Robust Diagnosis of a Fuel Cell Pumping System by Bond Graph Modeling Approach

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Abstract- This article presents works relized to verify the efficiency of a developed diagnosis system dedicated for a PEM Fuel Cell pumping system. The studied system is composed of PEM fuel cell powering an electrical pumping system via an electronic adaptation stage which consists of a cascade-connected DC-DC boost converter and a voltage inverter. The diagnosis system is developed based on Bond Graph approach which allows to model the studied system graphically in order to facilitate to investigate its working performances by simulating the developed model under the 20-Sim software. Obtained results show an efficient fault detection for different simulation scenarios carried out by imposing both mechanical and hydraulic faults to the system to test the reponse of the presented diagnosis algortihm.

Keywords PEM Fuel Cell generator; Motor Pump; Static Converters; Diagnosis System; Bond Graph; 20-Sim Software.

1. Introduction

The field of energies, mainly based on fossil resources, is expected to undergo a strong evolution due to the problems posed by the massive exploitation of these fuels. Environmental degradation and declining reserves, as well as new stand-alone or portable applications, are spurring the development of new energy technologies. Hydrogen, one of the ideal energy carriers to replace fossil fuels in the long term.

The fuel cell, an electrochemical element allowing to produce electricity from hydrogen, is one of the best ways to use this energy vector in order to supply electric charges. Thus, fuel cells are currently experiencing a renewed interest, both industrially and in research. Industrialists from different sectors (electronics, automotive, heating, pumping, etc.) are investing in the development of this technology with low emissions of harmful gases and low noise pollution.

The fuel cell pumping system is the ideal solution for supplying water in isolated areas that are not connected to the electrical grid. A fuel cell-based pumping installation is generally made of these different parts:

- a fuel cell: many types of fuel cells have been developed. Each one presents its advantages and withdrawals compared to other types. Researches are mostly interested with Proton Exchange Membrane (PEM) type for its portability and temperature working range advantages.

- A pumping unit: Electrical pumps have become the most used ones nowadays. An electrical pumping system is generally made of two parts (electrical motor and a pump).

- Static converters: a PEMFC is a DC generator and they are generally used for low voltage applications. Thus, a DC-DC Boost converter is generally used to adapt the PEMFC voltage to the voltage level required by the pumping motor. Also, a voltage inverter is used because the most used motors for pumping systems (Induction motors) are generally AC type motors.

From another hand, the importance of diagnosis systems in such applications resides in alarming supervisors in case of degradation in working performance of a single part of the system which may be helpful to avoid a full system shutdown or to take necessary precautions before stopping the system for repair. For example, in a water pumping system, this can help humans to store necessary water quantity before the system completely stops or even to avoid water waste in some cases by repairing the faulty part.

different types of detection algorithms dedicated to physical systems have been designed by researchers in the Automation community [10-13]. These methods are basically arranged in two categories: model-based and model non model-based methods and each one of these categories is split into two sub-categories (qualitative and quantitative methods).

Methods based on Bond Graph (BG) techniques are considered as model-based qualitative ones. BG modeling technique presents the advantage of simplicity in modeling the studied systems which facilitates the control and diagnosis tasks.

The work presented in this paper is organized as follows:

Section 2: presents the studied system and its BD modeling process.

Section 3: dedicated to presents the developed diagnosis system and show the obtained results with different simulation scenarios carried out to investigate the efficiency of the diagnosis process under different working conditions.

Section 4: A conclusion of the obtained results and future perspectives of the presented works are made in this last section.

2. System Description and Modeling

The studied system is composed of a PEM fuel cell generator powering a pumping system through two static converters which are a DC-DC Boost converter and a voltage inverter. The system topology is presented in Fig.1.

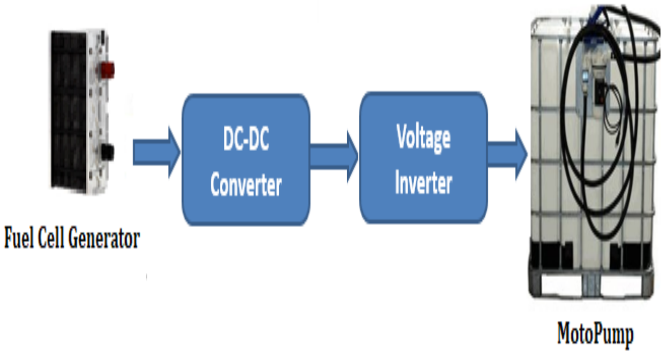

Fig. 1. System configuration.

1.1. General Overview on BG Method

Bond Graph (BG) method consists mainly on representing the energy exchanges that take place on a system using effort and flux variables [3]. In BG approach, the direction of the exchanged energy transfer is represented by a half arrow forms (also called leaps) which are labelled by e (for effort variables) and f (for flow variables). The power P that is carried by the hop is the resulting product of the flow and effort variables and is counted positively in the direction of the half-arrow. The main advantage of the BG model is the fact that the choice of the effort and flow is made according to the physical domain of modelled system as shown in Fig.2.

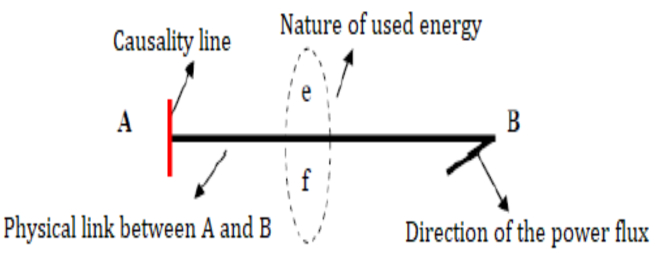

Fig. 2. BD modeling of a physical system.

The nine elements which intervene in the BG model can be grouped in 3 categories as follows [14-17]:

- Active elements: which are the elements that provides the power to the system and they are mainly the effort and flow sources (Se and Sf)
- Passive elements: which are the elements that dissipate the supplied power in heat form (R elements) or store it in different forms (C and I elements)
- Junction elements: which are mainly the elements that conserves the supplied power (0, 1, TF, GY).

Table 1. Different elements used in BG model

Symbol	Elements
R : r	Resistance, friction
I : i	Inductance, inertia
C : c	Capacity
GY	Gyrator, MCC
TF	Transformer
Se	Effort Source
Mse	Controlled Effort Source
Sf	Flow Source
Msf	Controlled Flow Source

1.2. BG Modeling of the studied system

The global Bond Graph model of the studied system which is composed of 4 different parts is shown in Fig.3 and the developed bond graph model of the fuel cell coupled with the boost converter is given in Fig.4 18] [19].

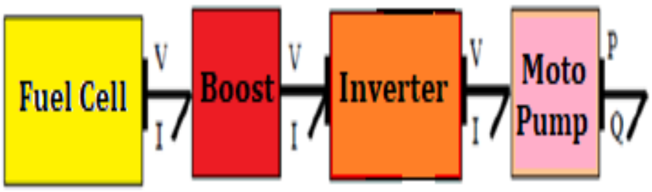

Fig. 3. Global BD modeling of the studied system.

Figure 5 presents the equivalent circuit (EC) model of the 3 phased voltage inverter used in this work, Fig.6 and Fig.7 present respectively the corresponding BG model developed under 20-Sim tool and the measured voltage at the output of one arm of the inverter (1 of the 3 phases) [6].

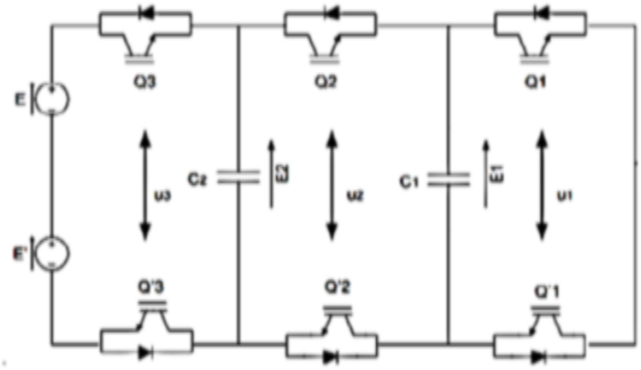

Fig. 5. EC model of the 3 phased inverter.

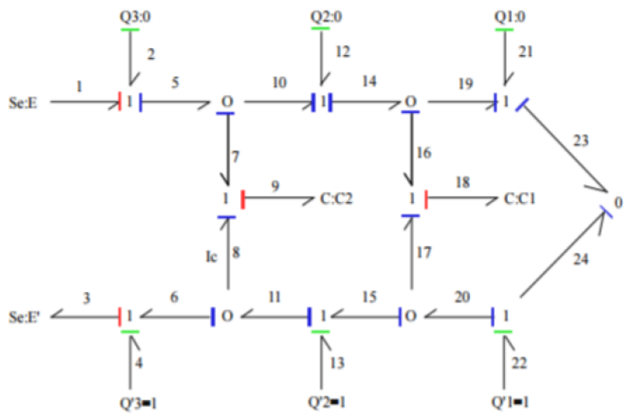

Fig. 6. Corresponding BG model of the 3 phased inverter.

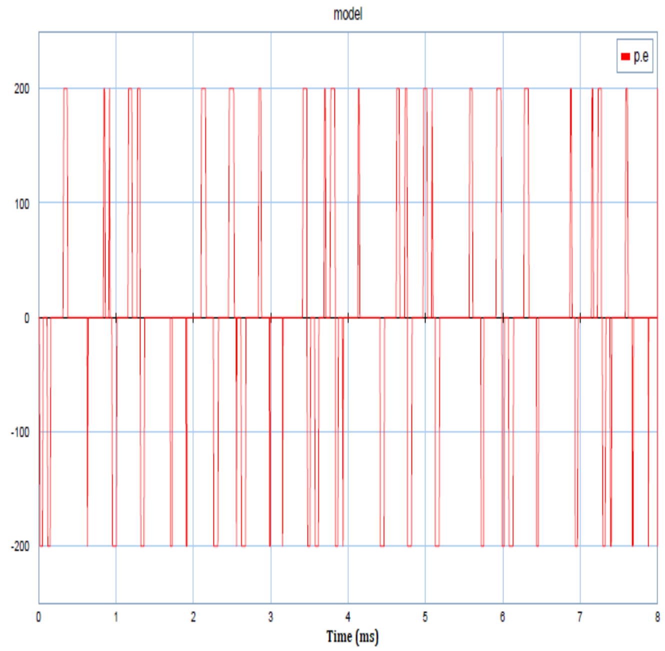

Fig. 7. Voltage signal measured at the inverter output (20-Sim simulation).

Figure 8 presents the developed BG model of the motor-pump system. Figure 9 presents the measured signals at the motor side (Torque and angular speed) and Fig.10 presents the measurements at the pump side 3 phased voltage inverter used in this work, Fig.6 and Fig.7 present respectively the corresponding BG model developed under 20-Sim tool and the obtained output voltage signals [6].

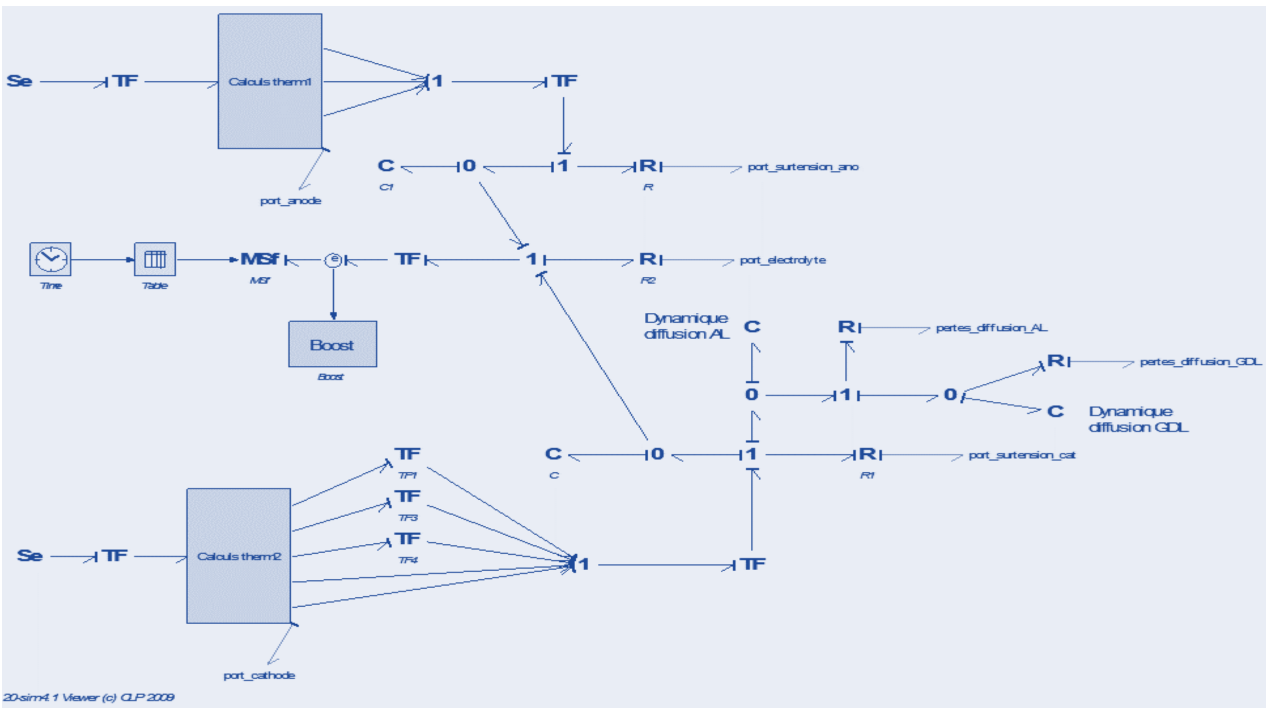

Fig. 4. Detailed BD modeling of the PEMFC+Boost converter.

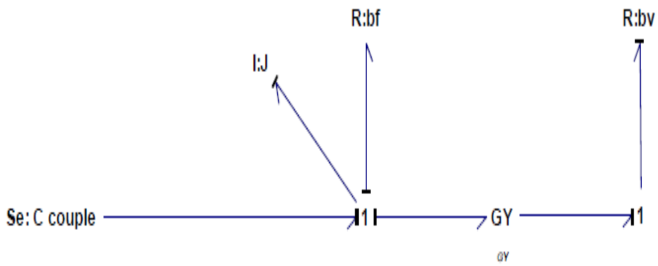

Fig. 8. Moto pump Bond Graph model

With:

bf (Nm / rd. $s-1$): friction of the motor;

Jp (Kg.$m2$): moment of inertia;

bv (Pa.s): viscosity of water;

GY presents the operator which converts mechanical energy into hydraulic energy

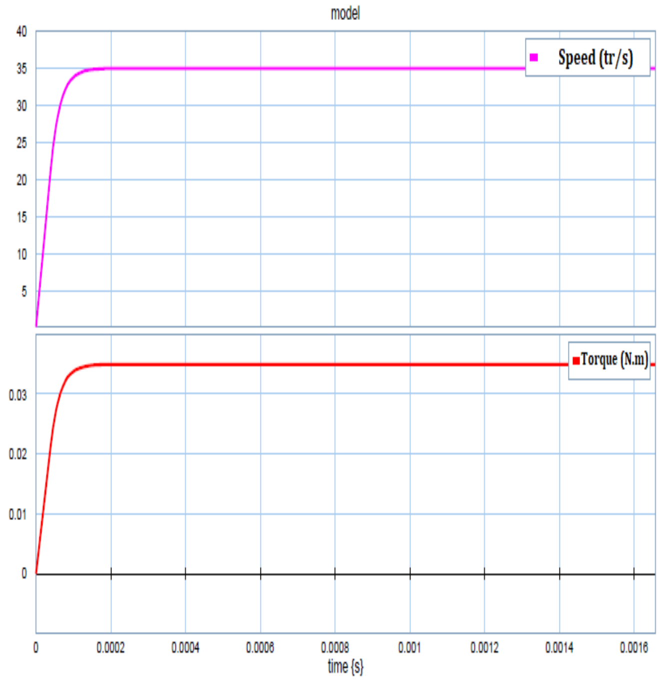

Fig. 9. Motor measurements of the developed BG model: (a) Angular speed, (b) torque

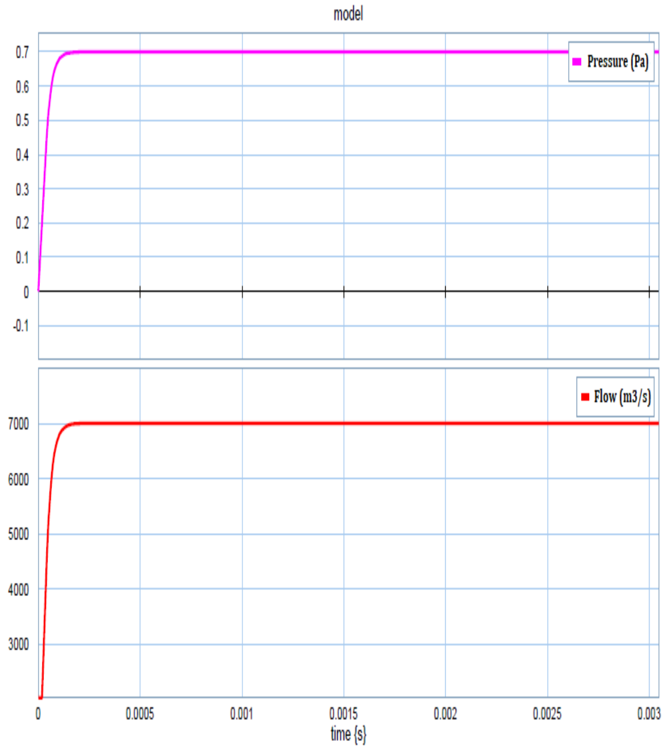

Fig. 10. Pump measurements of the developed BG model: (a) pressure, (b) water flow

3. Diagnosis System

3.1. Developed Diagnosis System

The studied motor-pump consists of two parts, an asynchronous motor and a centrifugal pump. Its bond graph model is presented in Fig.8.

The physical characteristics of the system (coefficient of friction **bf**, moment of inertia J, viscosity of water **bv**) are presented in Table 2:

Table 2. Different parameters of the pumping system

Parameters	Description	Values	Units
bf	Motor friction coefficient	0.001	*Nm/rd. s−1*
J	Moment of inertia	0.001	*Kg.m2*
bv	Water viscosity	0.0001	Pa.s

Table 3 contains the structural equations that can be formulated at the different junctions of the linear Bond Graph model shown in Fig. 8.

Table 3: Structural equations generated from the bond graph model

Function	***Equations***
Junction 11	$e1-e2-e3-e4=0$ $f1=f2=f3=f4$

	With : $f2=\omega$
Junction 12	$e5-e6=0$ $f5=f6$ With : $f6=Q$

With the flow $f2$ represents the angular speed ω and the flow $f6$ represents the flow rate of the pump Q.

The first junction 11 gives us as a structural equation from which the residue equation r1 can be obtained:

$$r1=e1-e2-e3-e4=C-bfDf1-JdDf1dt-mDf2 \quad (1)$$

With:

$$e1=C \quad (2)$$

$$e2=bff2=bff1=bf\omega \quad (3)$$

$$e3=Jdf3dt=Jdf1dt=Jd\omega dt \quad (4)$$

$$e4=mf5=mDf2 \quad (5)$$

The residue equation r2 is obtained through the structural equation at junction 12:

$$r2=e5-e6=mf4-bvf6=mf1-bvf5=mDf1-bvDf2 \quad (6)$$

The rows of the boolean fault signature matrix are associated with the set of residuals (r1, r2) and the columns with the variables of any faults Fj (j = 1…, 7).

If j = 1 (or 0), if the residue i sensitive (insensitive) to the fault j, the table of signatures presented in Table 4 can be obtained:

Table 4: Fault signature matrix for the motor pump considers

	F1: C	F2: $\boldsymbol{bf}$	F3: $\boldsymbol{Df}$ 1	F4: $\boldsymbol{Df}$ 2	F5: J	F6: m	F7: $\boldsymbol{bv}$
r1	1	1	1	1	1	1	0
r2	0	0	1	1	0	1	1

It can be seen from this table that F3, F4, F6 have the same signature S (1, 1) and therefore a fault at the level of the sensors $Df1$ and $Df2$ cannot be isolated. To solve this problem, a linear combination (equation 1) of these different residues r1 and r2 (equation 6) makes it possible to eliminate certain redundant variables are necessary.

3.2. Simulation Results of the Diagnosis System

In order to investigate the efficiency of the developed diagnosis system, a simulation model using 20-Sim software has been used to simulate different working scenarios. This BG based simulation model is presented in Fig.11:

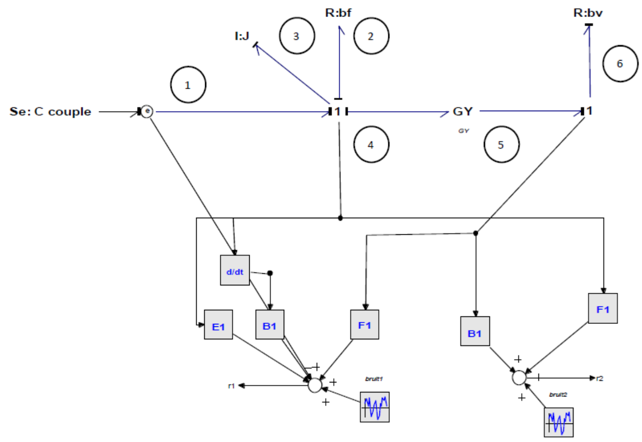

Fig. 11. Complete 20-Sim simulation model (BG model + Diagnosis system).

As a start, normal working performances are investigated (without introducing any type of anomaly), and as shown in Fig.11 both residues r1 and r2 diverges to zero. The obtained motor and pump measurements are the same presented previously in Fig.9 and Fig.10.

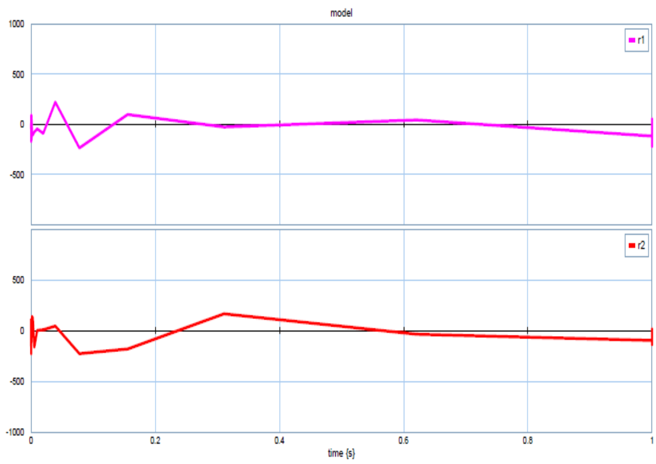

Fig. 12. Measurements of residues r1 and r2 in normal working conditions.

In order to investigate the diagnosis system performance in detecting the presence of a mechanical fault (fault in the motor shaft), a variation, presenting a sudden fault appearance at the level of the motor shaft, is introduced between the instants 0.003 s and 0.004 s.

Results presented in Fig.13 and Fig.14 show that all measurements at both the motor and pump levels are influenced at the time of the fault occurrence. Also, Fig.15 shows that both residues r1 and r2 are disturbed at the time of the appearance of the fault, which proves their efficient sensitivity to this type of faults.

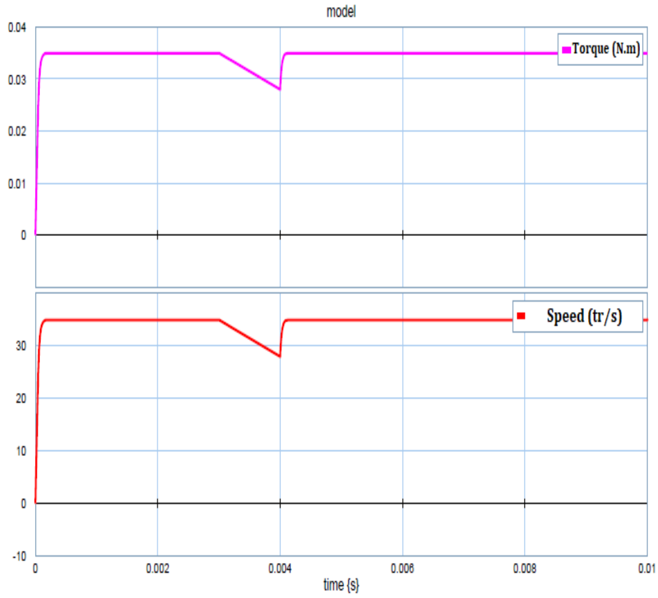

Fig. 13. Measurements at the motor side with a mechanical fault: (a) torque, (b) Angular Speed

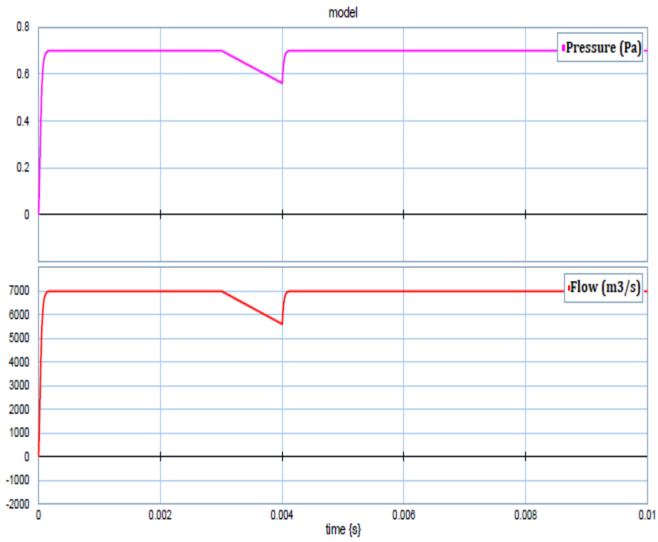

Fig. 14. Measurements at the Pump side with mechanical fault: (a) Pressure, (b) Flow rate

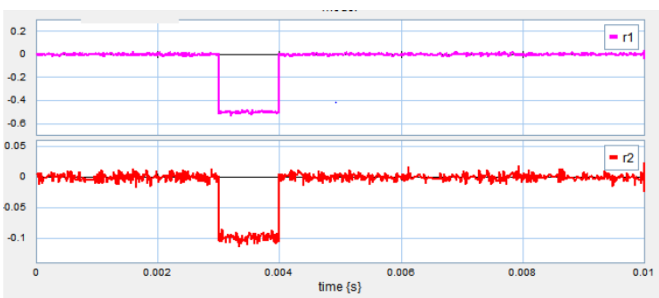

Fig. 15. Residues r1 and r2 with a sudden mechanical fault

In order to investigate the diagnosis system performance in detecting the presence of a hydraulic fault at the pump side, an inadequate viscosity value is introduced between 0.006 s and 0.007). As shown in Fig.16 and Fig.17, this fault influences both mechanical and hydraulic measurements. The residues r1 and r2 are both sensitive to the introduced fault which proves the efficiency of the diagnostic system in detecting hydraulic faults.

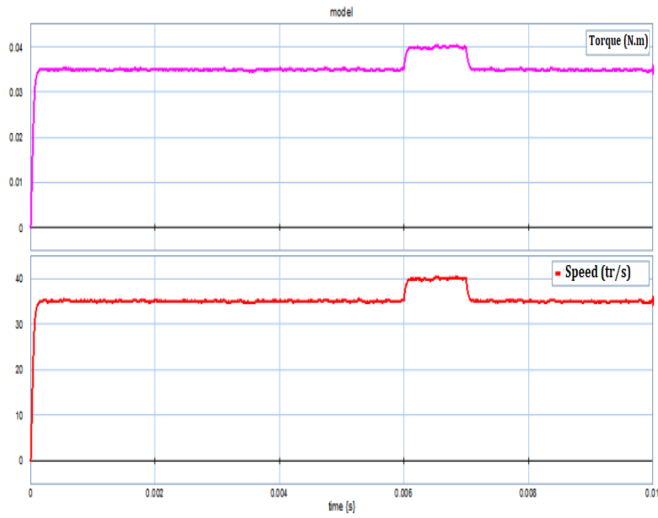

Fig. 16. Measurements at the motor side with a hydraulic fault: (a) torque, (b) Angular Speed

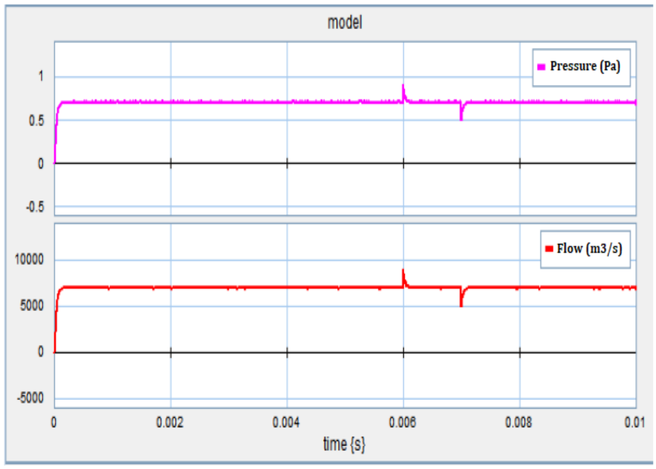

Fig. 17. Measurements at the Pump side with hydraulic fault: (a) Pressure, (b) Flow rate

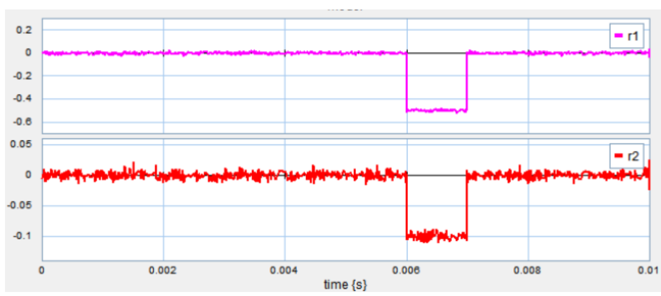

Fig. 18. Residues r1 and r2 with a sudden hydraulic fault

4. Conclusion

A graphical modeling approach (BG technique) was used to develop an adequate model of the studied system. Each part of the system was modeled separately and tested with 20-Sim software which is a dedicated tool for BG models simulation. Thanks to the developed BG model of the PEMFC pumping system, a diagnosis system was developed and tested by introducing different types of working anomalies: mechanical and hydraulic faults. The obtained results showed that the diagnosis system has proven its efficiency in detecting all introduced faults.

As a future scope of this work, a real time testing approach can be used in order to investigate the efficiency of the developed diagnosis system and compare the simulation results to real time measurements.

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