FAULT DETECTION IN POLYMER ELECTROLYTE MEMBRANE FUEL CELLS BY VARIABLE BEHAVIOR ANALYSIS

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Abstract. *In this work, the fault influence in polymer electrolyte membrane fuel cell variables is analyzed. A new method for fault detection through variable behavior analysis is introduced. Basically, a supervisor system is responsible for searching unexpected changes in some variables, since each fault cause is attributed to a pre-classified variable behavior. Fault detection considers faults in the reaction air fan, membrane-electrode assembly, hydrogen feed line, and refrigeration system based on the monitoring of electrical current, voltage, power, temperature, and output humidity. Tests show that the methodology as reliable, flexible (once it permits the addition of other modules) and easy to implement.*

Keywords: *fault detection; fuel cells; supervisor system; renewable and clean energy technology.*

1. INTRODUCTION

The demand for clean energy sources is increasing because environmental issues, such as greenhouse effects and pollutant gas emissions. Polymer electrolyte membrane fuel cells (PEMFC) are one of the best choice in the range of 0 – 200 kW and present several advantages, such as no pollutant gas emissions, quiet, reduced size and quick start-up. In PEMFC the electrical energy is obtained from the direct reaction between hydrogen and oxygen.

Despite these advantages, several researches are necessary to improve this technology, increasing its efficiency and reliability, and decreasing its manufacturing and operational costs.

In PEMFCs, hydrogen is supplied to the anode to reach a catalytic layer, where it is separated in protons and electrons. While electrons supply the electric circuit, protons pass through a polymer electrolyte membrane. In the cathode, protons, electrons, and oxygen react in a catalytic layer, producing water and residual heat (Larminie and Dicks, 2003).

Two improvements in PEMFC technology permit to increase its efficiency and reliability. The first one is the optimal control of the operational temperature, in which the stack operates at the highest possible temperature. The high the temperature, the lower the activation losses, so the optimal temperature control increases the efficiency of the fuel cell stack (Riascos and Pereira, 2009).

The second one is the fault tolerant fuel cell, in which a supervisor system is able to recognize when some fault is occurring in the stack and, if possible, act in order to recover the equipment from this condition. In this work, it will be presented a new methodology for fault detection. This methodology will be evaluated by simulation tests.

2. ANALYSIS OF VARIABLE BEHAVIOR

The main goal in the proposed methodology is search for unexpected changes in the variables. According to (D'Angelo, et al., 2010), a fault detector performs a signal analysis of the process. However, the knowledge of the mathematical model of the plant is essential, once it permits simulation test for understanding the interaction among the variables.

The selected variables should be directly influenced, in order to avoid false alarms; this analysis is performed when the process reaches the steady state. Basically, the analysis of variable behavior proposed can be described in three steps:

1. *Study of fault influence in each variable.* When the process reaches the steady-state, the influence of each fault in each variable should be defined. Commonly, faults generate abrupt changes in the variable or in their variation rate. In order to detect it, the value of the variable (or the variation rate) at instant t is compared with the value at instant $t - m$ (m is *a* positive number). In steady-state and normal conditions, the difference between these two values should be null. An abrupt variation will be defined as *fault-error*.
2. *Definition of a fault-error table for each variable associated to each fault.* The *fault-error* should be classified. These faults affect the variables in different intensities, and commonly a specific fault affects specific variables of the equipment. Then, each fault affects in a unique way the group of variables; the effects are different from one fault to another and that turns possible its identification.
3. *Intolerance patterns.* Each variable is separated in several ranges. The magnitud of these ranges depends on how the variables are affected by each fault. The n ranges will be defined as *intolerance pattern **n*** (P_n), once the values of the variables are off the tolerance range. The intolerance pattern 1 means that the variable is weakly influenced by the fault and the intolerance pattern n means that the variable is strongly influenced.

The intolerance patterns are included in the table proposed in step 2. In this table, the fault characteristic that affects the group of variables will be easier recognized.

When a system applies a feedback control, there is an alternative to the analysis of the controlled variable. When the system is in steady-state and the reference value is not influenced by the fault; then, the reference can be continuously compared with the real value of the variable. In case of faults, the variable can move away from the reference, so a difference between the value of the variable and its reference can be a fault signal.

3. CASE STUDY

The proposed methodology will be applied in a PEMFC stack composed by 4 cells of 64 cm^2 with polymer electrolyte membranes Nafion®, with optimal temperature controller, supplying a constant load demand of 10 W. Also, this stack is equipped with an extra-humidifier on the input air, which humidifies and warms the input air (Riascos and Pereira, 2009). To understand the variables and its dependence, the mathematical model of the PEMFCs is presented below.

3. 1. Mathematical model of PEMFC

The mathematical model is composed by the electrochemical model (which calculates the stack electrical current and voltage) and the thermodynamic model (which calculates the operational temperature and relative humidity).

Electrochemical model. The output voltage is calculated as follows:

$$V = nr(E_{Nernst} - V_{act} - V_{ohmic} - V_{con}) \tag{1}$$

where nr is the number of cells composing the stack, E_{Nernst} is the open-circuit voltage and V_{act} , V_{ohmic} , and V_{con} are voltage losses by activation of electrodes, resistance to protons and electrons flow, and concentration of mass, respectively.

The generated power is given by the following expression:

$$Power = V \cdot I_{FC} \tag{2}$$

where I_{FC} is the electrical current of the stack.

Thermodynamic model. The operational temperature is given by equation (3):

$$T(k) = T(k-1) + \frac{\Delta\dot{Q}}{M \cdot C_S} \tag{3}$$

where T is the operational temperature, k is the discrete instant of operation, $\Delta\dot{Q}$ is the difference between taxes of generated and removed heat, M is the total mass of the stack and C_S is the average specific heat coefficient of the stack. Heat is removed from the stack by three manners: by the reaction air (air from the environment is fed into the stack, to supplies the oxygen for reaction), by a refrigeration system, and by exchanges with the surround. The refrigeration system is controlled by a PI (proportional-integral) controller to make the operational temperature as high as possible; the higher the temperature, the lower the voltage losses (Riascos and Pereira, 2009). The limit temperature (ºC) is calculated according to equation (4); T_{limit} is the maximum operational temperature preserving minimum stoichometry of the reaction air and desired relative humidity (Riascos and Pereira, 2009):

$$T_{limit} = 96.25 + 23.55 \ln\left[\frac{1}{RH_{des}}\left(\frac{0.421 \cdot P_{air}}{\lambda_{min} + 0.188}\right) + P_{w_{in}} + 0.01751\right] \tag{4}$$

where RH_{des} is the desired relative humidity, P_{air} (bar) is the air pressure, Pw_{in} (bar) is the partial pressure of water in the input air and λ_{min} is the minimum air stoichometry, in this case $\lambda_{min} = 2$. The output relative humidity should be in the range of 80 – 100 % to avoid the membrane from drying (which increase the proton flux resistance) and to avoid the electrodes to be flooded (which blocks the flux of reactant gases) (Ge and Wang, 2007; Riascos, Simões and Miyagi, 2007).

Figure 1 shows the behavior of several variables (electrical current, voltage, power, temperature, and relative humidity) in normal conditions of operation.

More detailed of the fuel cell mathematical model can be found in (Larminie and Dicks, 2003), (Outeiro, Chibante, Carvalho and de Almeida, 2008) and (Riascos and Pereira, 2009). In (Riascos, Simões and Miyagi, 2007), the mathematical model includes factors to simulate the behavior of the stack when the fault occurrence.

3.2. Faults in PEMFC

In this work, four types of susceptible faults in PEMFCs are considered: faults in reaction air fan, faults in the hydrogen feed line, ruptures in the membrane-electrode assembly (MEA), and faults in refrigeration system.

Faults in the reaction air fan. The oxygen used in the chemical reaction is obtained from the air. Except in stacks with very low load demand (about a few miliwatts of power) (Büchi, 2003), a fan is used to feed the air into the stack. The power of this fan can be controlled in order to maintain the output relative humidity in the desired value; air stoichometry and relative humidity are related as described in equation (5) (Riascos, 2008):

$$\lambda = \frac{0.421 \cdot P_{air}}{RH_{des} \cdot Psat_{out} - Pw_{in}} - 0.188 \qquad (5)$$

where $Psat_{out}$ is the saturated vapor pressure of the output air.

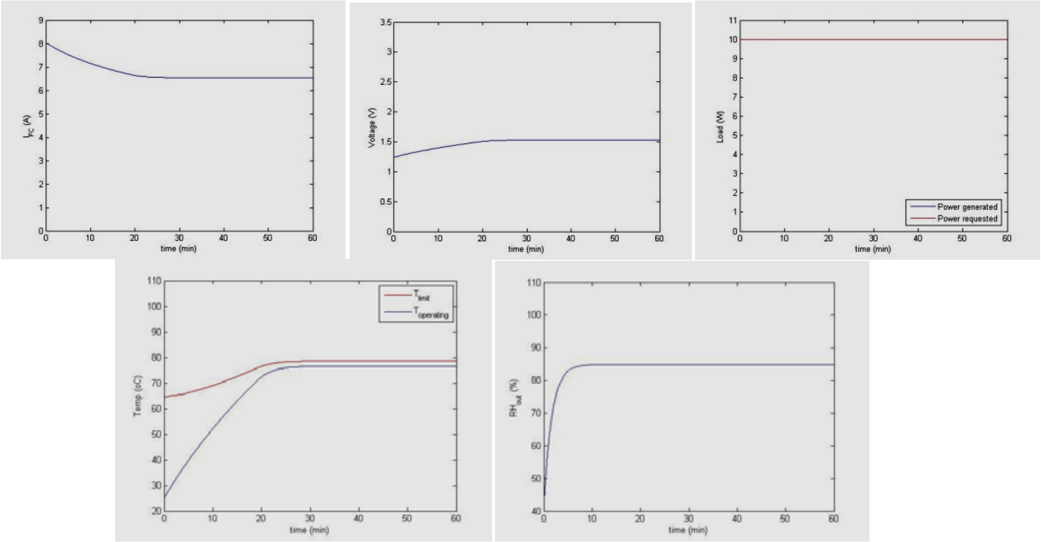

Figure 1. Behavior of variables in a PEMFC in normal conditions of operation

On the other hand, a warm reaction air has a drying effect on the polymer electrolyte membrane (Larminie and Dicks, 2003; Husar, Higier and Liu, 2008). Therefore, a fault in the reaction air fan can produce flooding of the electrodes, impeding the passage of reactant gases, this decreasing the open-circuit voltage and electrical current (because the reduction of the oxygen necessary for the chemical reaction). Also, other effects are measured such as increase of the input temperature, increase of the partial pressure of water, increases of the limit temperature, and increasing of the operational temperature. These combined effects reduce the load supply.

A reaction air fan decreasing below 40 % affects all the variables cited above. Over this limit, only the relative humidity is affected, but it does not overcome the secure limit. If the reaction air fan stops totally, the power generation stops instantaneously because of the absence of oxygen to the chemical reaction.

Figure 2 shows the behavior of the variables after a fault in the reaction air fan. At t = 40 min, the reaction air fan operates at 10 % of its total capacity.

Faults in the hydrogen feed line. The hydrogen is supplied into the stack from pressurized cylinders. The influences of this fault in the variable behavior are as follow: decrease of open-circuit voltage and rapid increase of the electrical current. However after a short period, the current decreases, decreasing the power generation.

The hydrogen pressure does not influence the conditions of neither the input air, nor the generated or removed heat, so it does not affect the operational temperature, limit temperature, and the output relative humidity.

Figure 3 illustrates the behavior of the PEMFC when the pressure of hydrogen decreases. The evolution of electrical current, voltage, power, temperature, relative humidity, and H_2 pressure are shown. At t = 40 min, the pressure of the hydrogen decreases to 10 % of the initial value.

Rupture in the membrane-electrode assembly. The membrane-electrode assembly (MEA) of PEMFCs is composed by a polymeric membrane with hydrophilic and hydrophobic regions (Larminie and Dicks, 2003). These two regions, in presence of enough water, conduct the protons from the anode to the cathode by attractive and repulsive forces. Two porous carbon-composed electrodes are added on each side of this membrane by a process similar to a printing process.

The polymeric membrane is susceptible to chemical and physical degradation due to continuous use, operation at high temperature, pressure, and low humidity (Borup, et al., 2007). The degradation process increases the phenomenon known as *fuel crossover*, in which part of the fuel (hydrogen) passes through the membrane without reacting, not producing electrical current, and increasing concentration losses (Larminie and Dicks, 2003). A little loss of electrical current can be considered as normal, but in some adverse conditions, the membrane (and, sometimes, the electrodes) may suddenly break down, and the effects on the variables are the follows: decrease of the electrical current, voltage (and consequently decrease of power generation), increase of operational temperature by insufficiency of the refrigeration system.

Figure 4 shows the behavior of the PEMFC's variables when the MEA break down at t = 40 min. and the J_n increases to 0.25 A/cm². The variables illustrated are: electrical current, voltage, power, temperature, relative humidity and J_n.

Faults in the refrigeration system. In the stack considered in this research, the refrigeration system is composed by a cooler which blows air from the surrounding through the stack, removing part of the residual heat.

The refrigeration system is responsible for controlling the operational temperature. Therefore, the immediate effect of a refrigeration system fault is the increase of the operational temperature, overcoming the limit temperature. Also, the output relative humidity is reduced, drying the electrolyte.

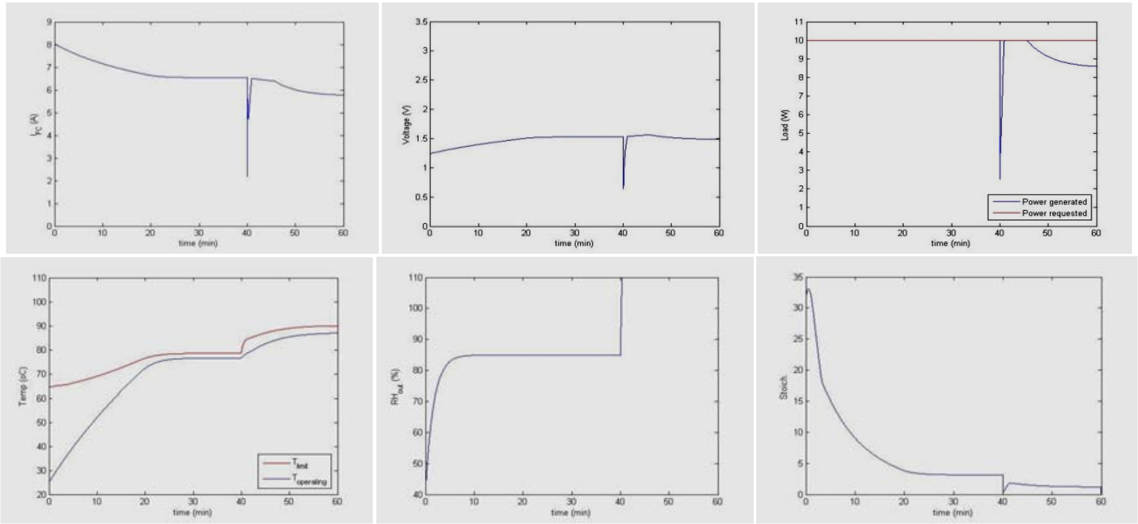

Figure 2 – Behavior of variables in case of fault in the reaction air fan

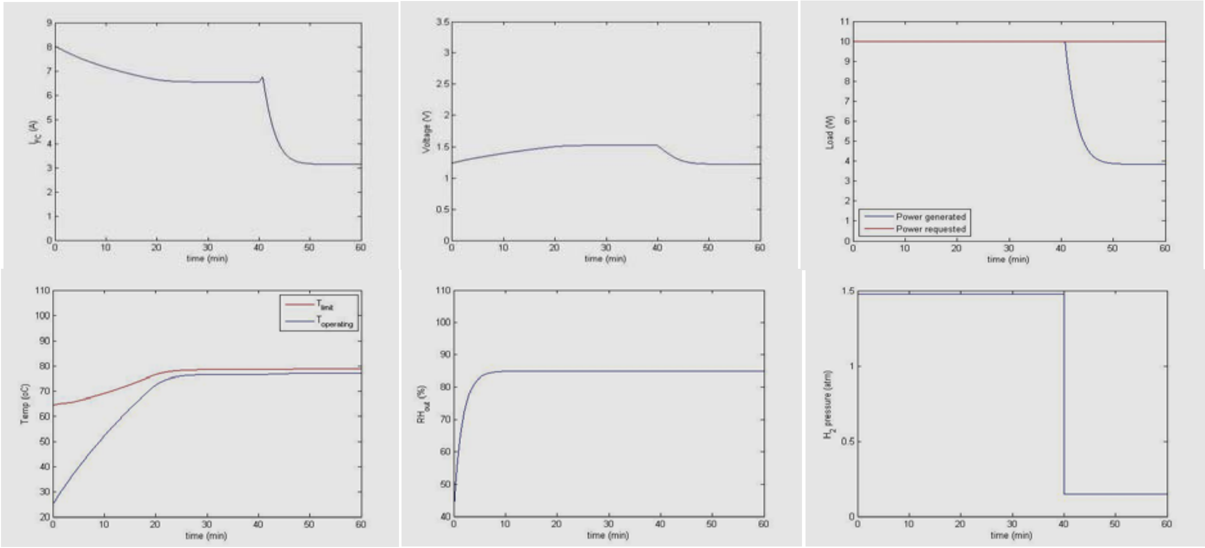

Figure 3 – Behavior of variables in case of fault in hydrogen feed line

The water reduction in the membrane increases the proton flow resistance, and decreases the electrical current. The high temperature reduces the voltage losses, so the generated power is maintained for a while.

Only efficiency reduction of the refrigeration system over 50 % affects the PEMFC's variables. Also, the decrease of efficiency produces a quick increase of operational temperature. The effects are worst when the refrigeration system stops completely.

Figure 5 shows the evolution of electrical current, voltage, power, temperature, relative humidity, and removed heat, when the refrigeration system fails totally at t = 40 min. As it can be noticed, relative humidity and power changes only several minutes later (at t = 47 min and t = 52 min, respectively).

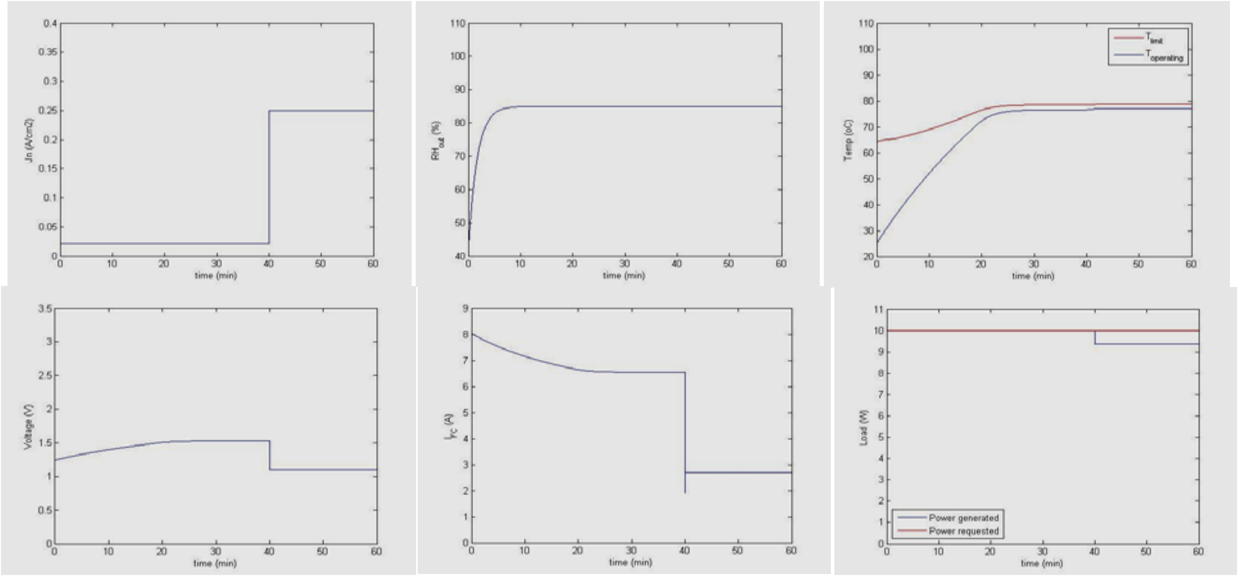

Figure 4 – Behavior of variables in case of sudden ruptures in MEA

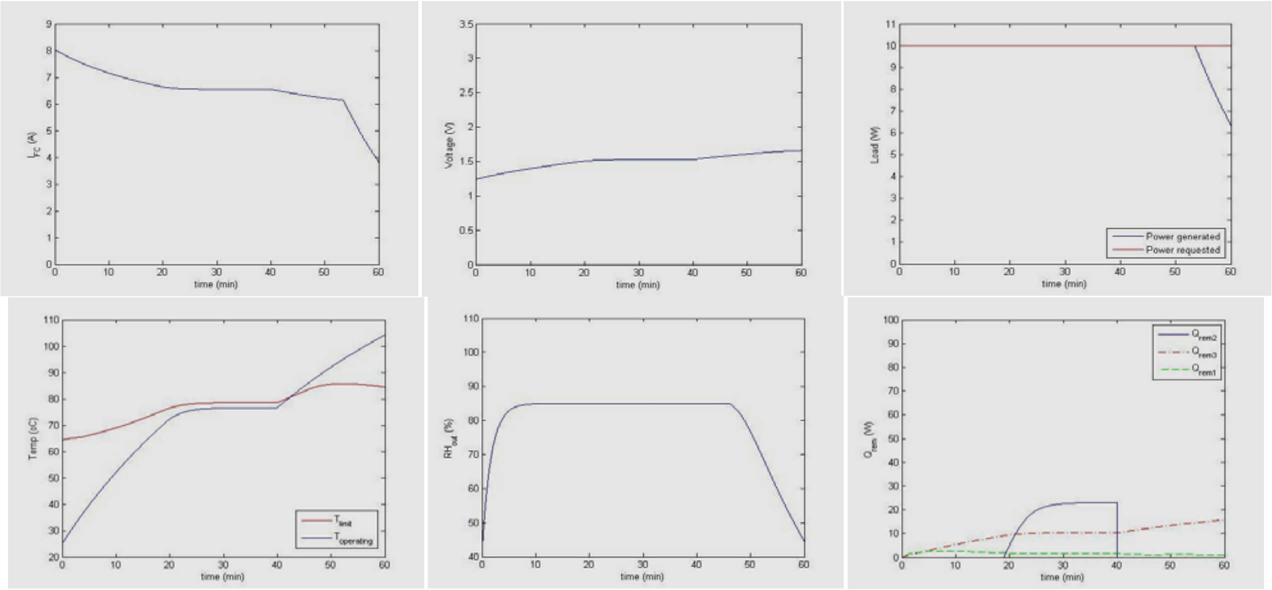

Figure 5 – Behavior of variables in case of fault in the refrigeration system

3.3. Analysis of variable behavior in PEMFC

The monitored variables are electrical current, voltage, power, temperature, and output relative humidity. The analysis method of each variable is described below.

Electrical current. A supervisor system compares, constantly, the value of the electrical current at instant *t* against the value of current of 20 seconds earlier searching for increases in the current. 20 seconds reduce false alarms by random picks. In faults in which the current decreases, a voltage reduction is followed by a current increase, permitting the supervisor system to detect this change.

Voltage analysis. The analysis of voltage is similar to the analysis of electrical current. However, in this case, the supervisor system searches for a *decrease* in voltage. However the mathematical model permits the monitoring of each component such as activation, ohmic, or mass concentration. Then, the voltage drop depends on the type of fault.

Power analysis. Changes in power generation are related with changes in electrical current and voltage, but in some cases the change is not instantaneous, while changes in current and voltage are always instantaneous. This characteristic permits the identification of several types of fault. Power is analyzed as a controlled variable, because there is a reference for comparing (the requested load). If the power generated is lower than the requested load, then an fault occurrence can be considered.

Temperature analysis. The operational temperature is compared against the limit temperature. If the operational temperature is higher than 78 ºC, and if the difference is higher than 1.6; then a fault is considered. This change will be declared as F_T1 (temperature fault type 1).

Also, the operational temperature at instant t is compared with its value, 4 seconds earlier. And the limit temperature is compared with its value, 10 seconds earlier. Changes of 0.6 ºC in operational temperature and 0.025 ºC in limit temperature are tolerated; over these limits, it will be declared as F_T2 (temperature fault type 2).

A more detailed work about analysis of temperature behavior can be found in (Riascos and Pereira, 2010).

Output relative humidity analysis. Faults in reaction air fan increase the relative humidity. Then, the supervisor system compares the relative humidity with its value 20 seconds earlier, and defines this change as relative humidity fault type 1 ($F_{RH}1$). A decrease of relative humidity is defined as relative humidity fault type 2 ($F_{RH}2$).

3.4. Fault classifications

In this section, the methodology of fault classification by intolerance patterns is applied for fault detection in PEMFC. Table 1 shows the range of errors in each variable due to several fault types. Faults in reaction air fan (F_{reac}) consider variations between 10 and 40 %; faults in hydrogen feed line ($F_{PH}2$) consider variations between 10 and 90 %; faults in refrigeration system consider variations up to 50 %; over those limits, the effects on the variables are not observed. For sudden ruptures in the membrane-electrode assembly, the density of internal current perform variations between 0.05 A/cm^2 and 0.35 A/cm². In normal operating conditions, the lost current by fuel crossover is lower than 0.025 A/cm².

In the Table 1, $err_{current}$ is the fault-error in electrical current, $err_{voltage}$ is the fault-error in voltage, and err_{power} is the fault-error in power. The abbreviation N.O. means *non-observed,* i.e. the fault does not affect that variable.

Table 1 – Errors by faults

	$err_{current}$	$err_{voltage}$	err_{power}
F_{reac}	$0.008 \leq e \leq 0.39$	$0.07 \leq e \leq 0.88$	$1.4 \leq e \leq 7.5$
$F_{PH}2$	$0.010 \leq e \leq 0.097$	$0.002 \leq e \leq 0.022$	$e \leq 1$
F_{MEA}	$9.3 \cdot 10^{-5} \leq e \leq 6.4 \cdot 10^{-4}$	$0.065 \leq e \leq 0.61$	$3.5 \leq e \leq 7.5$
F_{ref}	$0.006 \leq e \leq 0.013$	$0.0014 \leq e \leq 0.0030$	N.O.

In Table 2, the errors presented in Table 1 are separated in four intolerance pattern.

Table 2 – Intolerance pattern

	$err_{current}$	$err_{voltage}$	err_{power}
P_1	$e \leq 10^{-3}$	$e \leq 10^{-3}$	$e \leq 1$
P_2	$10^{-3} < e \leq 10^{-2}$	$10^{-3} < e \leq 10^{-2}$	$1 < e \leq 3$
P_3	$10^{-2} < e \leq 10^{-1}$	$10^{-2} < e \leq 10^{-1}$	$3 < e \leq 6.9$
P_4	$e > 10^{-1}$	$e > 10^{-1}$	$e > 7$

Finally, in Table 3 the considered faults are described by a unique combination of intolerance patterns and changes in temperature and output relative humidity.

Table 3 – Combination of intolerance pattern and thermo-dynamical variables.

Fault	$err_{current}$	$err_{voltage}$	err_{power}	Temperature	RH_{out}
F_{reac}	P_2, P_3, P_4	P_3, P_4	P_2, P_3, P_4	F_T2	$F_{RH}1$
$F_{PH}2$	P_3	P_2, P_3	P_1	N.O.	N.O.
F_{MEA}	P_1	P_3, P_4	P_3, P_4	F_T1*	N.O.
F_{ref}	P_2, P_3	P_2	N.O.	F_T1	N.O.

**Changes in temperature are detected in the worst cases of ruptures of the MEA*

4. FAULT DETECTION BY VARIABLE BEHAVIOR ANALYSIS FOR PEMFC

The supervisor system for fault detection in PEMFC operates as follow:

- An *intolerance index* is created for each variable. This index assumes a different value for each pattern of intolerance.
- A *fault index* is created for each fault. The fault index is defined as the sum of the intolerance index of the variables affected by the fault.

- Combining Table 3 and the intolerance index, it is possible to calculate the minimum and maximum value that each fault index can assume.

  Table 4 shows the intolerance indexes as adopted for fault detection.

Table 4 – Intolerance indexes

	iC	iV	iP
P_1	1	10	100
P_2	2	20	200
P_3	3	30	300
P_4	4	40	400

The fault indexes are defined as follow:

- For faults in reaction air fan: $iFanReac = iC + iV + iP$
- For faults in hydrogen feed line: $iPH2 = iC + iV + iP$
- For ruptures in membrane-electrode assembly: $iJ_n = iC + iV + iP$
- For faults in refrigeration system: $iRef = iC + iV$

During the PEMFC operation, the supervisor system calculates the errors in each variable and, depending on this error, a value of Table 4 is attributed (if the error is null, the intolerance index will be also null). The fault indexes are continuously calculated as defined above, also considering changes in temperature and relative humidity.

Table 5 shows the conditions in which the supervisor system declares a fault as detected.

Table 5 – Ranges and conditions for fault detection.

	Range of fault index		**Conditions**	
Fault Index	Min	Max	Temperature	Relative humidity
iFanReac	222	444	F_T2	$F_{RH}1$
iPH2	123	133	No fault	N.O.
iJ_n	334	444	F_T1, if iP > 200	N.O.
iRef	11	23	F_T1	N.O.

It is important to observe that changes in variable are not detected at the same time; the variables do not behave equally, so changes are observed at different instants. Therefore the fault detection needs a delay; the supervisor system waits 6 seconds before to declare a fault as detected. This delay is imposed for waiting the influence of any other intolerance index.

Figure 6 illustrates intolerance index, fault index, *iFanReac*, changes in Temperature (faultTemperature, 1 for F_T1 and 2 for F_T2) and changes in relative humidity ($F_{RH}1$) as signals generated by the supervisor system during the PEMFC operation. Those figures are related with fault in the reaction air fan (see also Figure 2). The fault was detected by the supervisor system only 17.8 seconds after the occurrence of the fault (time to attend all the conditions of Table 5 and the 6 second delay). Although values of *iFanReac*, iPH_2 and iJ_n are considered, only *iFanReac* satisfies the conditions presented in Table 5; then, only this fault was detected.

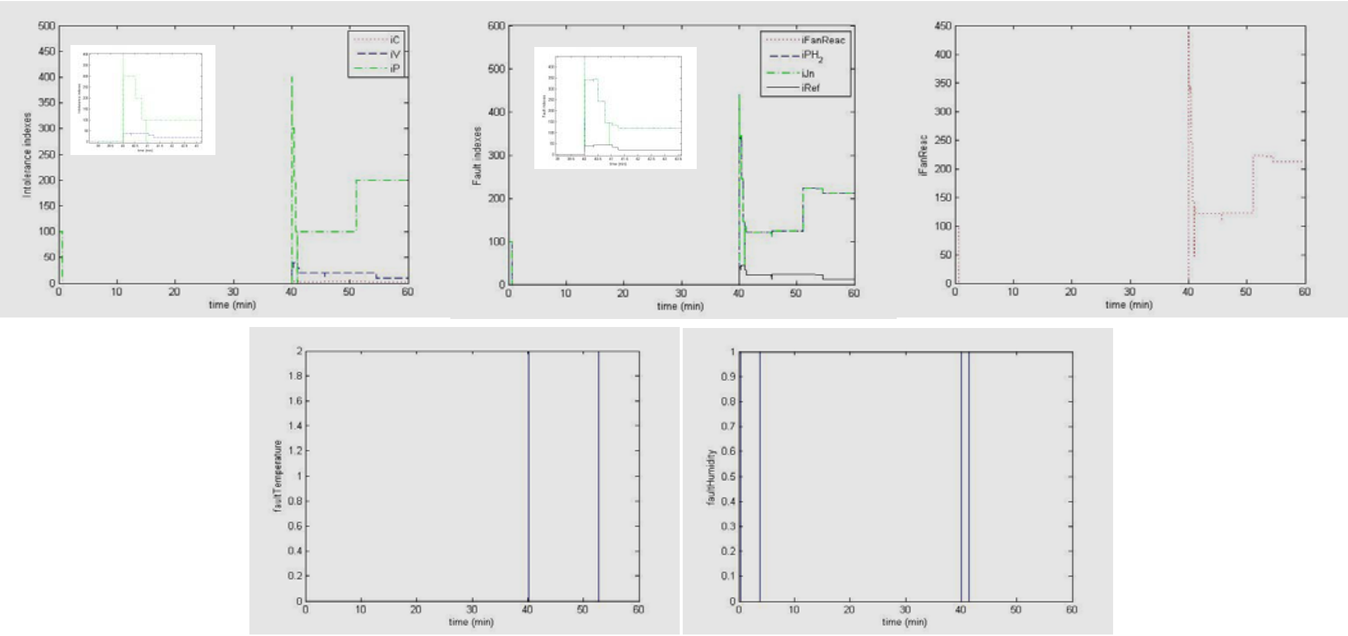

Figure 6 – Indexes in fault in reaction air fan

Figure 7 shows intolerance index, fault index, iPH_2, fault-Temperature and fault-Humidity for the fault in hydrogen feed line (see also figure 3), the hydrogen pressure is dropped to 10 % of the initial value (approximately 0.14 atm). The time to declare the fault as detected, including the 6 second delay, was 8.2 seconds. Again, values of fault indexes are considered but only the fault in hydrogen feed line is detected.

In Figure 8, intolerance index, fault index, iJ_n, fault-Temperature and fault-Humidity are shown for sudden ruptures in membrane-electrode assembly (see also Figure 4). The value of J_n increased suddenly from 0.022 A/cm² to 0.25 A/cm² at t= 40 min. The supervisor system spent 56 seconds to detect this fault (including the 6 second delay). Fault indexes are considered but only iJ_n satisfies the conditions of Table 5.

Figure 9 illustrates the signals generated by the supervisor system (intolerance index, fault index, *iRef*, fault-Temperature and fault-Humidity) for faults in the refrigeration system (see also Figure 5). Including the 6 second delay, the supervisor system spent 32.8 seconds to detect this fault. Two particularities should be noticed. First, fault in the refrigeration system is detected only if changes in temperature are declared as fault type 1. Second, changes in relative humidity are disregarded; actually, relative humidity fault type 2 is detected, but at t = 49 min (9 minutes later the occurrence of fault).

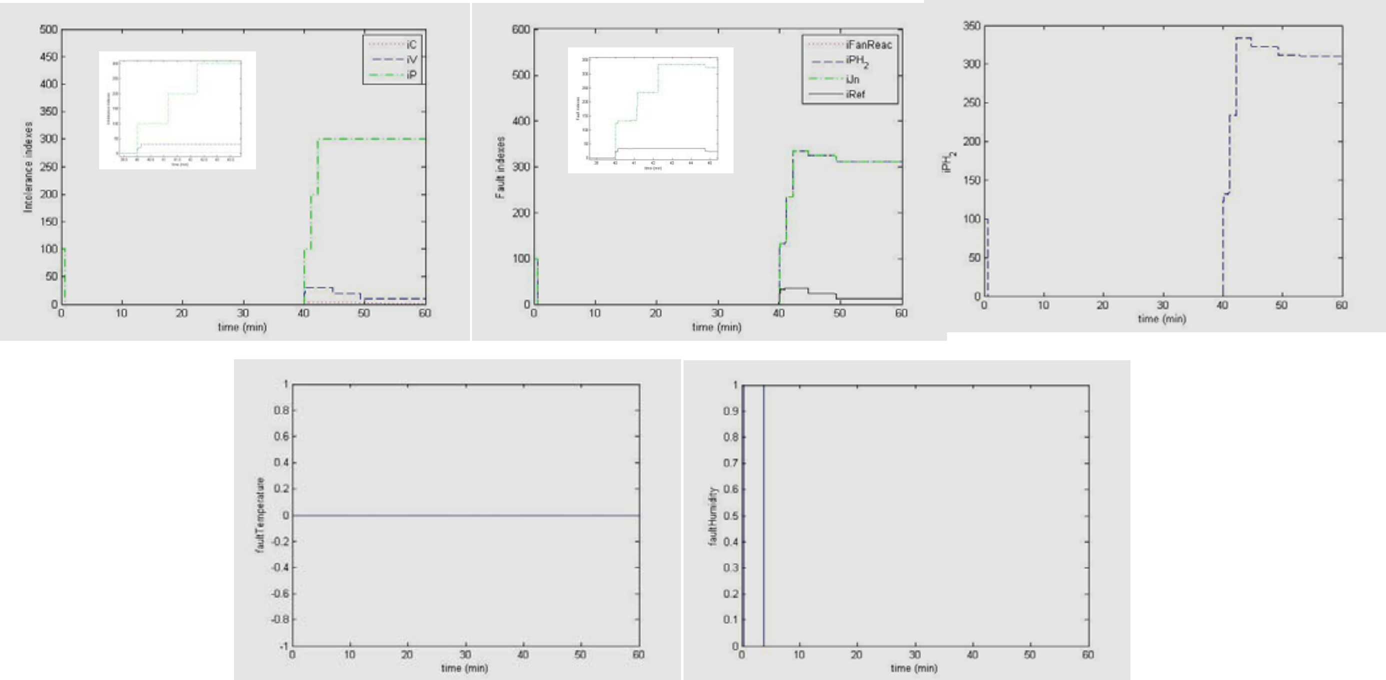

Figure 7 – Indexes in fault in hydrogen feed line

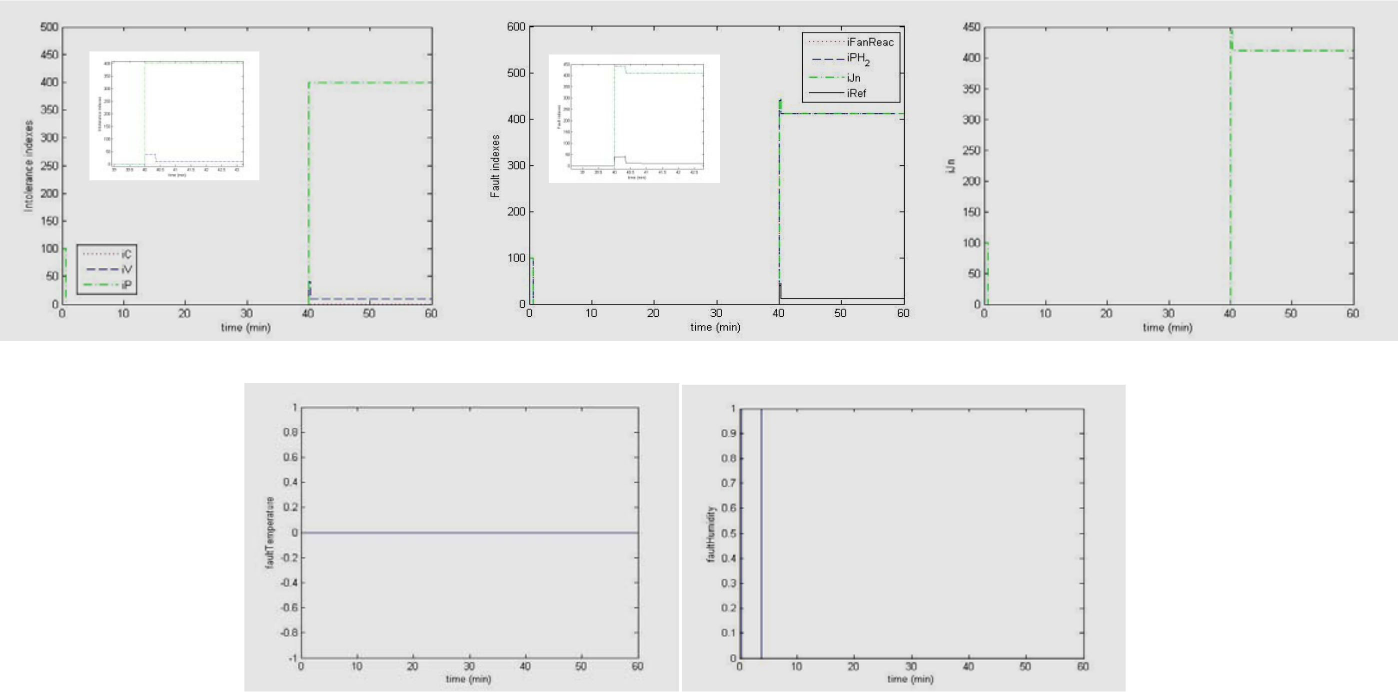

Figure 8 – Indexes in ruptures in MEA

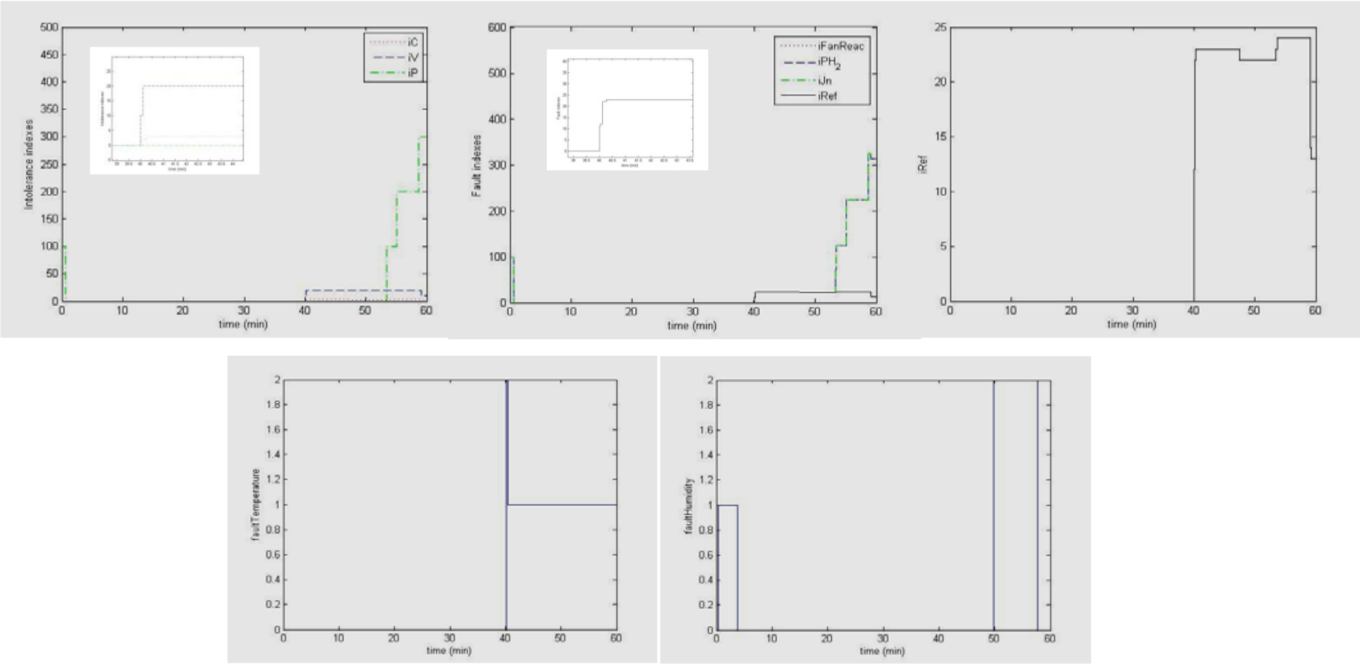

Figure 9 – Indexes in faults in the refrigeration system

5. CONCLUSIONS

Polymer electrolyte membrane fuel cells are a good choice among clean and renewable energy technologies, by their high efficiency and no pollutant emissions. However, more researches are needed in order to improve this technology and become possible the substitution of the traditional energy technologies, such as internal combustion engines.

The design of a supervisor system for fault detection (analysis of variable behavior) was introduced. The proposed methodology searches for abrupt changes in the variable behavior when the process is in steady-state. Several faults are detected based on a group of influenced variables. The tests have shown agreement between the fault detection results and the original fault cause.

The diagnostic process was based on the variable effects that can be easily monitored by sensors such as voltmeters, ammeters, thermocouples, etc. This permits and easy implementation of fault detection processes in PEMFC systems.

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