydrogen tank (m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(R)</td>
<td>universal gas constant (8, 314 J K(^{-1}) m(^{-1}))</td>
</tr>
<tr>
<td>(R_0)</td>
<td>starting radius of the fan blades (m)</td>
</tr>
<tr>
<td>(R_{in})</td>
<td>hydraulic resistance between the inlet and outlet of the cathode (Pa m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(R_{fan})</td>
<td>radius of the fan blades (m)</td>
</tr>
<tr>
<td>(R_{conv,FC})</td>
<td>internal resistance of the DC motor ((\Omega))</td>
</tr>
<tr>
<td>(R_{purge})</td>
<td>hydraulic resistance between the tank and the anode inlet (Pa m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(R_{mem})</td>
<td>membrane resistance ((\Omega))</td>
</tr>
<tr>
<td>(R_{purge})</td>
<td>hydraulic resistance associated with hydrogen purge (Pa m(^3) s(^{-1}))</td>
</tr>
<tr>
<td>(\Delta S_{conv,FC})</td>
<td>entropy exchange rate from the fuel cell to the air (W K(^{-1}))</td>
</tr>
<tr>
<td>(\Delta S_{air})</td>
<td>entropy exchange rate from the air to the fuel cell (W K(^{-1}))</td>
</tr>
<tr>
<td>(\Delta S_{purge})</td>
<td>entropy exchange rate from the fuel cell to the air (W K(^{-1}))</td>
</tr>
<tr>
<td>(\Delta S_{purge})</td>
<td>heat generated by the electrochemical reaction (W K(^{-1}))</td>
</tr>
<tr>
<td>(T_0)</td>
<td>standard temperature (298,15 K)</td>
</tr>
<tr>
<td>(T_{aero})</td>
<td>resistant torque created by drag forces on the fan blades (N m)</td>
</tr>
<tr>
<td>(T_{air})</td>
<td>air temperature (K)</td>
</tr>
<tr>
<td>(T_{FC})</td>
<td>mean fuel cell temperature (K)</td>
</tr>
<tr>
<td>(T_{n})</td>
<td>torque provided by the DC motor (N m)</td>
</tr>
<tr>
<td>(t_{f})</td>
<td>membrane thickness (m)</td>
</tr>
<tr>
<td>(t_{loss})</td>
<td>resistant torque composed of the magnetic and mechanic losses (N m)</td>
</tr>
</tbody>
</table>
The first section presents the energy management problem introduced by hybrid vehicle. Two levels of energy management are introduced to account for the different levels of redundancy. The first level distributes the load between the fuel cell and the battery. The second level of energy management distributes the parts of the load attributed to the fuel cell system to the different fuel cells. It is accomplished through the use of power distribution methods. Three of them are presented in Section 2. The fuel cell system model used in simulations is presented in Section 3. In Section 4, the normal and degraded operation are presented and compared. Fuel consumption results on a driving cycle obtained on the mobile laboratory of the Hydrogen Research Institute are presented along with a discussion of those results.

## 2 Energy management architecture of a hybrid MFC/battery vehicle

### 2.1 Hybrid fuel cell/battery vehicle

The hybrid fuel cell/battery architecture and MFC/battery architectures are presented in this section.

The fuel cell/battery hybrid architecture is presented in Fig. 1. The hybridisation of a fuel cell system and a battery pack provides a new degree of freedom. This degree of freedom enables the distribution of the load’s power request between the battery and the fuel cell (FC) system. The fuel cell system presented in this paper is based on the Hydrogen Research Institute’s test bench and is composed of an air breathing fuel cell stack, a hydrogen supply system and a DC–DC converter to adapt the power output. The study would yield similar results if adapted to other fuel cell system architectures.

The MFC system can replace the aforementioned fuel cell system. Multiple architectures are available for MFC systems [4]. The isolation of a failed segment or stack impacts the system differently depending on the chosen electrical architecture. Series configurations require by pass systems to isolate failed stacks and can lead to current peaks damaging the system during the reconnection of the recovered stack. Parallel and cascaded configurations do not require by pass systems and are not subject to current peaks because they provide individual current control. The parallel architecture is the one considered in this study because of its increased modularity and ability to efficiently integrate degraded mode operation capabilities. Each FC system of the MFC system is composed of a fuel cell stack and a dedicated DC–DC converter. This hybrid architecture is presented in Fig. 2.

When coupled with an MFC system, additional degrees of freedom are introduced. They can be used to distribute the load’s power demand between the multiple fuel cell of the system. The multiple degrees of freedom can be decoupled in order to define two different energy management strategies:

(i) The battery/MFC system level energy management strategy that splits the power between the batteries and the MFC system.

(ii) The MFC system level energy management that distributes the power between the different fuel cells.

Energy management strategies [10] can be used to maximise efficiency and/or to minimise degradation [11, 12]. In this study, the battery/MFC system level energy management will aim at minimising degradations while the MFC system level management will focus on maximising efficiency.

![Fig. 1 Hybrid system architecture](image-url)

The Institution of Engineering and Technology 2016
2.2 Battery/MFC system level energy management strategy

The battery/MFC system level energy management focuses on minimising the ageing of the MFC system and the battery system. The ageing of the fuel cell systems is affected by the dynamics of the current reference or other factors like start and stop cycles, operation time, shutdown procedure or the environment. The battery’s ageing is affected mainly by the depth of discharge. The following constraints have been chosen accordingly to design the vehicle level energy management strategy:

(i) The fuel cell system requires current reference with slow dynamics (maximum rate: $4 \text{ A s}^{-1}$ [13]).

(ii) The variation of the battery state of charge (SOC) between the beginning and the end of the driving cycle must be kept between 60 and 80%.

The input degrees of freedom are the individual fuel cell powers ($P_{\text{FC}_i}$). The output is the required total power output ($P_{\text{tot}}$)

$$P_{\text{tot}} = \sum_{i=1}^{N} P_{\text{FC}_i}$$

i. Equal distribution: The equal distribution splits the power reference equally between the $N$ fuel cells, that is

$$\forall i \in \{1, \ldots, N\}, \quad P_{\text{FC}_i} = \frac{P_{\text{tot}}}{N}$$

This distribution has an energetic behaviour close to the single-fuel cell system.

ii. Daisy-chain algorithm: The daisy-chain power sharing method is a sequential method. When one fuel cell cannot achieve the output, other fuel cells are used to try achieving it. If fuel cell 1 operates at maximum power

$$P_{\text{FC}_2} = P_{\text{tot}} - P_{1,\text{max}}$$

If fuel cell 2 operates at maximum power

$$P_{\text{FC}_3} = P_{\text{tot}} - P_{2,\text{max}} - P_{1,\text{max}}$$

If fuel cell $k$ operates at maximum power

$$P_{\text{FC}_{k+1}} = P_{\text{tot}} - \sum_{i=1}^{k} P_{i,\text{max}}$$

As it is a sequential method, it requires a fuel cell order. The fuel cell order that provides the best average efficiency for the daisy-chain method is the one that ranks the fuel cells according to their average efficiency

$$\eta_{\text{average}} = \frac{1}{P_{\text{max}}} \int_{P=0}^{P_{\text{max}}} \eta(P) \, dP$$

iii. Optimal distribution: The optimal distribution provides the different power reference $P_{\text{FC}_i}$ for each fuel cell in order to maximise efficiency and satisfy the total power demand. This is

2.3 MFC system level energy management strategy

The MFC system level energy management strategy distributes the power demand between the different fuel cells of the system. This can be done through the use of power sharing methods designed for MFC systems [5]. Three power sharing methods will be presented in this subsection.
translated into the following optimisation problem

$$ F = \max_{p_{FC}} \eta(P_{tot}) $$

$$ \forall i \in \{1, \ldots, N\}, \ 0 \leq P_{FC_i} \leq P_{p_{max}} $$

$$ \sum_{i=1}^{N} P_{FC_i} = P_{tot} $$

where the efficiency of the system is

$$ \eta(P_{tot}) = \frac{P_{tot}}{\text{LHV} \cdot \text{flow}(P_{FC_1}, \ldots, P_{FC_N})} $$

The optimal distribution is obtained offline and implemented online through a look-up table, whereas the other distribution can be implemented online directly.

3 Fuel cell system model

A model including the fuel cell stack and its ancillaries is required to obtain a relevant evaluation of the fuel consumption during operation and to solve the aforementioned optimisation problem. Air breathing fuel cells are usually paired with blowers and a power converter. The blowers act as the cooling system and provide the oxidant to fuel the reaction. The converter adapts the power output to meet the requirement of the application and regulates the power delivered by the fuel cell. The models chosen for the fuel cell stack, blower system, power converter and battery pack will be detailed in the following subsections.

3.1 Electrochemistry

The cell voltage, internal heat generation and consumption of reactant inside the fuel cell are based on the laws of electro-chemistry.

1. Potential calculation: The static potential of the cells is calculated through (11). This equation defines the polarisation curve

$$ V_{cell,t} = E_a - \Delta V_{act} - \Delta V_{conc} - \Delta V_{fl} $$

The Nernst potential is given by [14]

$$ E_a = \frac{-\Delta H - T \Delta S}{2F} + \frac{RT_{FC}}{2F} \ln \left( \frac{P_{H_2} \times P_{O_2}}{P_0^{1/2}} \right) $$

The different voltage losses are calculated through the following equations [15]

$$ \Delta V_{act} = K_1 \frac{RT_{FC}}{F} \ln \left( \frac{j + j_{loss}}{j_0} \right) $$

$$ \Delta V_{conc} = K_2 T_{FC} \ln \left( 1 - \frac{j}{j_0} \right) $$

$$ \Delta V_{fl} = R_{m_{FC}} $$

$$ j_0 = K_2 \frac{P_{O_2}}{P_0} \exp \left( \frac{E_a}{RT_{FC}} \left( 1 - \frac{T_{FC}}{T} \right) \right) $$

$$ R_{m} = K_3 \frac{t_{mb}}{b_{11} \times A_{ab} - b_{12}} \exp \left( -K_5 \times \left( \frac{1}{T} - \frac{1}{T_{FC}} \right) \right) $$

Multiple dynamic phenomena take place inside the fuel cell. The charging of the double layer capacity, the diffusion of gas in the gas diffusion layer or the membrane hydration have been thoroughly studied [16]. The model is to be used for energy management purposes, thus, the dynamic impact of membrane hydration on voltage will be the only phenomenon considered as it is the one with the most significant impact on energy calculations. This phenomenon is modelled using an empiric approach. As it is a consequence of current transients, the following differential equation has been considered

$$ V_{cell,d} + \tau \frac{dV_{cell,d}}{dt} = k \frac{dl}{dt} $$

The fuel cell voltage is obtained by adding the static and dynamic cell voltages and multiplying it by the number of cell. This equation is valid under the assumption that all cells work at the same operating point and are equally aged

$$ V_{FC} = N_{cell}(V_{cell,s} + V_{cell,d}) $$

ii. Reactant consumption: The consumption of reactant depends on the stack current through the following equations:

$$ q_{H_2,t} = \frac{N_{cell} \rho_{PAC}}{2F} $$

$$ q_{O_2,t} = \frac{N_{cell} \rho_{PAC}}{4F} $$

iii. Heat generation: The electrochemical reaction is exothermic. The internal heat generation is given by

$$ \Delta S_q = N_{cell}(\Delta H/2F - V_{cell})\rho_{PAC} $$

3.2 Reactant supply

The model of the reactant supply subsystem presented in this paper is based on two equivalent electric circuits. The air supply subsystem is modelled as presented in Fig. 4a. The hydrogen supply subsystem is modelled as presented in Fig. 4b.

1. Air supply: The flow of air between the inlet and outlet of the cathode is given by

$$ q_{air,in} = \frac{P_{air,out} - P_{air}}{R_{air}} $$

$$ q_{air} = q_{air,in} - N_{O_2,t} \cdot q_{O_2,t} $$

The pressure in the space confined between the blowers and the cathodic chamber is based on the ideal gas law

$$ P_{air} = \frac{1}{C_{AIR}} \int (q_{air} - q_{air,t}) \, dt $$

with

$$ C_{AIR} = \frac{V_{mol,air} \times V_{fan}}{RT_{FC}} $$

The blowers are located at the cathode outlet and draw up air into it. A complete model of the blower subsystem is detailed in Section 3.4.

2. Hydrogen supply: The pressure loss between the hydrogen tank and the anode inlet is obtained through the following equation:

$$ q_{H_2,in} = \frac{P_{H_2,in} - P_{H_2}}{R_{H_2}} $$
The pressure in the anodic chamber is obtained through the following equation

\[ P_{H_2} = \frac{1}{C_{AN}} \int (q_{H_2\text{in}} - q_{H_2\text{c}}) dt \]  

with \( C_{AN} = \frac{V_{\text{mol}} \times V_{\text{AN}}}{RT} \)  

(27)

The flow of hydrogen at the anode inlet \( q_{H_2\text{c}} \) is the sum of the flow consumed by the reaction and the flow expelled through the purge

\[ q_{H_2\text{c}} = q_{H_2\text{out}} + q_{H_2\text{r}} \]  

(28)

The dead-end mode operation of fuel cells requires a purge in order to evacuate excess water. The flow of hydrogen evacuated during the purge depends on the geometry of the purge orifice, the pressure difference between the anodic chamber and the outlet as well as the state of the purging valve

\[ q_{H_2\text{out}} = K_{\text{purge}} \frac{P_{H_2} - P_{H_2\text{out}}}{R_{\text{purge}}} \]  

(29)

### 3.3 Thermal behaviour

The temperature of the fuel cell is affected by multiple phenomena. Its calculation will consider the forced convection, free convection and internal heat generation as the heat transfer sources. The internal heat generation is caused by the electrochemical reaction and has been covered in Section 3.1. The forced and free convection are covered in this subsection. The considered fuel cell temperature is the mean temperature of the stack.

(i) **Free convection**: The free convection on the stack’s external surface is obtained through the following equation

\[ q_{\text{conv,free}} = h_{\text{free}} A (T_{FC} - T_{\text{Air}}) \]  

(30)

(ii) **Forced convection**: The model presented in this section originates from [17] and was used with air breathing fuel cell systems [18]. The heat transfer rate is calculated with the following formula

\[ q_{\text{conv,forced}} = h \overline{\rho C_p} \overline{\theta}_{\text{b,lm}} \]  

(31)

The variables \( h \) and \( \overline{\theta}_{\text{b,lm}} \) are highly dependent on the air flow considered for the convection. Those dependencies are detailed in [18]. The total convection heat exchange is the sum of the free and forced convections

\[ q_{\text{conv}} = q_{\text{conv,free}} + q_{\text{conv,forced}} \]  

(32)

### 3.4 Blower subsystem

The blower (Fig. 5) is composed of a DC electrical motor power rotating fans that evacuates air out of the fuel cell stack.

The behaviour of the current in the windings of the motor depends on an internal resistance and an internal inductance through the
following equations
\[ V_1 = V_{\text{FAN}} - R_{\text{FAN}}I_{\text{FAN}} \quad (33) \]
\[ I_{\text{FAN}} = \frac{1}{L_{\text{FAN}}} \int (V_1 - E)dt \quad (34) \]

The electromechanical conversion is described by (35) and (36). Iron and mechanic losses are subtracted to the electromechanical torque
\[ E = k \Omega \quad (35) \]
\[ T_m = kd_{\text{FAN}} - T_{\text{loss}} \quad (36) \]

The behaviour of the motor axis and the fan blades is dependent on their total inertia
\[ \Omega = \frac{1}{J_{\text{FAN}}} \int (T_M - T_{\text{aero}})dt \quad (37) \]

Conversion of the blades rotation into air flow is given by (38). Drag forces lead to a resistive torque on the motor’s axis
\[ q_{\text{air}} = \eta_{\text{base}} k_{\text{base}} \Omega \quad (38) \]
\[ T_{\text{aero}} = N_b \int_{r=R_0}^{R_a} \left( \frac{1}{2} \rho_{\text{air}} C_d \theta_k (r \Omega \cos \theta)^2 \right) - r \cdot dr \]
\[ = N_b \left( \frac{1}{8} \rho_{\text{air}} C_d \theta_k (R_a^4 - R_0^4) (\Omega \cos \theta)^2 \right) \quad (39) \]

3.5 DC–DC converters

Fuel cells are often coupled to scale-up converters because they are low-voltage high-current power sources [19]. Using a dedicated inductance, the output current control is performed in the converter
\[ I_{\text{conv}} = \frac{1}{L_{\text{conv}}} \int (V_{\text{bus}} - V_{\text{conv}}) - I_{\text{loss}}dt \quad (40) \]

The voltage step-up stage is modelled by (41) and (42) which correspond to that of a boost converter
\[ V_{\text{conv}} = \frac{1}{1 - \alpha} V_{\text{FC}} \quad (41) \]
\[ I_{\text{FC}} = \frac{1}{1 - \alpha} I_{\text{conv}} \quad (42) \]

3.6 Battery model

The battery is modelled as a constant voltage source coupled to a resistance. The voltage source represents the open circuit voltage and the resistance models the internal resistance of the battery [20]. The output voltage is dependent on current and is calculated through the following equation
\[ V_{\text{bat}} = \text{OCV} - R_{\text{bat}}I_{\text{bat}} \quad (43) \]

The state of charge of the battery is calculated through the following equation
\[ \text{SOC} = \frac{1}{C_{\text{bat}}} \int I_{\text{bat}}dt \quad (44) \]

where \( C_{\text{bat}} \) is the capacity of the battery.
dedicated DC–DC converter for individual power control. The steady-state efficiency curves of the different FC systems are presented in Fig. 8. The fuel cells exhibit different behaviours in terms of efficiency because of different ageing and because of a manufacturing process that does not guaranty identical behaviours.

4.2.1 Complete system: The effect of the MFC system level energy management on the MFC system efficiency is evaluated over the complete power range of the system. The optimal power distribution resulting from the optimisation problem presented in Section 2 is shown in Fig. 9a.

The optimal and daisy-chain distribution clearly offer an advantage over the equal distribution in the lower power range. Nevertheless, in 800–1600 W power range, the equal distribution provides results similar to those of the optimal distribution. Finally, the daisy-chain distribution falls behind after 800 W.

4.2.2 System without fuel cell 3: Degraded mode operation will be simulated by removing the third fuel cell (the less efficient one) from the system. The optimisation process is then conducted to obtain the optimal power distribution for this system (Fig. 9b) and the comparison of the different power sharing methods (Fig. 9d).

The results are similar to that of the complete system with the exception that the daisy-chain distribution is now the less efficient distribution above 400 W (one-third of the rated power of the system). The system still retain the ability to provide power whereas the single-fuel cell architecture cannot.

4.3 Simulation results

The aforementioned driving cycle is linked to a corresponding power profile. That power profile is scaled down in order to reduce the average power to two-third of the system’s rated power (1600 W). The resulting power profile is presented in Fig. 10a. The battery/MFC system level energy management strategy is applied to that power profile and depending on the scenario evaluated (normal or degraded mode operation) a new power profile is generated for the MFC system (plain and dashed curves in Fig. 10a). The resulting effect of this power profile on the SOC’s variation is presented in Fig. 10b and respects the constraints introduced in Section 3. Considering that the power profile imposed to the MFC system for the normal and degraded operation does not vary by a large margin (Fig. 10a), the power provided by the batteries remains similar. Therefore, the batteries are not subject to critical degradations due to high power peaks. However, these results are highly dependent on the system’s sizing.

The fuel consumption results are presented in Table 1 for the two scenarios and additional scenarios in which the removed fuel cell system differs.

4.4 Discussion

The system has been sized so that the average power required by the load is two-third of the rated power of the MFC system. Thus, even with the loss of one stack the system can still operate as it did before. The fuel consumption during normal and degraded mode operation presented in Table 1 do not differ by a large margin. There is however a small difference depending on the removed fuel cell. The difference depends on the performance of that fuel cell compared with the others. Thus, the loss of a fuel cell with a higher efficiency like the first fuel cell will increase the hydrogen consumption of the system. The difference between the scenarios in which the first and the third fuel cell are removed results in a difference in hydrogen consumption of 1.3% in favour of the later.

The loss of one stack does not lead to substantial change in the simulation results. The main factor ruling the changes is maximum power rating of three FC systems. With 1.2 kW the
fuel cell power reference cannot remain the same as with four FCs. The change in power reference leads to change in the evolution of the SOC during the cycle. However, the SOC remains within acceptable limits. With only three FCs, the fuel cells will work closer to their maximum power rating and could thus age more rapidly.

**Fig. 9** Comparison of the complete system and the system without fuel cell 3

- a Optimal power distribution for the complete system
- b Optimal power distribution for the system without fuel cell 3
- c Efficiency comparison of the different distribution method for the complete system
- d Efficiency comparison of the different distribution method for the system without fuel cell 3

**Fig. 10** Simulation results

- a Power profiles for the different scenario
- b Evolution of the State of Charge for the different scenario
The sizing was constant in this study but should be variable in future works. Depending on the fault emerging on the fuel cell stacks they could be used at a reduced power level before being turned off. Furthermore, the loss of more than one stack would impose a reconfiguration of the system. The only requirement being that a reconfiguration of the system is an important factor. It impacts the capabilities in degraded mode operation. Higher peak power for the MFC system could lead to better capabilities in degraded mode such as allowing the possibility of a second stack failing. However, it could also lead to a reduced sizing of the battery, which could lead in turn to high current damaging it during degraded operation. The sizing was constant in this study but should be variable in further studies to account for other optimisation such as durability and operation cost optimisations. This could lead to less advantageous system sizings which could lead to different results.

The loss of one stack has been considered in this study. However, depending on the fault emerging on the fuel cell stacks they could be used at a reduced power level before being turned off. Furthermore, the loss of more than one stack would impose a reconfiguration of the maximum acceleration and speed of the vehicles which has not been covered in this study either and shall be addressed in future works.

### References