Interactions Between Fuel Cell and DC/DC Converter for Fuel Cell Electric Vehicle Applications: Influence of Faults

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***Abstract*—Over the last few decades, the proton exchange membrane fuel cell (PEMFC) has been named by public and private researchers as excellent candidate for automotive applications with a high degree of autonomy and zero pollutant emissions (gases, noise). However, before the commercialization of fuel cell electric vehicles (FCEV), some challenging issues remain to be solved, especially the reliability of power trains in case of faults. In this perspective, the purpose of this paper is to study the influence of faults on the interactions between fuel cell and DC/DC converter. The main contribution of this work is to study different faults which could occur during the operation both for FC and DC/DC converter.**

Keywords—Fuel cell; Interleaved DC/DC converter; Electric vehicles; Influence of faults.

NOMENCLATURE

C_p	Specific heat capacity of the stack (J mol^{-1}K^{-1}).
E_o	Standard reference potential at standard state (V).
E_{loss}	Voltage drop that results from losses in the fuel cell.
E_{th}	The reversible voltage including the effect of gas pressures and temperature (V).
F	Faraday constant (96485 C mol^{-1}).
i	Current density (A cm^{-2}).
i_L	Limiting current density (A cm^{-2}).
i_o^{ref}	Reference exchange current density (at reference temperature and pressure, typically 25°C and 101.25 kPa) per unit catalyst surface area (Acm^{-2}Pt).
m_{stack}	Total mass of the FC stack (kg).
n	Number of exchanged electrons per mole of reactant (2 for the PEM fuel cell).
N_{cell}	Number of cells in the stack.
P	Gas pressures (Pa).
$\dot{Q}_{chem}$	Available power produced due to chemical reaction (J).
$\dot{Q}_{elec}$	Electrical energy produced by FC (J).
$\dot{Q}_{loss}$	Heat loss which is mainly transferred by air convection (J).
$\dot{Q}_{net}$	Net heat energy generated by the chemical reaction (J).
$\dot{Q}_{sens+latent}$	Sensible and latent heat absorbed during the process (J).
R	Gas constant (8.314 J mol^{-1}K^{-1}).
R_i	Total cell internal resistance (Ωcm2).
$R_{i,c}$	Contact resistance (Ωcm2).
$R_{i,e}$	Electronic resistance (Ωcm2).
$R_{i,i}$	Ionic resistance (Ωcm2).
T	Temperature (K).
V_{fc}	Fuel cell stack voltage (V).
α	Electron transfer coefficient, 0.5 for the hydrogen fuel cell anode (with two electrons involved) and α = 0.1 to 0.5 for the cathode.
ΔH	Enthalpy (kJ mol^{-1}).
ΔS	Entropy (kJ mol^{-1}).
ΔV_{act}	Voltage drop due to activation losses (V).
ΔV_{con}	Voltage drop due to concentration losses (V).
ΔV_{ohm}	Voltage drop due to ohmic losses (V).

Superscripts and subscripts

a	Anode.
c	Cathode.
H_2	Hydrogen.
O_2	Oxygen.

I. INTRODUCTION

In the last few years, fuel cells (FCs) have gained a growing interest for power generation both for stationary and transportation applications. Fuel cells are electrochemical devices that convert chemical energy directly from an oxygen and hydrogen reaction into electrical energy releasing water and heat. By providing simplicity, quietness of operation, reliability and enabling zero-emission transportation, FCs have become essential components in development of electric vehicles (EVs) [1]. Among existing technologies, proton exchange membrane fuel cell (PEMFC) seems to be a potential candidate for distributed generation and ground vehicle applications, because of high power density, solid electrolyte and low-temperature operation enabling rapid start-up time [1]. In contrast, some issues are still of concern, especially their low and unregulated voltage produced at the output. For this reason, a DC/DC converter is necessary in order to raise the level of the voltage from fuel cell stack up to the level of the main DC bus voltage. Additionally, these DC/DC converters must respond to challenging issues in order to meet the requirements of fuel cell electric vehicle (FCEV) applications such as [2]:

1) Weight and volume reduced;
2) High efficiency;
3) High power density;
4) Low cost;
5) Low electromagnetic interference (EMI);
6) Reduced current ripple for prolonging fuel cell lifetime.

Furthermore, the reliability and continuity of service of power trains remain major concerns in order that fuel cell electric vehicles can access to the mass automotive market. As a matter of fact, FCs and DC/DC converters can undergo malfunctions and breakdowns during operation. For example, in PEMFC, the membrane electrode assembly (MEA) can be subjected to different failures such as [3]:

1) Membrane break;

2) Internal gases leakage;
3) Cell flooding or drying.

By comparison, DC/DC converters can be subjected to power semiconductors failures such as [4]:

1) Open-circuit faults;
2) Short-circuit faults.

In order to understand the influence of faults on the interactions between FC and DC/DC converter, a thorough study must be carried out. However, very few studies in the literature have been performed on the interactions between fuel cell and DC/DC converter. In [5], the authors study the influences of current harmonics on a fuel cell stack; whereas in [6] the authors show the influence of the input capacitor of the static converter on the electrical response dynamics of the FC. Otherwise, the effects of the FC internal impedance on the dynamic performance of the DC/DC converter are studied in [7] and in [8], where the electrical interactions between FCs and power converters are analyzed. This paper deals with studies based on the influence of faults on the interactions between PEMFC and its DC/DC converter. Besides, different degraded operating modes have been taken into consideration in this study.

It has been chosen to focus on an interleaved DC/DC converter, enabling to take into account the requirements of FCEV applications. The selected topology is a floating-interleaving boost converter (FIBC) [9]. The schematic representation of this topology combined with PEMFC system is drawn in Fig. 1. The benefits of this topology and the choice of number of phases have been explained in details in a previous work [2]. In order to fulfill the fault tolerance requirements, fuses have been added in series with each power semiconductors in Fig. 1. The fuses allow isolating faulty phase in case of short-circuit faults (SCF).

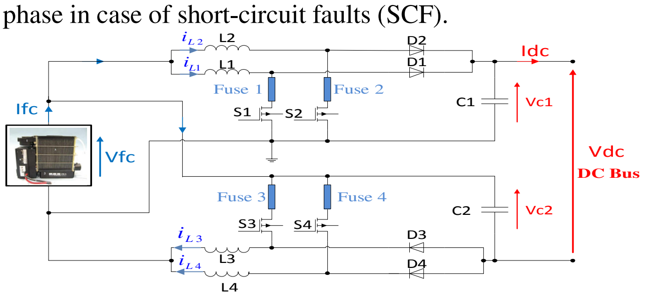


Fig. 1. PEMFC and four phases floating-interleaving boost converter (FIBC).

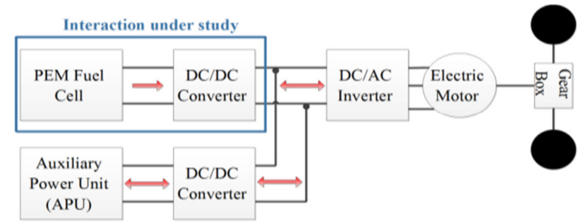


Fig. 2. Block diagram of a FCEV [10].

The FCEV, as shown in Fig. 2, uses a FC as the main power source and the auxiliary power source (e.g. batteries or supercapacitors) to assist the propulsion of the vehicle during transients and to absorb the kinetic energy during regenerative braking. Moreover, this configuration allows improving FC lifetime and autonomy [10].

The paper is organized as follows: the modeling of the PEMFC and interleaved DC/DC converter is presented in section II. A review of considered faults both for PEMFC and DC/DC converter is given in section III. Finally, simulation results for the influence of faults on the interactions between PEMFC and interleaved DC/DC converter are illustrated in section IV.

II. Modeling and Control of the Studied System

A. *Modeling and validation of FC model*

In order to reproduce accurately the behaviour of FC system in case of faults, a multi-physical modeling of the latter has been used. This modeling covers the electrical and thermal domain. In this section, the mathematical expressions are presented for building a multi-physical model for a PEMFC stack. The latter are derived under seven assumptions [11]-[12]:

1) 1-D modeling.
2) Ideal and uniformly distributed gases.
3) Constant pressures in the fuel-cell gas flow channels.
4) The fuel is humidified H_2 and the oxidant is humidified air. Assume the effective anode water vapor pressure is 50% of the saturated vapor pressure while the effective cathode water pressure is 100%.
5) The FC works under 100°C and the reaction product is in liquid phase.
6) Thermodynamic properties are evaluated at the average stack temperature, temperature variations across the stack are neglected, and the overall specific heat capacity of the stack is assumed to be a constant.
7) Parameters for individual cells can be lumped together to represent a FC stack.

Fig. 3 shows the block diagram of the multi-physical modeling with its different inputs and outputs:

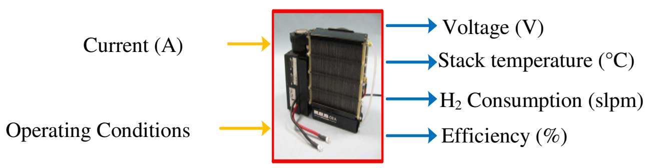


Fig. 3. Block diagram of the multi-physical modeling of FC.

The electrical domain allows describing the polarization curve and the associated losses (e.g. activation, ohmic and concentration). Taking into account these losses, the output voltage, E_{cell} produced by FC can be expressed by the following equation [11], [12]:

$$E_{cell} = E_{th} - E_{loss} \tag{1}$$

Where E_{th}, the theoretical potential can be expressed as the difference between the reversible potential at anode and cathode [11]:

$$E_{th} = E_c - E_a \text{ with } E_a=0 \quad (2)$$

Then, E_{loss} is the voltage drop resulting from losses (activation, ohmic and concentration) and can be expressed as follows:

$$E_{loss} = (\Delta V_{act,c} + \Delta V_{act,a)} - \Delta V_{ohm} - \left(\Delta V_{con,c} + \Delta V_{con,a}\right) \quad (3)$$

According to assumption (5), the corresponding Nernst equation used to calculate the reversible voltage is:

$$E_{c(T,P)} = E_{O,cell} + \frac{RT}{nF} ln\left(P_{H_2} P_{O_2}^{0.5}\right) \quad (4)$$

The theoretical cell potential, $E_{O,cell}$ changes with temperature [11]:

$$E_0 = -\left(\frac{\Delta H}{nF} - \frac{T\Delta S}{nF}\right) \quad (5)$$

Hence, the temperature increase in a cell results in a lower theoretical cell potential. Besides, both ΔH and ΔS are functions of temperature:

$$\Delta H = h_{298.15} + \int_{298.15}^{T} C_p dT \quad (6)$$

$$\Delta S = s_{298.15} + \int_{298.15}^{T} C_p dT \quad (7)$$

Specific heat energy, C_p for any gas is also a function of temperature. An empirical relationship may be used [11]:

$$c_p = a + bT + cT^2 \quad (8)$$

Where a, b and c are the empirical coefficients, different for each gas. These coefficients are given for each gas in [11].

Activation voltage for oxygen reduction reaction (ORR) is:

$$\Delta V_{act,c} = \frac{RT}{\alpha_c F} ln\left(\frac{i}{io,c}\right) \quad (9)$$

In comparison, activation voltage of hydrogen oxidation reaction (HOR) is:

$$\Delta V_{act,a} = \frac{RT}{\alpha_a F} ln\left(\frac{i}{io,a}\right) \quad (10)$$

The overall ohmic voltage drop can be expressed as:

$$\Delta V_{ohm} = R_i i \quad (11)$$

Where:

$$R_i = R_{i,i} + R_{i,e} + R_{i,c} \quad (12)$$

The concentration overpotential for ORR is:

$$\Delta V_{con,c} = \frac{RT}{nF} ln\left(\frac{i_{L,c}}{i_{L,c} - i}\right) \quad (13)$$

The concentration voltage (HOR) is:

$$\Delta V_{con,a} = \frac{RT}{nF} ln\left(\frac{i_{L,a}}{i_{L,a} - i}\right) \quad (14)$$

Finally, applying assumption (7), the total ouput voltage of the FC stack can be obtained as:

$$V_{fc} = N_{cell} E_{cell} \quad (15)$$

Compared with the electrical domain, the thermal domain describes heat generation, heat exchanges by convection in the channels, heat diffusion by conduction or by mass transport, radiation, natural convection and latent heat due to water phase change [12]. According to assumption (6), the net heat generated by the chemical reaction inside the FC, which causes the rising or falling of temperature, can be written as:

$$m_{stack} C_{P,stack} \frac{dT_{stack}}{dt} = \dot{Q}_{net} \quad (16)$$

$$\dot{Q}_{net} = \dot{Q}_{chem} - \dot{Q}_{elec} - \dot{Q}_{sens+latent} - \dot{Q}_{loss} \quad (17)$$

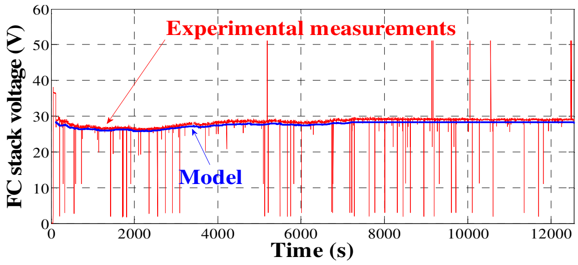
At steady state, $\dot{Q}_{net} = 0$ and consequently the FC operates at some constant temperature. During transitions (e.g. load change, operating conditions change, faults), the temperature of the FC stack will rise or drop according to Eq. 16 [12].

In addition, efficiency and H2 consumption have been implemented in the FC model (Fig. 3). All the mathematical expressions allowing determining efficiency and H2 consumption are given in [11].

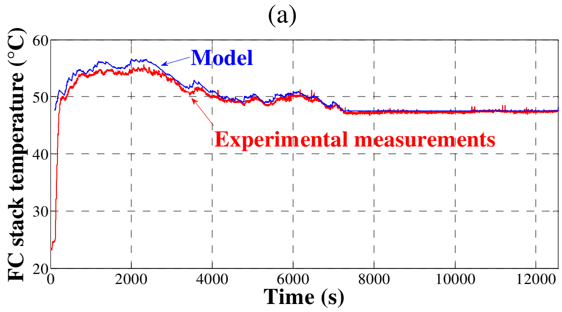
Experimental tests have been carried out in order to compare them with the multi-physical modeling. The test bench of the FC in climatic chamber for the tests at different operating temperatures is shown in Fig. 4.

Fig. 4. Test bench in climatic chamber.

Fig. 5 compares the experimental results both for the electrical and thermal domain. As it can be observed, the multi-physical modeling allows giving an excellent fit of experimental results. The voltage drop shown in fig.5a results from the opening of H_2 purging valve in order to eliminate the water and impurities on the hydrogen side (anode) during the operation.



(a)



(b)

Fig. 5. (a) validation of electrical model, (b) validation of thermal model.

B. *Modeling and control of FIBC topology*

In order to design controller for given performances purposes, appropriate dynamic models are required. Consequently, averaged small-signal modeling [13] has been applied for FIBC topology in order to take into account its nonlinearities due to power switches, inductors and so on. The averaged small-signal model taking into account the resistances of windings has been obtained in a previous work [2].

For the purpose of designing correctly the controller, it is crucial to establish the control objectives in healthy and degraded mode, which can be formulated as following:

- The DC bus voltage must be regulated at every moment during variations of load and operating conditions (e.g. temperature, pressure, relative humidity) ;
- Equal current sharing between phases. The input current waveforms must be equal in order to avoid overloading one of the phases, particularly for heavy loads. Furthermore, the phase currents must be correctly shifted from each other in order to minimize the input current ripple which is undesirable in fuel cell applications;
- To always guarantee the stability and dynamic performances of the closed loop system.

For this purpose, a multiloop PI control seems the most appropriate in order to fulfill the control requirements. In fact, a classic PI control with a current loop is used in [14] for controlling an interleaved boost converter (IBC) associated with a FC. When a power semiconductor fault occurs, the controller cannot equal current sharing between faulty phases. Consequently, one phase inductor is overloaded compared with the other one. This leads up to an additional stress of the phase inductor as this is explained in [2]. A fault management (e.g. control reconfiguration) [15] is required for this control in order to equal current sharing between phases unlike to a multiloop control. Indeed, adding a voltage loop, the controller becomes more robust particularly in case of faults.

III. A REVIEW OF CONSIDERED FAULTS IN THE CASE UNDER STUDY

A. *Considered faults in fuel cell*

In a FC, failures can be caused by:

1) Long time operation (natural ageing);
2) By operation incidents, such as MEA contamination or reactant starvation.

A common consequence to these failures is the voltage. In fact, if a fault occurs in FC, the voltage can be either increase or decrease according to the fault [11]. In summary, FC stack voltage is a first indicator of a degraded working mode. Different categories of faults in PEMFCs are likely to occur during the operation as shown in Fig. 6 [16].

Water management and temperature are effects crucially important for healthy operation of a PEMFC. In this paper, the effects of humidity, temperature and pressure in fuel cell are reviewed.

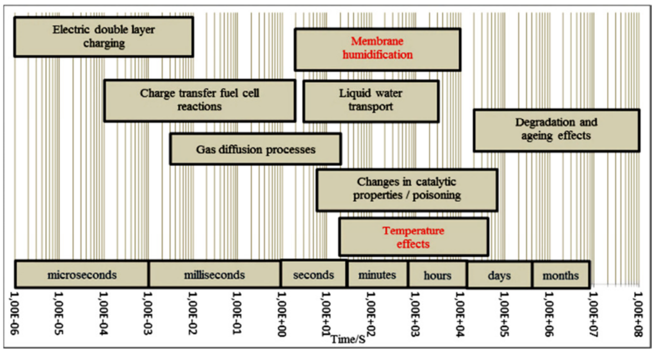


Fig. 6. Overview of the wide range of dynamic processes in FC [17].

B. *Considered faults in DC/DC converter*

Electrolytic capacitors and power semiconductors have higher failure and degradation rates among all of the components in DC-DC converters. Indeed, 60% of malfunctions and breakdowns are reported to be due to aluminum electrolytic capacitors and 31% due to power semiconductors failures [17]. Several works have been reported in the literature concerning the impact of the degradation or the failure of the capacitor in DC-DC converters [17], [18]. Thus, these prior works lead to the study to emphasize power semiconductor devices. The most common failures in power semiconductors are open-circuit faults (OCFs), gating faults and short-circuit faults (SCFs) [4]. Besides, the failures in this component can be attributed to a variety of factors, such as:

1) Driver failure;
2) Incorrect gate voltage;
3) Rupture of the device which may be a consequence of a short-circuit fault;
4) High voltage or current conditions;
5) Transients.

Furthermore, open-circuit faults can be a consequence of short-circuits or gating faults. In this study, only open-circuit faults are considered. It is important to point out that degraded power semiconductors affect both FC current ripple and efficiency of the DC/DC converter in a very significant way.

IV. FAULTS INFLUENCES ON THE INTERACTIONS BETWEEN FUEL CELL AND INTERLEAVED DC/DC CONVERTER

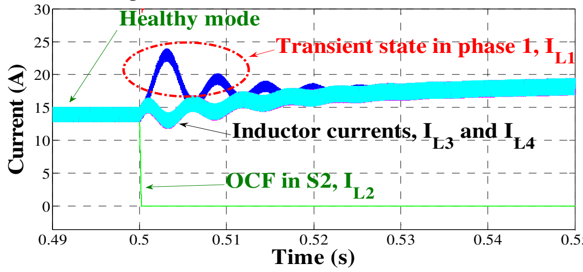
A. *OCF in DC/DC converter and its effects*

First and foremost, the fuel cell model and interleaved DC/DC converter with its PI control of the input current and output voltage have been implemented in numerical simulations. With this regard, the Matlab®-Simulink® has been adopted as the simulation tool, with the system parameters shown in Table 1.

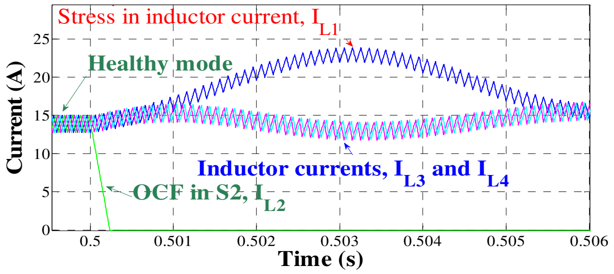
TABLE 1
SYSTEM PARAMETERS

Parameter	Value
Fuel cell rated power, P_{fc}	1 [kW]
Fuel cell voltage range, V_{fc}	24-36 [V]
Fuel cell rated voltage, V_{fc}	26 [V]
Fuel cell rated current, i_{fc}	42 [A]
DC bus voltage, V_{dc}	100 [V]

In order to study the impact of faults both for fuel cell and DC/DC converter, an OCF has been simulated at t=0.5s when the FC operates in steady state at rated power. Hence, the effects on the inductor currents, FC stack current and DC bus are shown in Fig. 7.



(a)



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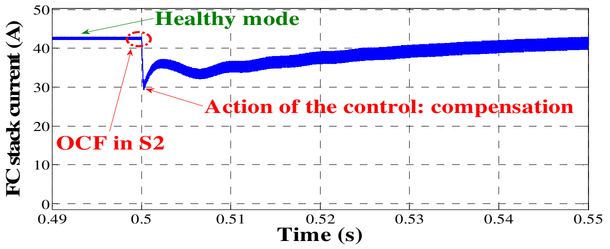

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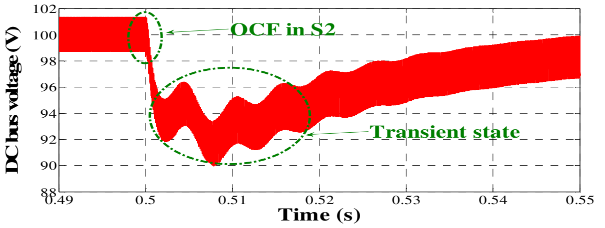

(d)

Figure 7. Faults effects on FC and DC/DC converter: (a) inductor currents, (b) stress in phase inductors, (c) FC stack current, (d) DC bus voltage.

As it can be seen in Fig.7d, the DC bus voltage is subjected to a transient phase after the OCF. In fact, this fault has been created in the floating part, causing an unstable state between this part (faulty) and the non-floating part (healthy). Despite this, the converter continues to supply power to the load without interruption. Moreover, the loss of one phase leads up not only to the increasing of the healthy phases currents but also to additional stress of the inductors [2] emphasized in Fig. 7a and b. As a result, FC stack current increases as it is emphasized in the Fig.10c. The increasing of the FC current ripple has negative effects on FC such as FC lifetime and additional internal losses produced by the harmonics of the current [5], [7]. The results are summarized in the radar diagram in Fig. 8 enabling to emphasize the effects of a degraded working mode.

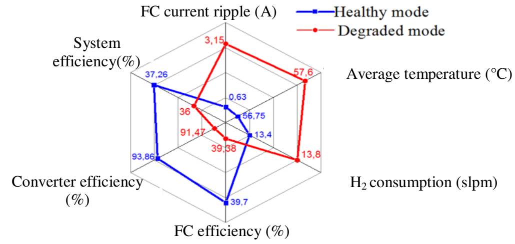

Figure 8. Radar diagram of the effects of a degraded working mode.

B. *Faults in Fuel cell*

1)Temperature Effect

Temperature is one of the most important operating parameters that need to be properly controlled. Temperature can also affect proton transport inside the membrane, resulting in membrane conductivity change. For example, at the same water content level, increasing temperature can reduce membrane resistance, thereby improving fuel cell performance [11]. The variation of FC and phase inductor currents according to different temperatures between 24 °C and 64 °C is given in Fig. 9. Increasing the stack temperature, FC stack current decreases, as this is highlighted in Fig. 10. As a result, the DC bus voltage as shown in Fig. 10, undergoes a small disturbance but the bus voltage level is maintained at 100V.

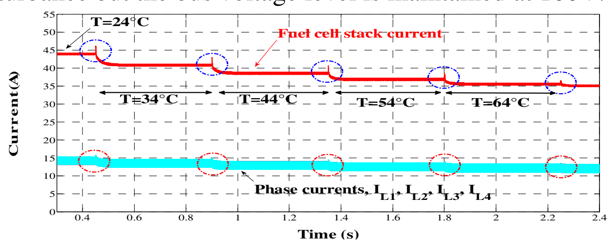

Figure 9. Evolution of the currents according to the temperature.

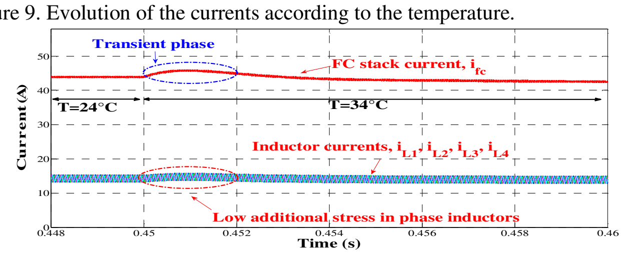

Figure 10. Stress in phase inductors due to operating condition change.

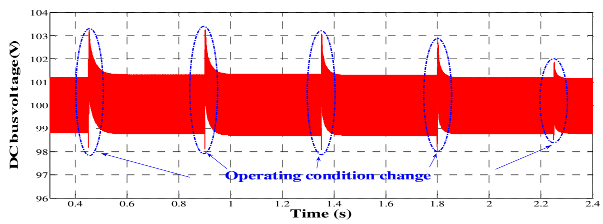

Figure 11. Variation of DC bus voltage according to the temperature.

2) Humidity Effect

Water management is an important issue in the performance of PEMFC [3], [11]. Besides, a high water level can block oxygen transport. If water content is elevated due to its generation at the cathode, it can directly affect the ORR kinetics and also contribute indirectly to the state of contact between the platinum (Pt) catalyst and the ionomer. If there is not enough water at the reaction interface, the ionomer will shrink. In this case, humidified gas streams are necessary for fuel cell feeding. The humidification cut-off at the cathode causes a large difference in both the membrane resistance and the kinetic resistance. Fig. 12 shows the fluctuations of DC bus voltage according to the variation of the humidity. As it can be observed in this figure, the variation of humidity has insignificant effects on the DC bus voltage due to the robustness of the control of the converter.

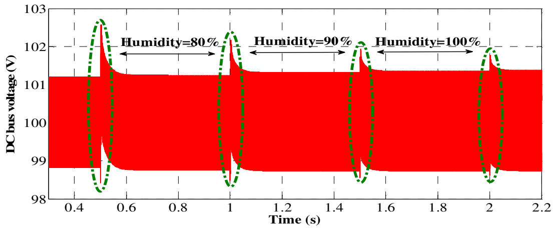

Figure 12. Variation of DC bus voltage according to the humidity.

3) Flow Rate Effect

It is generally recognized that the oxygen reaction in ORR kinetics is first order with respect to the oxygen concentration. In order to facilitate the ORR, a pressurized gas stream is often used to increase the reactant concentration, especially at high current densities, when mass-transport effects are more dominant than at low current densities [11]. The variation of DC bus voltage due to different oxygen pressure is shown in fig. 13. Similarly to the variation of the humidity, the effects on the DC bus voltage are negligible. To summarize, the faults effects from the FC system to the DC/DC converter do not have impacts on the operation of the FCEV.

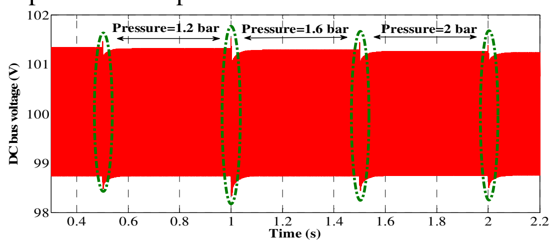

Figure 13. Variation of the DC bus voltage according to the pressure change.

V. CONCLUSION

The main contribution of this work is to study the influence of faults on the interactions between FC and DC/DC converter. For this purpose, different degraded working modes have been considered. It had shown that the faults from FC and converter had minor effects on the DC bus voltage, enabling consequently to supply power to the load without interruption. However, the occurrence of one OCF leads up not only to the increasing of FC stack current ripple but also to additional stress of the inductors. Besides, it is obvious that the impacts of faults are minimized with an interleaved DC/DC converter compared with a classic DC/DC boost converter. On the other side, the results of this study can be obtained from other converter topologies, but with suitable controllers. As a result, some functions of converter (e.g. DC bus voltage) will be damaged, being able to have impacts on the whole power train. Starting from this study, experimental tests will be carried out in order to validate the obtained results.

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