Faults Diagnosis Between PEM Fuel Cell and DC/DC Converter Using Neural Networks for Automotive Applications

Ali.Mohammadi[1,2], *IEEE Student Member*, Damien Guilbert[1,2], *IEEE Student Member*, Arnaud Gaillard[1,2], *IEEE Member*, David Bouquain[1,2], Davood Khaburi[3] , Abdesslem Djerdir[1,2], *IEEE Member*
[1)]Research Institute on Transportation, Energy and Society
IRTES-SET, UTBM, 90010 Belfort Cedex, France
[2)] FCLAB FR CNRS 3539, 90010 Belfort Cedex, France
[3)] Iran University of Science & Technology (IUST), 1684613114 Tehran, Iran
Email : (ali.mohammadi, damien.guilbert, arnaud.gaillard, david.bouquain, abdesslem.djerdir)@utbm.fr
khaburi@iust.ac.ir

***Abstract*—Fault tolerance in proton exchange membrane fuel cell (PEMFC) and power converters for automotive applications has become crucial in order to increase the reliability of the power train. As a matter of fact, the occurrence of faults in PEMFC and power converters has undesirable effects on the whole power train such as decreasing of the efficiency and lifetime of the components (PEMFC, converters). The purpose of this paper is to present a fault diagnosis method for PEMFC and DC/DC converter. This fault diagnosis is based on neural networks (NNs) modeling approach combined to numerical simulation in which a new developed sensitive model of PEMFC and an interleaved DC/DC converter have been especially used. Specifically, in this study drying and flooding faults that usually occured in PEMFC according to operations condition variation such as temperatue, humidity and pressure have been considered. Moreover, the power semiconductor failures in DC/DC converter have been taken into consideration in this study.**

Keywords—PEM Fuel cell, Interleaved DC/DC converter, fault diagnosis, Neural networks.

I. INTRODUCTION

Over the last few decades, PEMFC have gained a growing interest for power generation especially in transportation applications such as fuel cell electric vehicles (FCEVs). Due to their high power density, solid electrolyte (no leakages and low corrosion) and working operations at low temperature, PEMFC appear to be the most suitable compared with others existing technologies of fuel cell (FC) [1]. On the other hand, their low and unregulated voltages produced at the output require the use of DC/DC converter in FCEV in order to raise the level of the voltage up to the main DC bus voltage. Furthermore, FC must deal with specific requirement related to automotive applications such as [2]:

1) Extend the lifetime of fuel cell to 5000 hours[1] (around 241 000 kilometers) in order to compete with the current automotive engines.

By comparison, the DC/DC converter must meet the requirement of FCEV such as [3]:

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 FC lifetime.

Besides, the reliability and continuity of service of power trains remain major concerns in order that FCEVs can access to the mass automotive market. Several works have been reported in the literature on fault detection in FC. There are many ways to categorize the different diagnosis, but totally have been considered in two mainly groups, Model-free and Model-based methods. The general idea of fault diagnosis model based methods is to compare the available measurements of the monitored system with their corresponding predictions obtained using a system model [4]:

1) Analytical;
2) Qualitative.

In analytical model, fuzzy and neural are applied to fault detection. However, in the qualitative model-based approach which just applies qualitative of models of the system plant [5]. In comparison, even though many papers have studied fault detection methods in DC/AC converters [5]-[8], an increasing number of recent papers are focused on fault diagnosis in DC-DC converters [9]-[14]. Moreover, the electrolytic capacitors and power semiconductors have higher failure and degradation rates among all of the components in DC/DC converters [14]. Several works have been reported in the literature on fault detection of aluminum electrolytic capacitors [14], [15]. Thus, this paper emphasizes power semiconductors failures.

The aim of this paper is to present a fault diagnosis method based on neural networks (NNs) in PEMFC and DC/DC converter. In previous works, studies of influence of faults on the interactions between FC and DC/DC converter have been carried out [3]. In this paper, the method emphasizes the model-based fault detection and isolation using feed forward neural network.

In the following, the architecture of FCEV and the modeling of sensitive FC and DC/DC converter are presented

[1] 20000 hours in steady state conditions

in section II. Then, a review of considered faults in the case under study is introduced in section III. Afterward, the explanation of the fault diagnosis method based on NNs and results obtained by simulation are presented in section IV.

II. ARCHITECTURE OF FCEV AND MODELING OF SENSITIVE FC AND DC/DC CONVERTER

A. *Configuration of the power train of FCEV*

The FCEV, as shown in Fig. 1 utilizes a PEMFC as the main power source and the auxiliary power unit (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 [16]. In this paper, the fault diagnosis study focuses on two specific elements of the power train. In point of fact, these components play a large part in maintaining normal operation of the vehicle. On the other side, if a fault occurs in PEMFC or DC/DC converter, the vehicle works in degraded mode leading up to the decrease of its performances. That's why, it is very important to detect the faults very quickly. Once the fault has been detected, the effects on the powertrain must be reduced. In order to ensure good performances, a fault tolerant strategy must be used (e.g. reconfiguration of the control of DC/DC converter in case of faults) [17]. This strategy could allow finding either an improved degraded mode (e.g. fulfilling a null FC current ripple) or a healthy mode (e.g. ensuring a FC constant power) to obtain the best efficiency.

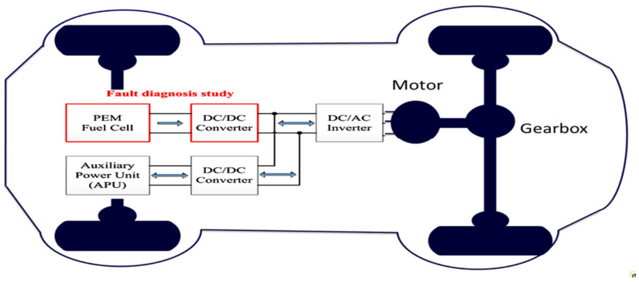

Fig. 1. Block diagram of FCEV [19].

B. *Sensitive model of FC*

It can be seen that after about 20 years, in numerical modeling of PEMFC performance, researchers have become aware that the polarization curve comparison is enough for the validation of a comprehensive model [18]. However, in this paper, sensitive model is proposed. It is important to point out that operation parameters (e.g. temperature, humidity, pressure, and so on) influence the parameters of model (e.g. R_{con}, R_{act}, R_{ohm}, etc.) and consequently the performances of FC. For this reason, in this model, the 2D variations of temperature, pressure and humidity have been taken into account by adopting a different equivalent circuit for each elementary cell. Indeed, these parameters according to dimension (X, Y and Z direction) and coefficients material are not uniform distribution in each cell of FC. Therefore, assuming an NxM elementary cells one can obtain NxM equivalent elementary circuit. Furthermore, for accurate diagnosis fault in PEMFC, it has been chosen to divide each cell of the FC stack in different elementary cells as it is shown in Fig. 2. Besides, a detailed explanation of this modeling can be found in [18].

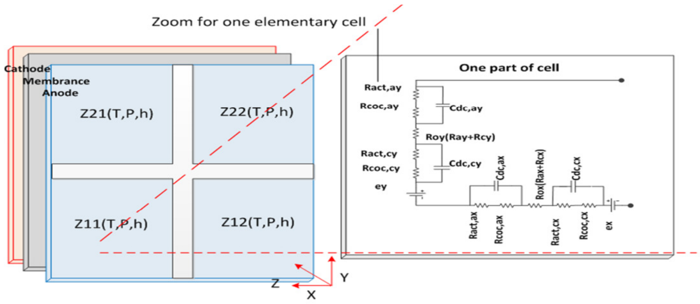

Fig. 2. Demonstration of one cell in 2D of PEMFC stacks.

C. *DC/DC converter*

Basing on challenging issues in FCEV applications, it has been chosen to focus the fault diagnosis study on interleaved DC/DC converter. The selected topology is a floating-interleaving boost converter (FIBC) [19]. The schematic representation of this topology combined with fuel cell system being a part of FCEV is drawn in Fig. 3. In order to respect the balance of DC bus, interleaving number must be necessarily pair. Additionally, the choice of N=4 phases is justified by a compromise between volume of inductors, efficiency, input current ripple, redundancy and cost [3]. In order to fulfill the fault tolerance requirements, fuses have been added in series with each power semiconductors in Fig. 3. The fuses allow the faulty phase to be isolated in case of short-circuit faults (SCF). Due to the parallel connection of the non-floating and floating boost topology [19], this topology has several benefits compared with other topologies of DC/DC converters for FC applications [20], including compactness, high-efficiency, reliability, reduced current ripple and adaptability for degraded working modes. Furthermore, due to its redundant architecture, if a fault occurs on a phase, the others phases can be used as backup system, avoiding consequently any power delivery interruption.

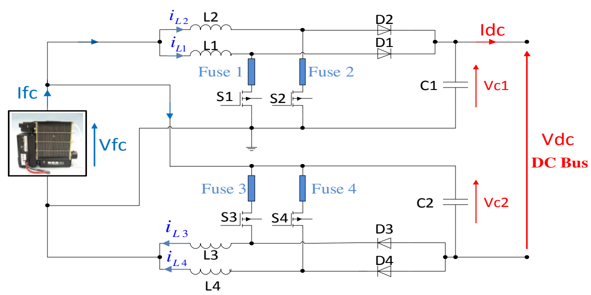

Fig. 3. Four phases floating-interleaving boost converter (FIBC).

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

A. *Considered faults in fuel cell*

In a fuel cell, failure can be caused by:

1) Long time operation (natural ageing);

2) Operation incidents, such as Membrane Electrode Assembly (MEA) contamination or reactant starvation.

A common consequence to all "fault" incidents is a voltage drop. Voltage is therefore a first indicator of degraded state.

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

Fig. 4 emphasizes the link between the relative humidity and the state of the membrane, which can be either wet or dry. It can be readily seen that for most operating conditions, the membrane of the FC is either too wet or too dry. Furthermore the humidity should be above 60% to prevent excess drying, but must be below 100% to prevent of flooding.

Higher temperatures cause better performance, mainly because the cathode overvoltage reduces. However, once over 60 °C the humidification problems increase [21]. Furthermore, if the pressure increases, the FC performances are improved due to the raise of open circuit voltage (OCV) added to a reduction in cathode activation overvoltage. As well as these benefits, there is also sometimes a reduction in the mass transport losses, with the effect that the voltage being to fall down at a higher current [21].

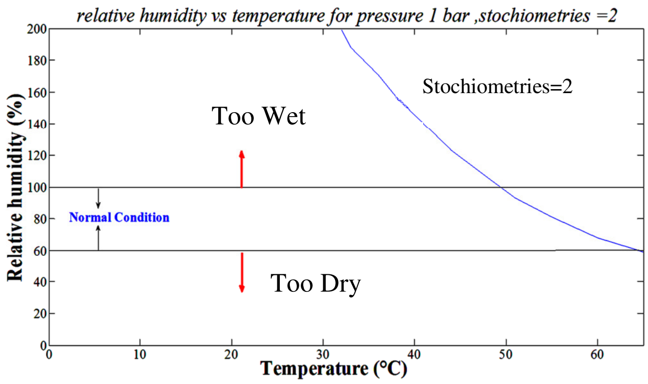

Fig.4. Relative humidity according to the stack temperature for the exit air of the FC with air stoichiometry of 2.

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. As a matter of fact, 60% of malfunctions and breakdowns are reported to be due to aluminum electrolytic capacitors and 31% due to power semiconductors failures [14]. The Fig.5 shows the distribution of failure for each power component in a half-bridge DC/DC converter.

Several works have been reported in the literature concerning the impact of the degradation or the failure of the capacitor in DC-DC converters [14], [15]. Thus, this study emphasized power semiconductor devices. The most common failures in power semiconductors are open-circuit faults (OCFs), gating faults and short-circuit faults (SCFs) [22]. 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 studied. In fact, a discussion in a previous work [3] about short-circuit faults has been carried out. 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 [3].

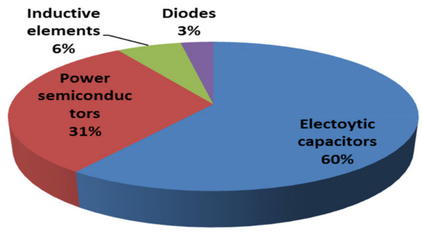

Fig. 5. Distribution of failure for each power component in a half-bridge DC/DC converter [14].

IV. FAULT DIAGNOSIS METHOD BASED ON NNS

A. *Presentation of NN*

A Neural Network (NN) consists of a number of processing units (neurons) that communicate by sending information to each other. The link between two neurons is done via weighted connections. The most common neural network is the multilayer perceptron (MLP) [23]. Feed forward networks consist of a series of layers. The first layer has a connection from the network input. Each subsequent layer has a connection from the previous layer. The final layer produces the network's output. Feed forward networks can be used for any kind of input to output mapping. A feed forward network with one hidden layer and enough neurons in the hidden layers can fit any finite input-output mapping problem. Fig. 6 shows the main structure of feed forward of NN.

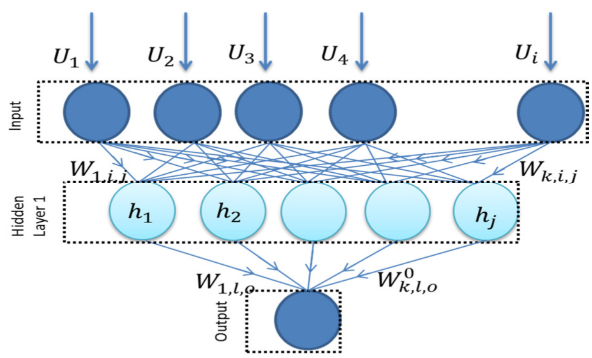

Fig.6. Topology one hidden layer feed forward NN.

B. Classification and identification of each faults both for FC and DC/DC converter

In order to classify and identify accurately the different faults in FC and DC/DC converter, a harmonic analysis has been used. For this study, the most significant FC stack voltage harmonic ranks have been selected, from the 2nd until to the 7th harmonic. In order to perform Fourier analysis, the FFT analysis tool of Matlab®-Simulink® has been used. The fundamental frequency of the signal tallies with switching frequency from DC/DC converter. Hence, the harmonic analysis enables to split the different categories of faults. In addition, the total harmonic distortion (THD) has been determined in order to analyze the measured signal into its constituent harmonics. In Fig. 7, a radar diagram has been plotted to summarize the effects of FC faults such as temperature change on the amplitude of harmonics and THD. It is important to emphasize that a PEM fuel cell in operation is always between too much water and not having enough water. Too much water may cause flooding in either the catalyst layer or the gas diffusion layer or even in gas channels. By comparison, too little water is likely to cause membrane drying, which in turn increases cell resistance and reduces cell potential [24].

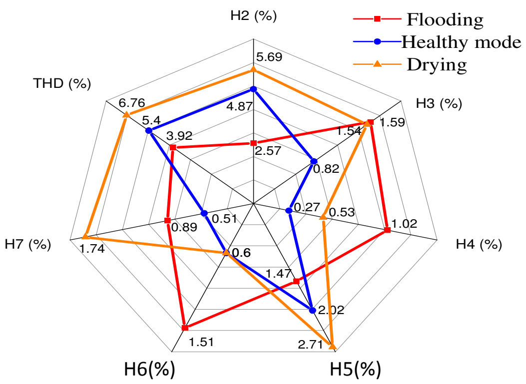

Fig. 7. Radar diagram of classification of FC faults according to the operating temperature.

In the same way, a radar diagram has been plotted in Fig. 8 to summarize the effects of DC/DC converter, namely OCF faults on amplitude of harmonics and THD. Starting from this classification by harmonic analysis, NNs can be used for identifying accurately the category of fault.

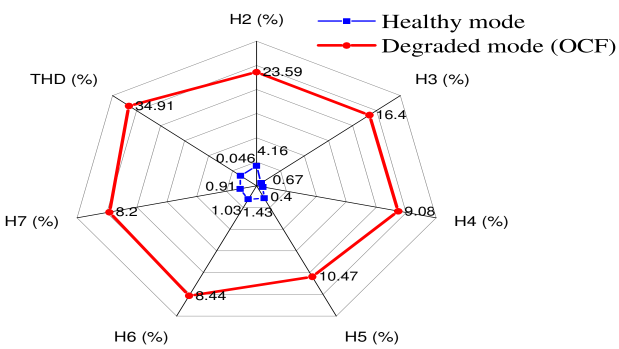

Fig.8. Radar diagram of classification of OCF faults in DC/DC converter.

C. Training and validation of the proposed fault diagnosis method

NN train is based on the input of weights of every neuron. The selected back propagation algorithm is named Levenberg–Marquardt, which provides a very accurate weight adaptation with moderate time consumption. The training is started with a gradient algorithm. When a minimum is approached, this gradient takes increasingly low values, and convergence toward this minimum is strongly slowed down. Then, to speed up the convergence, the quasi-Newton algorithm is used [25].

The aim of the NN model is the classification of occurring faults in FC and DC/DC converter according to the different operating conditions and open circuit faults. The common faults in FC (flooding, drying) which has been taken into account in this study are the increasing of gas temperature, the air humidity which may be too low or too high and the augmentation of pressure of air which could lead up to faults. Therefore, the NN is trained by harmonics magnitude and THD of FC stack voltage according to different conditions as explained previously. Fig.10 compares different faults which occurred in FC and DC/DC converter. Considering the shape, it can be deduced the different output of stack voltage between two working mode operations (e.g. healthy mode and degraded mode). In order to improve the accuracy of fault-diagnosis in fuel cell, it is more appropriate to use the sensitive modeling of PEMFC that the NN is trained by changing impedance and voltage in each elementary of cell according to variation of operation conditions that is fully discussed in a previous article [18]. In the following, the different operating conditions are explained in details.

For instance, if the humidity gases inlets increased, more water would accumulate in the cell. Hence, flooding could occur and block the gas inlet. By comparison, if the humidity was too low, less water would accumulate in the cell, leading up to drying [24]. For this reason, humidity range has been selected between 50% and 120% in order to take into account flooding, drying and normal mode. Besides, if the humidity range is included between 80% and 100%, the FC works in healthy mode; whereas for more than 100%, flooding case occurs and less than 80%, drying case occurs.

In the same way, if the inlet gases pressure increased, flooding water would occur; while in low pressure, would lead up to drying. According to characteristic of the FC, pressure has been chosen with different range. Hence, for this paper pressure range has been selected between 0 and 2.2 bar. In other words, FC operates in healthy mode for a specific range, namely between 0.7 and 1 bar. On the other hand, if the pressure is included between 1 and 2.2 bar, indicates the presence of flooding in the FC; whereas a pressure lower than 0.7 bar leads up to drying.

Besides, if temperature increased, this would cause the evaporation of water in the FC. Hence, this could lead up to drying. Conversely, at low temperature, this conducts to flooding [21], [24]. Indeed, the temperature is included between 0 and 70 °C. This range depends strongly on the technical characteristics of FC. In this paper, for healthy mode, temperature has been selected between 30°C and 50 °C.

Likewise, if the temperature increased beyond 50°C, drying would occur in the FC. On the other hand, if the temperature was lower than 30°C have an effect of the low evaporation water in the FC. Eventually, flooding could take place. Starting from these different operating conditions, a 3-D fault diagram has been sketched in Fig. 9. The latter allows summarizing the studied faults in FC, namely drying and flooding in terms of temperature, pressure and humidity. Concerning the DC/DC converter, the OCF is simulated creating a gating fault in the control of FIBC topology.

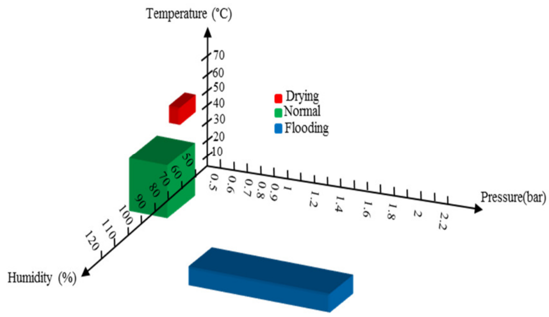

Fig.9. 3-D fault diagram according to operating conditions of FC.

All in all, faults introduced previously, are classified by flooding, drying and open circuit faults. As illustrated in table 1, whole faults and healthy mode, are coded with binary code (e.g. 0 and 1). In other words, in this table the outputs of NN are normalized in various categories with 0, 1. In addition, NN pattern recognition tool has been used to classify between healthy mode and degraded mode: either FC faults (e.g. flooding and drying) or DC/DC converter faults (OCF). According to Fig. 7 and 8, the inputs of NN can be summarized in three inputs (H_2, H_7, and THD). The choice of three inputs results from a compromise between training NN and simulation time.

In order to improve the classification of faults according to FC operating conditions and DC\DC converter operation, the outputs of NN are synthesized into four combinations including a binary code. The latter are given in Table 2 according to the category of fault. Besides, a healthy working mode has been taken into consideration for the outputs of NN.

Table 1 .Normalization output of NN in different operation condition

Fuel Cell Operating Condition according to categories of faults												
RH [%]	50%	60%	70%	80%	90%	100%	110%	120%				
Outputs	Flooding			Normal			Drying					
Pressure	0.5	0.6	0.7	0.8	0.9	1	1.2	1.4	1.6	1.8	2	2.2
Outputs	Drying	Normal					Flooding					
Temperature [°C]	0	10	20	30	40	50	60	70				
Outputs	Flooding			Normal			Drying					

Table 2 .Categories of faults with binary code for output neural network

Faults	Flooding	Drying	OCF	Normal
Output	1	0	0	0
	0	1	0	0
	0	0	1	0
	0	0	0	1

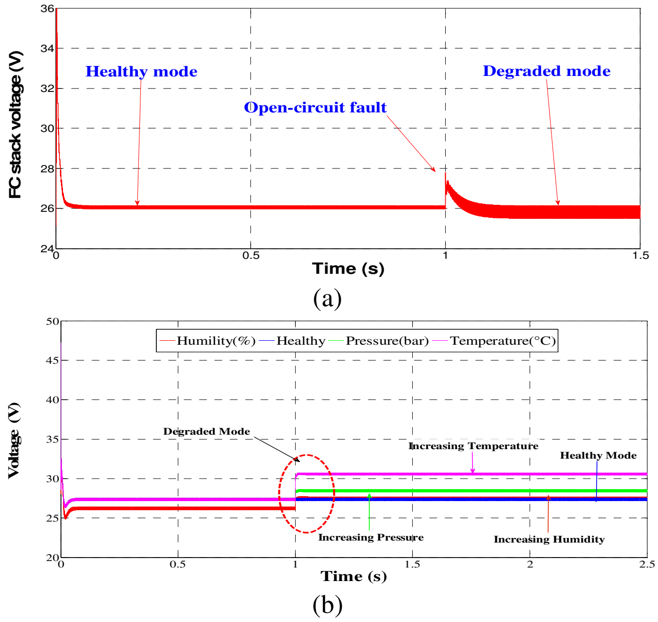

Fig.10. Comparison of FC stack voltage for different faults occurred in FC and DC/DC converter.

The Fig. 10a compares the FC stack voltage in healthy mode (without faults) and degraded mode (occurrence of one OCF); while the Fig. 10b compares the same voltage in healthy mode and degraded mode in case of faults related to relative humidity, pressure and temperature. As it can be seen in Fig. 10 when a fault occurs both for FC and DC/DC converter; the FC behavior is altered compared with a healthy working mode. For instance, the loss of one phase due to the OCF in DC/DC converter leads to the decreasing of FC stack current during a very short time, causing the increasing of FC stack voltage [3] as that is highlighted in Fig. 10a. Moreover, if the temperature rises, the FC performances will become better, mainly because the cathode overvoltage reduces. However, once over 60°C the humidification problems increase and the extra weight and cost of the humidification equipment can exceed the savings coming from a smaller and lighter fuel cell [26]. Afterward, the fault diagnosis method has been implemented in Matlab®-Simulink® with its three inputs as shown in Fig. 11.

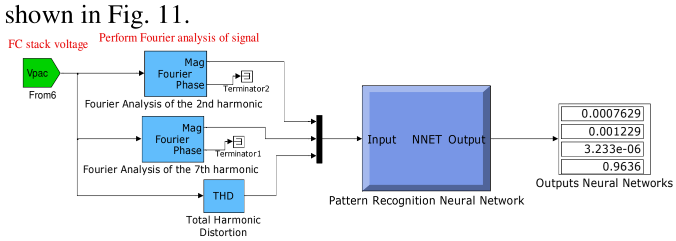

Fig. 11. Fault diagnosis online in healthy mode.

First and foremost, a simulation of the FC and FIBC topology in healthy mode has been performed in order to verify the performances of NNs. As it can be seen in Fig. 11, the output of NNs matches the binary code in Table 2, resulting in healthy mode. Then, a flooding fault has been simulated by reproducing operating conditions shown in Table 1.

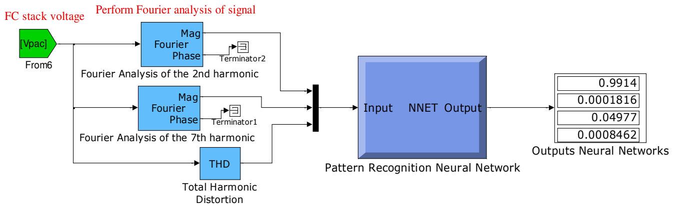

Fig. 12. Fault diagnosis online in degraded mode.

Similarly to the healthy mode, the fault diagnosis based on NNs allows giving excellent results for a flooding case as shown in Fig. 12.

V. CONCLUSION

The purpose of this work is to propose a fault diagnosis method based on artificial neural networks for the faults classification both for FC and DC/DC converter. For this study, a new developed sensitive model of PEMFC and an interleaved DC/DC converter have been especially used. Each fault being able to occur in FC and DC/DC converter has been characterized and classified using a harmonic analysis. The characterization of each fault has been implemented in NNs. Basing on the results obtained by simulations, the proposed method with NNs offers excellent performances for faults classification. Starting from this work, improvements of the method will be proposed by using wavelet transform. Then, instead of using FC stack voltage for OCF in DC/DC converter, the phase currents of the latter could be used for diagnosing accurately where the fault has occurred. Finally, a fault tolerant strategy based on control reconfiguration could be proposed in order to minimize the effects in degraded mode.

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