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***Abstract*—Proton exchange membrane fuel cell is a well-known technology that has shown high efficiency and performance as a power system compared to conventional sources such as internal combustion engines. Especially, open cathode proton exchange membrane is growing more popular thanks to its simple structure, low cost and low parasitic losses. However, the open cathode fuel cell performance is highly related to the operating temperature variation and the airflow rate which is adjusted through the fan voltage. In this regard, the present study investigates the thermal management of an open cathode proton exchange membrane fuel cell. The objectives are the stack performance improvement and the stack degradation prevention. Indeed, a safety and optimal operating zone governed by the load current, the stack temperature and the air stoichiometry, is designed. This optimal operating zone is defined based on the system thermal balance and the operating constraints. Hence, the proposed control strategy deals concurrently with the stack temperature regulation and the air stoichiometry adjustment to guarantee the goals achievement. The performance of the proposed control strategy is verified through experimental studies with different operating conditions and results prove its efficiency. To properly design an appropriate control strategy, a multiphysic fuel cell model is developed based on acausal approach by mean of Matlab/Simscape and experimentally validated.**

***Keywords*—Open cathod proton echange membrane fuel cell; control strategy; Fuel cell dynamique behaviour; airflow control; Stack temperature control; multiphysic model;**

I. INTRODUCTION

PEM fuel cell system occupies over the last decades a central position as a clean energy conversion in a variety application such as automotive applications and renewable energy system [1][2][3][4] by generating electricity with water and heat production via chemical energy [5]. Nevertheless, water content in membrane and the stack operating temperature are considered as a vital factor which affect fuel cell performance and durability [6][7]. Therefore, water and thermal management are the two main issues to success the *PEM* fuel cell design and to improve its efficiency [8].

The *PEM* fuel cell system is a set of three subsystems, known as the balance of plant *(BOP)*, consisting of the anode loop, the cathode loop and the cooling loop [9]. Generally, cooling subsystem consumes primary energy produced by the fuel cell and occupies space which leads to the stack efficiency decrease. Indeed, the cooling process energy consumption reaches around 4.6 % of the *PEM* fuel cell primary energy [10].

The open cathode *PEM* fuel cell mainly characterized by its cathode channels exposed to the ambient air. It is considered as an interesting system because of its simple structure, low cost and low parasitic losses [11]. In such

structure fans act to ensure the stack temperature regulation by forced convection and the reactant feeding (gas stoichiometry) [12] [13]. Because there is an only actuator for functions already mentioned, a fine and adapted control strategy is required to ensure the best balance and the best efficiency of the stack system, for a large range of operating conditions, such as ambient temperature, relative humidity, load current and aging process.

Several research studies focus on the thermal management of closed or an open cathode fuel cell system based on only one criterion. For example, in [14] the ancillary is controlled to carry out an optimal fuel cell temperature that maximizes the output voltage. This temperature setting is modified with the stack current. A PID control is used to control the cooling fan. The disadvantage of this method is that the fan control follows the dynamic of the temperature (few minutes), while the air stoichiometric ratio has to be set at a much smaller time scale (few seconds).In [15] the strong coupling between the optimal temperature control strategies, the stability and the efficiency of an open cathode *PEM* fuel cell system is demonstrated. From a multi-physic and dynamical model, a control structure is proposed to ensure the best efficiency and a sufficient stability. In this work, and unlike previous work [14], anticipation is added to quickly reach the equilibrium point, regardless of the thermal time constant. In [16] the *PEM* fuel cell was adopted as a power source for robots. To improve the operating conditions a fuzzy incremental *PID* control was developed to control the temperature inside cells. The study's results show that the output power improvement is realized by the fitting operating temperature at an optimal value.

Yet, not many research works focuses on thermal management of on open cathode fuel cell system based on more than one criterion. In [17] an electrochemical and thermal model of an open cathode PEM fuel cell was developed combining PI controller and the Extremum seeking controller in order to control the stack temperature, and by considering the air stoichiometric ratio as a secondary parameter. However, this method seems efficient in steady state, especially around a single operating point. In [18] a no dimensional flooding number is defined which is able to predict the best stoichiometric ratio for different operating points . But, the optimal operating conditions obtained can be outside the limits of thermal operation. Therefore, it is necessary in this case to degrade these optimal solutions to take the thermal stresses into account. In [19] a multi-input multi-output fuzzy logic controller was performed in order to regulate stack temperature and humidity simultaneously. The temperature regulation was based on the fan speed control considering that the regulation with a criterion based on these two parameters permit to increase the stack performance. In [20] an appropriate control strategy through oxygen mass flow rate regulation is achieved to avoid overheating and to concurrently prevent air shortage of the open cathode fuel cell system. The airflow control is performed by selecting an optimal oxygen excess ratio for both the power net improvement and the overheating protection. Experimental results show that this control strategy improves the lifetime of the fuel cell system compared to other classical operating schemes.

The present work takes into consideration concurrently two requirements to enhance the fuel cell performance which are the temperature regulation and the air stoichiometric adjustment. Moreover, the axial fans are the only actuator for the stack cooling by forced convection and the cathode air feeding. Thus, with such simple structure, it is more difficult to carry out the control of these issues simultaneously. In this study, the axial fan voltage is regulated to specify the stoichiometric ratio, which allows defining an optimal operating zone governed by three main parameters, which are the stack temperature, the fan voltage and the load current. Two sets of operating constraints applied on both stack temperature and fan operating voltage. By combining the thermal balance equation and the operating constraints, the fuel cell optimal operating zone is defined guaranteeing the stack performance improvement and the stack degradation prevention. In order to design a pertinent control strategy, a multi-physic fuel cell model is developed using

MATLAB/Simscape, to reproduce the stack dynamic behaviour at different operating conditions. An experimental study is carried out by a 2kW open cathode fuel cell system to valid the developed model and to evaluate the control strategy performance. This model will be very interesting to explore the proposed control strategy of the open cathode *PEM* fuel cell system. Thus, the challenge in this study is to guarantee the stack performance improvement and the stack degradation prevention while combining simultaneously both temperature regulation and air stoichiometric adjustment via fan voltage input. Hence, an optimal operating zone is defined in order to ensure the objectives achievement with respect to the thermal behavior of the open cathode *PEM* fuel cell and the environmental conditions variations (Ambient temperature).

This study is organized as follows: the first section details the fuel cell models. The second section presents the experimental validation of the proposed model and its parameter estimations. The third part is dedicated for the proposed control strategy and its evaluation. The last part contains the conclusion.

II. FUEL CELL MODEL

In this section, a multi-physic fuel cell model is developed by taking into account different physical phenomena taking place within the stack. It offers the possibilities to design and test control strategies. In fact, an accurate and precise model is needed to emulate the *PEM* fuel cell dynamic behavior. So, two kinds of model are needed which are electrical and thermal ones.

A. Electrical fuel cell model

In literature, there are several equivalent circuit models of *PEM* fuel cell that describe its dynamic behavior. The adopted electrical model of the *PEM* fuel cell is presented in *Fig.1*.

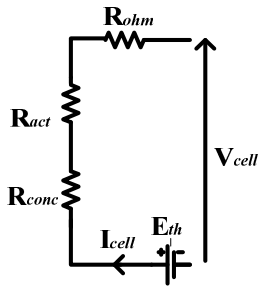

Fig.1. Static electrical PEM fuel cell model

The adopted *PEM* fuel cell model is a static model using electrical circuits. It is composed of continuous voltage source E_{Nernst} associated with three resistors modeling the *PEM* fuel cell losses: activation losses, concentration losses and ohmic losses [25].

According to Nernst's equation (1), the cell potential depends on the temperature and reactants flow pressures (air and hydrogen). Decreasing the pressures of the reactants and / or increasing the temperature leads to the increase of the *PEM* fuel cell voltage output.

$$E_{Nernst} = E_0 + \frac{RT_{amb}}{2F}\left(\ln(P_{H2}) + \frac{1}{2}\ln(P_{O2})\right) \qquad (1)$$

Where E_{Nernst} is the thermodynamic potential, E_0 reversible single cell potential, R is the molar gas constant, T_{amb} is ambient temperature, F is faraday constant, P_{O2} and P_{H2} are reactants pressure.

At standard conditions (P=1bar, T=25°C), the E_{Nernst} calculated value is based on either the high heating value *HHV* assuming the product water inside a fuel cell in the liquid phase, is approximately 1.48V. Or, it is based on the low heating value *LHV*, supposing the product water is in the gaseous phase, is about 1.25V [26]. Therefore, several cells are connected in series to be adapted for applications with high power. The *PEM* fuel cell output voltage V_{st} is given by the following equations:

$$V_{st} = NV_{cell} \quad (3)$$

Where N is the number of cells connected in series, V_{cell} is the output voltage of an elementary cell.

$$V_{cell} = E_{Nernst} - V_{act} - V_{ohm} - V_{conc}) \quad (3)$$

Where V_{act}, V_{ohm} and V_{conc} are the voltage drop corresponding to activation loss, ohmic loss and concentration loss taking place inside the stack.

$$V_{act} = -\frac{RT}{2\alpha F}\ln(\frac{I_{\mathrm{st}}}{S_{cell}\, J_0}) \quad (4)$$

Where J_0 is the exchange current density, S_{cell} the active area, I_{st} is the stack current and α is the transfer coefficient.

$$V_{conc} = -\frac{RT}{2F}\ln(1 - \frac{I_{\mathrm{st}}}{I_{max}}) \quad (5)$$

Where I_{max} is the limit current.

$$V_{ohm} = R_{ohm} I_{\mathrm{st}} \quad (6)$$

$$R_{ohm} = R_{mem} + R_c \quad (7)$$

Where R_{ohm} is the ohmic resistance which presents the membrane resistance R_{mem} and the contact resistance between different *PEM* fuel cell layers R_c.

B. Thermal fuel cell model

1) Heat generation

Basically, there are four sources of heat generation within *PEM* fuel cell system, which are the entropy change of reactions, the irreversible loss of electrochemical reactions, and heat resulting from both the ohmic resistance and the water vapor condensation [27][28]. Knowing that the heat produced by entropy change, irreversible loss and ohmic resistance is comparable to the fuel cell power output, they present around 55%, 35% and 10% of the total produced heat, respectively [29]. Indeed, heat generation gives rise to temperature variation within the fuel cell. Therefore, heat evacuation is considered as a key part to ensure an optimal performance of the fuel cell.

Thus, the cooling phenomenon is necessary in order to insure a powerful and efficient fuel cell operation and to improve the lifetime of the different components. There are three types of cooling methods which are air cooling, liquid cooling and cooling through phase change [30]. Yet, the air cooling method is the most used widely in applications with a nominal power less than 5KW insuring the same time a minimum *BOP*, while liquid cooling is used to evacuate waste heat on high power *PEM* fuel cell greater than 5KW [31] and finally phase change cooling is employed for the enthalpy of vaporization to evacuate waste heat from the fuel cell [30]. It should be noticed that the cooling through phase change is benefits compared to conventional liquid cooling [32].

Generally, produced heat within the fuel cell is evacuated by two transfer modes. The first one is the natural and forced convection. In fact, the stack is exposed to the ambient air for this reason it can be cooled by natural convection.

Furthermore, in cathode side, the heat removal from the stack is achieved due to fans which explain forced convection within the stack. The second mode is the conduction which ensures the heat transfer between different layers of fuel cell. However, heat transfer by forced convection within fuel cell is the most efficient mode [33] because the great part of generated heat is removed by this transfer mode [21].

The generated heat or the dissipated losses in the stack is given by the equation (8)

$$P_e = (N\ E_{Nernst} - V_{st})I_{\mathrm{st}} \qquad (8)$$

This equation (8) proves that the generated heat and the fuel cell current vary proportionally. Since, the heat generation increase is caused by the increase of the stack current, it results also a decrease in the fuel cell voltage. This explains why the heat generation is more significant at high current demand. Namely, that the high current densities cause a low system efficiency [34]. Therefore, produced heat should be eliminated from the *PEM* fuel cell system.

2) Temperature variation

Fuel cell operating temperature is considered as a critical parameter since its variation influences the performance and the efficiency of *PEM* fuel cell [24][35].On one hand, temperature increase boosts the reaction kinetics and increases the fuel cell gas diffusivity hence generating a gradual improvement of fuel cell performance at the start up step [23] [36]. On the other hand, temperature increase beyond a value fixed by the manufacturer causes the fuel cell performance decrease, since it causes a decrease on membrane conductivity and an increase of membrane resistance. Also, it engenders a decrease in both relative humidity and water content which results on membrane dehydration [36] as well as a decrease in the output power of fuel cell system [30]. Therefore, the temperature within the fuel cell needs to be controlled and the amount of heat produced within the fuel cell must be absolutely eliminated in order to avoid overheating of the different fuel cell layers which are considered as the critical fuel cell components since their degradation causes performance loss [37].

Thus, a temperature control strategy is essential to limit the performance degradation and improve the *PEM* fuel cell lifetime. Therefore a fuel thermal model is needed to supervise the temperature variation within the stack.

Firstly, the used fuel cell for this study is an open cathode *PEM* fuel cell. Thus the thermal management and the air supply are ensured by a single actuator piloted by dual axial fans. Consequently, the breakdown of the temperature control and reactant supply is not evident, therefore, it is necessary to found good compromises between these two concepts. For this reason, the air supply equation and the thermal equation which takes into account the different losses sources and heat evacuation modes are considered, in order to design the open cathode *PEM* fuel cell thermal behavior.

Equation (9) presents the airflow Q_{air} demanded (given en L min^{-1}) by the electrochemical reaction tacking place inside the stack to generate load current.

$$\mathrm{Q_{air}} = 60000\ \frac{5\ \mathrm{N\ R}}{4\ \mathrm{P_a\ F}}\mathrm{T_{st}I_{st}S_c} \qquad (9)$$

Where T_{st} is the stack temperature and S_c is the air stoichiometric coefficient, it can be know from equation (9) that the airflow variation depends on the stack temperature, the stack current and the air stoichiometric coefficient. Consequently, there is a strong coupling between these parameters.

Knowing that, the airflow affects the stack temperature, indeed, it is critical parameters which have an influence on the fuel cell performance. On one hand, if the supplied airflow is lower than the demanded airflow for cooling purpose the stack temperature increases. In this case, the airflow lack can cause electrolyte membrane degradation. On the other hand, an excess airflow reduces the average stack temperature, which leads to a chemical reaction rate decrease. In addition, this excess airflow creates an overall humidify decrease and the membrane dehydratation, thereafter a proton

conductivity decrease. Thus, it is evident that the airflow control is an important process to ensure the optimal performance of an open cathode *PEM* fuel cell [38].

Assuming that the generated heat within fuel cell is removed by three mechanisms. The first one is the natural convection P_{nat} which is explained by the fact that the fuel cell system is exposed to ambient air, so, heat will be removed from the fuel cell surface to the external environment. The removal heat by natural convection can be expressed as [39]:

$$P_{nat} = h\, S_{eq}(T_{st} - T_{amb}) \tag{10}$$

Where h is the natural convection coefficient, S_{eq} is the equivalent exchange surface.

The second one is the forced convection in the cathode side ensured by the axial fans P_{fan} which is defined as following [39].

$$P_{fan} = \frac{1}{60}\rho_{air} Q_{air} C_{pair}(T_{st} - T_{amb}) \tag{11}$$

Where ρ_{air} is the air density, C_{pair} is the air specific heat.

The third mechanism is heat dissipation by phase change liquid/gaseous of water produced inside the *PEM* fuel cell which is expressed by the following equation [39].

$$P_{l/g} = \sigma_{H2O}\frac{N\,R}{4\,P_a\,F} T_{st} L_{H20} I_{st} k_w \tag{12}$$

Where σ_{H2O} is the water volume density, L_{H20} is the latent heat of evaporation of water, k_w is an empirical coefficient representing the water rate produced in liquid forms and then evaporated.

Based on energy conservation, the open cathode *PEM* fuel cell thermal equation which describes the heat dissipation mode is given as following:

$$\frac{dT_{st}}{dt} = \frac{1}{m\,C_{fc}}\left[\Delta P - P_{nat} - P_{fan} - P_{l/g}\right] \tag{13}$$

Where m is the fuel cell mass, C_{fc} is the fuel cell specific heat.

On the right hand side, the first is the source term ΔP which presents the overall rate of generated heat minus the rate of the evacuated heat by the natural convection, the forced convection and the phase change of produced water.

All previous equations which describe the fuel cell thermal domain prove that temperature variation within the stack depends on generated heat, flow rate of cooling air and also the specific heat value. Hence, under the same heat flux the stack temperature T_{st} is slowly rising, as the specific heat value is higher [23].

C. proposed model

In order to design an appropriate control strategy, fine and precise fuel cell model is necessary. First of all, the fuel cell is a multi-physic system which requires a coupling between electrical and thermal domain. Indeed, the electric and thermal models are strongly coupled. In fact, through the electrical model, it is possible to determine the fuel cell polarization curve, and to calculate fuel cell and accessory losses. These losses are taken into account to estimate the stack temperature variation through the thermal model.

Thus, the proposed model is a combined model which couples electrical and thermal fuel cell models. It is developed in order to reproduce the dynamic behaviour of fuel cells with respect to operating conditions variation. This new custom component implemented in Matlab/Simscape, includes all equations presented above, in the same block.

Matlab/Simscape is multi-domain toolbox which is based on an acausal approach. This approach is considered as a relevant approach for this kind type of modeling. Since, it allows assembling several different models such as electrical, thermal, mechanical and aging domain in the same model.

The Simscape choice as toolbox to develop our model is justified by the fact that the physical system description does not imply a system behaviour linearization, as with to the Laplace transform or state equations. Consequently, this kind type of toolbox offers the possibility of not being limited to linear systems, further it enables to create physical models which are more in accordance with reality [40]. It should be noticed that the fuel cell proposed model required a coupling between electrical and thermal model which reveals different time scales. Generally, the fuel cell electrical model has a time constant on the order of few seconds, whereas thermal model is extended to a few minutes.

The proposed model has as output both the stack temperature T_{st} and the losses inside fuel cell, as an input the fan voltage V_{fan} and an electrical port to allow its integration with other devices in the same application model such as static converters, loads and sources/storages components. Therefore, this proposed model is built to supervise and to control the temperature variation within fuel cell through the fan voltage input, also to test control strategies performance.

(The Simscape code of the multi-physic model is given on TABLE II in the APENNDIX 1)

III. EXPERIMENTAL ESTIMATION OF THE MODEL PARAMETERS

The experiment described below was to study the identification of different parameters of the model in order to use them later in the proposed control strategy, which supervises the air stoichiometric ratio and the stack temperature.

A. Test bench

For experimental validation of the proposed model *« MP_FC »,* a commercial open cathode *PEM* fuel cell is used. The installed test bench is composed of an ***H-2000*** open cathode *PEM* fuel cell, from Horizon technologies. This open cathode *PEM* fuel cell system is self humidified and air cooled stack. It is composed of 48 cells in series. According to the manufacturer's datasheet, the voltage range is 22-48V, the maximum current is 90A and the maximum operating temperature is fixed at 65 °C. It contains two axial fans to ensure simultaneously air supply and air cooling functions. These two fans were powered by an external 12V battery. The maximum fan voltage is about 12V. This stack is embedded with one thermocouple to obtain the temperature variation inside the fuel cell system in real time.

Fig.2 presents the schematic of the open cathode *PEM* fuel cell system used for experimental tests.

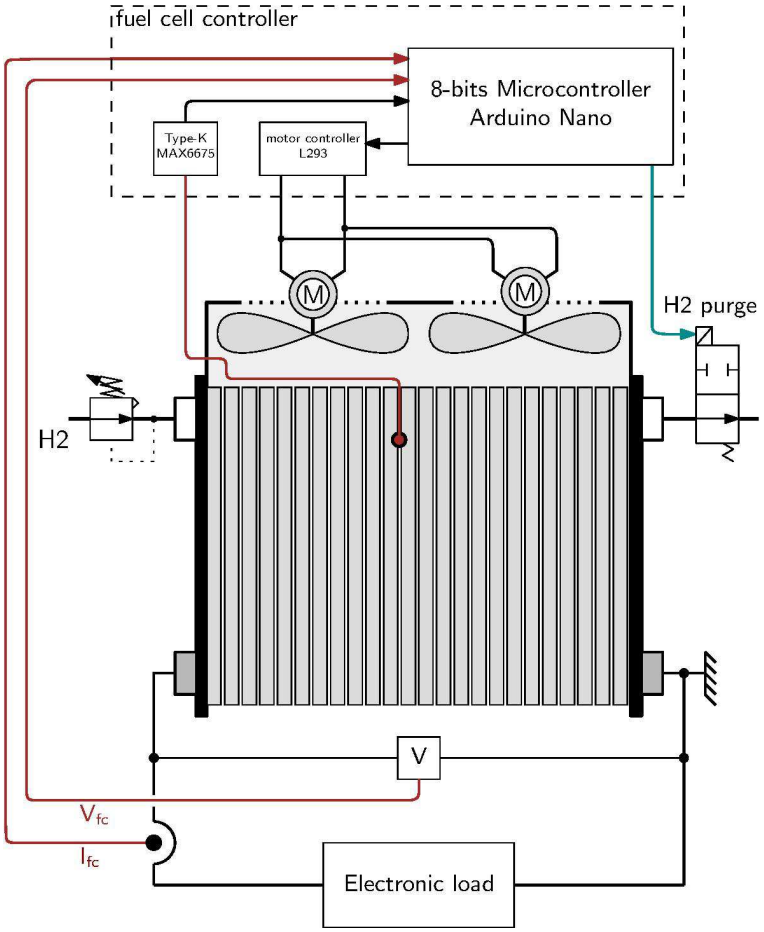

Fig.2. Schematic diagram of the H-2000W open cathode PEM fuel cell system with accessories

In addition the test bench includes a programmable load and an acquisition cart that consists of an analog circuit for voltage temperature and current sensing, associated with an Arduino Nano microcontroller.

B. Validation of the electric model of the PEM fuel cell

In order to validate the fuel cell electric model, experimental measurements in static mode were carried out. Experimental tests were conducted for different stack current and with the ancillary controller of the manufacturer.

With the equations (1) to (7), a reduced set of parameters must be chosen to make the model close to theses experimental data. Here, we can only consider fitting the transfer coefficient α, the exchange current density J_0 and the total resistance R_{ohm}. Fig.3 shows the fuel cell polarization curve, obtained from the experimental static measurements and compared to results generated by model. The comparison between experimental data and simulation results shows that the electrical fuel cell proposed model follows the characteristics of ***H-2000*** with acceptable error ranges. It can be seen that such a simple model is accurate enough to faithfully reproduce the electrical behavior of the fuel cell.

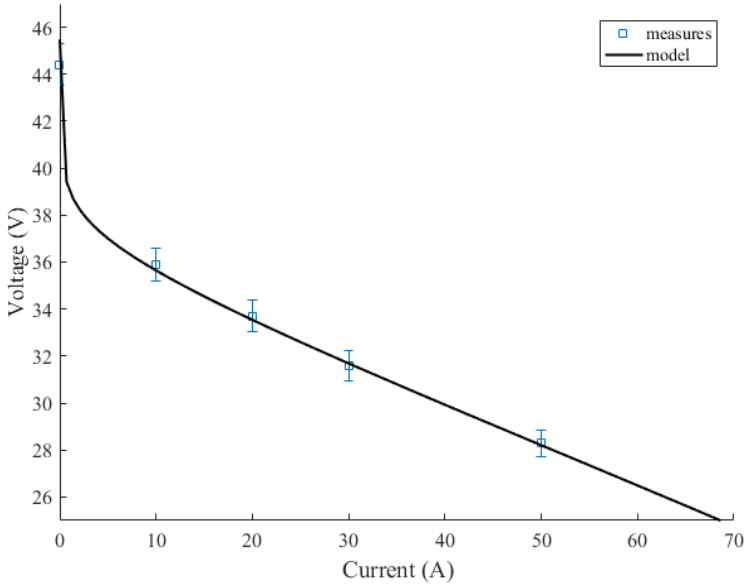

Fig.3. Polarization curve of the used fuel cell

C. Validation of the thermal model of the PEM fuel cell and fan caracterisation

In order to validate the thermal model developed above, both experimental profiles of stack current I_{st} and fan voltage V_{fan} tests were established. During the experimental tests, different fuel cell currents have been imposed and a constant fan voltage has been applied, in order to maintain a stack temperature T_{st} in the range of the rated values (between 40 and 65 °C).

At thermal balance ($\frac{d\,T_{st}}{dt} = 0$), the relation between the airflow rate Q_{air} and the fans voltage V_{fan} can be defined from the previous measurements and by knowing these parameters: the electric losses P_e, the stack current I_{st}, the stack temperature T_{st}, and the forced convection term. For this analysis, a measurement error is considered of +/- 2 degrees on the stack temperatures and +/- 25% on the evaporation terms of and natural convection. The identification results obtained are given in *Fig.4*. As expected maximum operating voltage is 12V and below the value of 2.0V, the fans do not produce any airflow.

The empirical relationship obtained by regression is:

$$Q_{pair}(V_{fan}) = 600\sqrt{V_{fan} - 2.0} \tag{14}$$

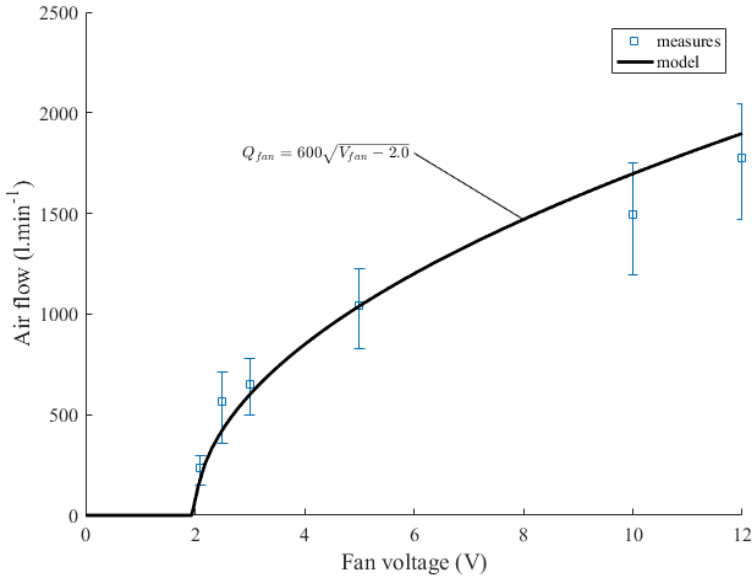

Fig.4. Relation between airflow and the fan voltage

Finally, considering the dynamical behavior of thermal model, the mass *m* and the equivalent specific heat capacity C_{fc} have to be identified. The fuel cell mass is given by the manufacturer. The equivalent specific heat capacity C_{fc} is identified experimentally from measured dynamic responses. Comparison between the model and the experimental measures is done for a current step and by keeping the fan voltage V_{fan} constant (see *Fig.5*).

The thermal model shows an acceptable error in its static and dynamic parts. It can be noted that the model take into account the large time constant of the temperature conditioner, which is about 10 seconds. Finally, the position of temperature sensor inside the stack has a quite high influence on the measurement, because of a non uniform temperature distribution, itself due to the insufficient heat conduction from the core to the edge of stack [23] . For this reason, the temperature sensor is placed as close as possible to the hot spot, which seems to be at the center of the stack.

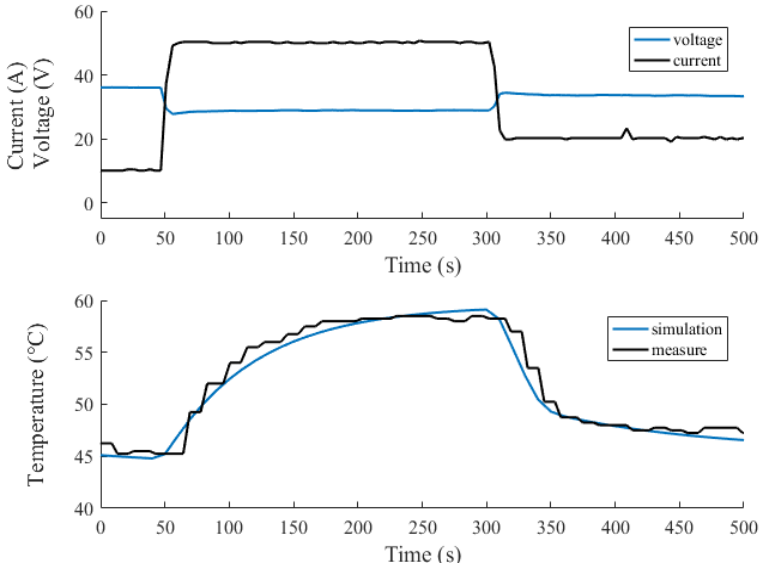

Fig.5. Dynamic response of the fuel cell system, with a constant fan voltage (Vfan=12V).

Subsequent to experimental and simulation results of the developed electrical and thermal model, similarities between both studies were depicted. As a conclusion, the custom model emulates the *PEM* fuel cell dynamic behaviour.

IV. CONTROL STRATEGY

The control strategy designed in this study is based on the stack temperature regulation and the air stoichiometry adjustment while supplying the needed power. To succeed this objective, the thermal balance equation and the operating constraints applied especially on the stack temperature and the fan voltage are considered in order to design an optimal and safety operation area.

1) Thermal balance study

The open cathode *PEM* fuel cell thermal equation (13) can be studied at thermal balance, which gives the following equation:

$$\Delta P - \sigma_{H2O}\frac{N\,R}{4\,P_a\,F}T_{st}L_{H20}I_{st}k_w - \frac{1}{60}\rho_{air}Q_{pair}C_{pair}(T_{st}-T_{amb}) - h\,S_{eq}(T_{st}-T_{amb}) = 0 \quad (15)$$

As mentioned above, the main two parameters that must be controlled during the fuel cell operation are the stack temperature T_{st} and the air stoichiometry coefficient S_c in order to improve the fuel cell performance and efficiency. However, in the case of an open cathode *PEM* fuel cell, these two parameters are strongly coupled. For this reason, there are basically two approaches based on either the operating temperature control [17] or the air stoichiometry adjustment [18] to succeed the stack performance improvement and maximize its efficiency.

That's why; a functional analysis of equation (15) is done as a first step. Then a robust control strategy is deduced especially in the case of unstable operation.

As a reminder, the problem is governed by 3 main parameters strongly coupled to each other. These parameters are the stack temperature T_{st}, the stack current I_{st} and the air stoichiometric ratio S_c which is directly regulated by the fan

voltage. In this context, it is appropriate to add operating constraints particularly applied on the stack temperature and on the fan operating voltage. These constraints are presented in the equation (16).

The following set of equations (16) is obtained by combining both the thermal balance equation (15) and the airflow equation (9):

$$\begin{cases} \Delta P - \sigma_{H2O}\frac{N\,R}{4\,P_a\,F}T_{st}L_{H20}i_{cell}k_w - \rho_{air}(1000\,\frac{5\,\mathrm{N\,R}}{4\,\mathrm{P_a\,F}}\mathrm{I_{st}S_c}C_{pair}T_{st})(T_{st}-T_{amb}) - h\,S_{eq}(T_{st}-T_{amb}) = 0 \\ T_{st}^{min} < T_{st} < T_{st}^{max} \\ V_{fan}^{min} < V_{fan} < V_{fan}^{max} \end{cases} \quad (16$$

The stack temperature is limited commonly between two values which are T_{st}^{min} around 30-35 °C and T_{st}^{max} around 65-70°C, also the fans voltage V_{fan}^{max} is limited by the nominal value given by the manufacturer and for V_{fan}^{min} it should be noted that the various electrical losses and mechanical stress prohibit to fall below 10-20% of the nominal voltage. Hence, according to the previous equation (16), all the iso-temperature curves $\{I_{st}; S_c\}$ can be drawn. This result is given in Fig.6 by considering only the stack temperature between 35 and 70°C, and the fan voltage between a little more than 2V and 12V. It can be observed from these results that the fuel cell controllable zone is situated between 2 and 60A. It is crucial to constantly remember that respecting these defined intervals guarantee a safety operating zone for the stack since its proper operation is very linked to these parameters. At the top, above the defined controllable zone the temperature constraint cannot be respected, since the fan voltage limit is exceeded. Besides, below this zone fan is not sensitive and accurate enough to control the airflow properly.

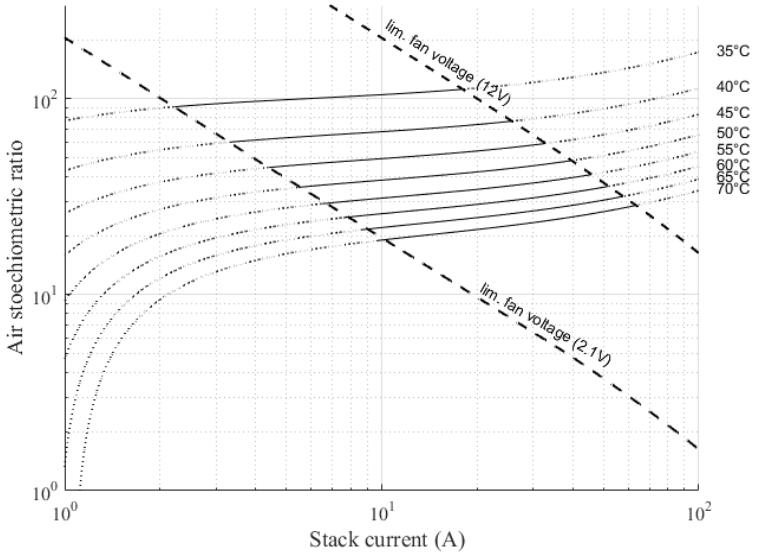

Fig.6. Synthesis of the static operating points of the used Open cathode PEM fuel cell. The ambient temperature is 25 ° C

Taking into account the different operating constraints, an experimental part is done in order to specify stoichiometric ratio ranges for various current values, which lead the studied system to operate in optimal operating zone. These results are illustrated in Fig.7. The red dashed lines are the experimental values obtained with a performance decrease less than 2% compared to the optimal solution.

As results of this experimental study, an operating zone appeared where a stable and efficient operation is ensured.

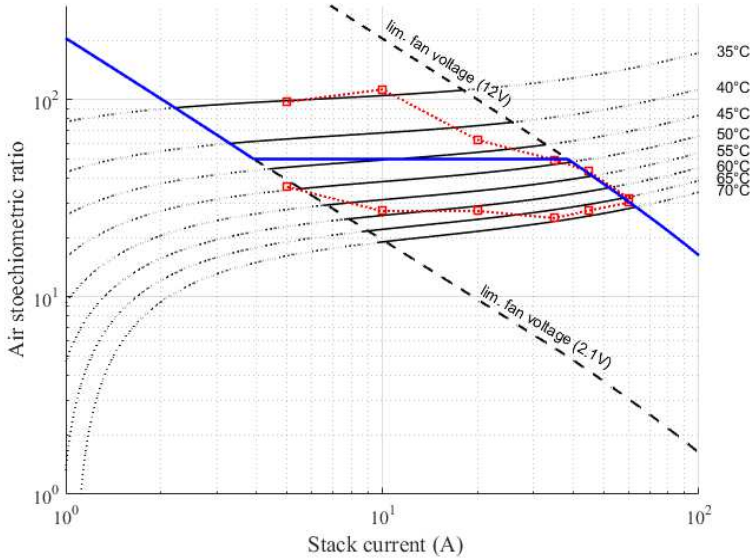

Fig.7. The obtained reference area defining the fuel cell optimal operating zone

The main result that can be retired from this configuration is the simple control function, which ensures the studied system to operate in the safety and optimal operating zone. This latter is a constant stoichiometric ratio, limited by the operating fan voltage range (2 and 12V), at standard operating conditions (ambient temperature 25 °C), the stoichiometric coefficient is around 40. Thus, for fan control, it is just sufficient to measure the stack temperature T_{st} and the stack current I_{st}, to apply them directly in equation (9), then the fan voltage is deduced from the equation (14).

With such control strategy, the temperature is not taken into account and it will be depend on environmental conditions such as the ambient temperature and the fuel cell performance, which can change significantly over time (reversible and irreversible damage). Therefore, an over-stoichiometry is added to the control strategy in order to insure the stack maximum temperature control in transitional or steady state.

To achieve this step, the natural temperature curve in *Fig.8* , imposed by the constant stoichiometry control strategy is considered. It seems that for two different stoichiometric values surrounding the optimum value of S_C= 40, the temperature variation is especially high. Thus, this correlation imposes a secondary temperature control. In order to ensure system robustness, an average trajectory is chosen.

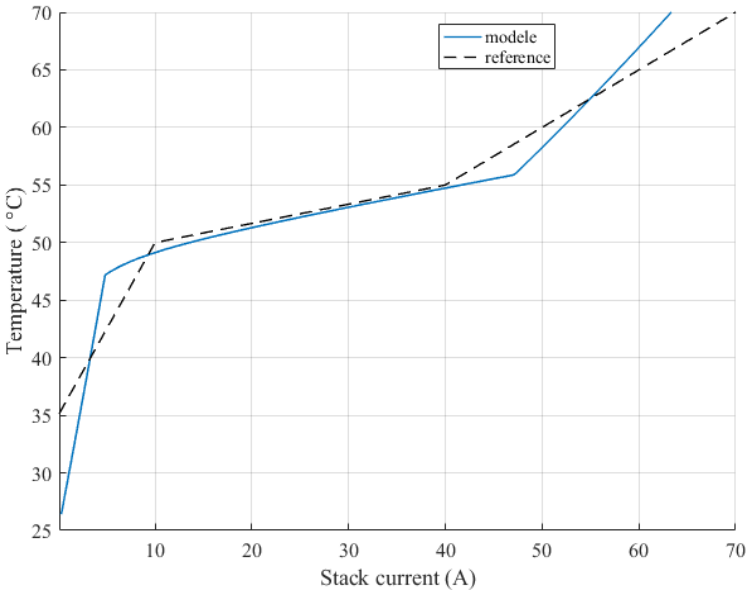

Fig.8. Fuel cell temperature in steady state, for different value of stack current and stoichiometric coefficient

2) Control architecture and implementation

As mentioned in the previous section, the main goal of the proposed control strategy is to define an optimal and safety operating zone for an open cathode *PEM* fuel cell by considering concurrently two criterion, which are the stack temperature regulation and the air stoichiometric adjustment. *Fig.9* shows the control architecture adopted to succeed the goal achievement, which is composed of two paths. The first one considers the calculation of the airflow rate that respects the stoichiometric ratio *Sc*. The second path calculates the airflow correction to achieve a proper stack temperature. It can be noticed that the temperature regulation can only acts by over stoichiometric action, i.e by increasing the airflow rate, which permits to avoid air starvation. Then, this controller try to find the best balance between both operating temperature and air stoichiometric coefficient with the aim of improving the stack performance.

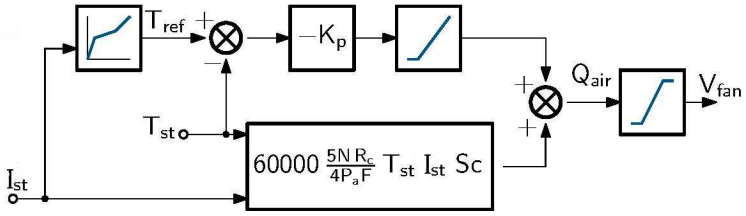

Fig.9. Control architecture for the temperature regulation and air stoichiometric adjustment

In order to evaluate the control strategy performance, simulations are carried out using the same current profile used above. The proposed control strategy integrated with the developed open cathode *PEM* fuel cell model is implemented in Matlab/Simulink environment in *Fig.10*. It can be seen that our developed model of the fuel cell system is easy to be integrated with various components from different library, allowing the proposed control strategy evaluation.

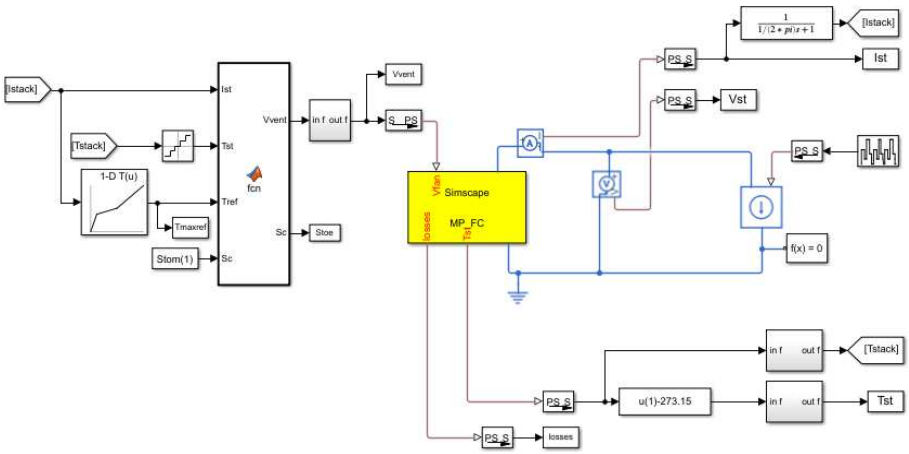

Fig.10. Model implementation in Malab/simulink

As a summary, the proposed work can be divided into the following steps:

1. Identification of both thermal and electrical parameters of the studied system from experimental results (TABLE I),
2. Identification of both fan characteristic curve and fan empirical equation (Fig.4),
3. Definition of controllable zone based an thermal analysis in static mode and operating constraints consideration (Fig.6),
4. Specification of the optimal air stoichiometric curve with respect to the electric characterization of the fan (Fig.7),
5. Integration of an over stoichiometric loop in order to ensure a safety thermal operation,
6. Achievement of experimental and simulation studies and discussion (Fig.12).

3) Results and discussions

Previously mentioned, on one hand the airflow Q_{air} and the cooling fan voltage V_{fan} are strongly linked. On the other hand, the airflow Q_{air} generated to ensure air supply and air cooling depends on theses three parameters, the stack current I_{st}, the stack temperature T_{st} and the air stoichiometric coefficient S_C, respectively. In this section, an analysis of the mutual independence between those parameters is carried out**.**

The measured stack temperature T_{st}, air stoichiometry, fan voltage V_{fan} and stack voltage V_{st} across different stack current values I_{st} are compared with experimental data taken at different air stoichiometric coefficient value 20, 30, 40, 50 respectively. The considered sets of current values are 0, 30, 10, 50, 20, and then 0 A respectively. The ambient temperature is about 25 °C. The fan voltage V_{fan} is varied between 2.1 and 12V. The air stoichiometry is varied between 30 and 150.

*Fig.*11 shows in red colour the experimental results obtained for several stoichiometric coefficients, 30, 40, and 50 respectively. These results appeared in the optimal operating area defined in the previous section.

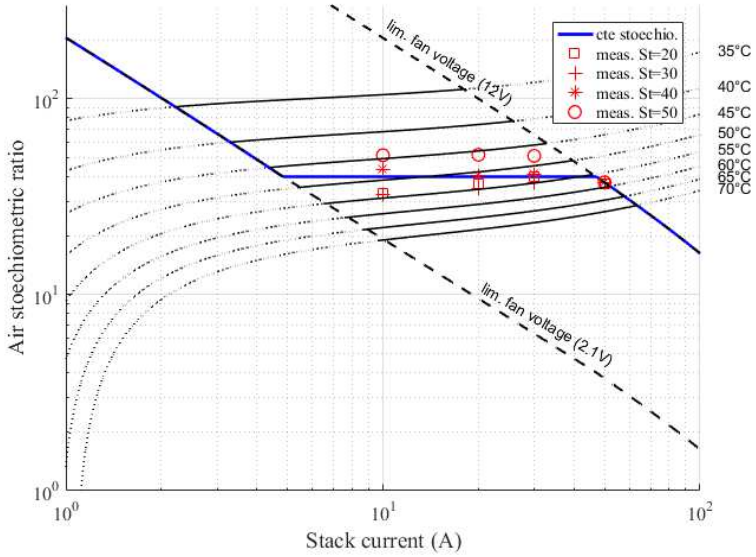

Fig.11. Experimental results implementation in the obtained diagram

a) Fan voltage and fuel cell temperature

As shown in Fig.12**,** it can be seen that both the fan voltage V_{fan} and the stack temperature variation T_{st} over time depend on current value I_{st}. So, an increase in the stack current leads to an increase in the stack temperature which requires the fan intervention and vice versa.

Since the stack current I_{st} increase, the fan voltage V_{fan} increase to insure simultaneously both air supply for electrochemical reaction taking place inside the stack and the temperature regulation by generated heat evacuation allowing the temperature decrease within the fuel cell system. Accordingly, a high value of fan voltage V_{fan} is needed because of the temperature increase resulting from heat generation. Subsequently, the fan voltage value V_{fan} is relatively low due to the lower stack temperature value. In order to confirm this concept taking the example, at I_{st} = 50 A and S_C = 30 , it can be seen that the temperature increase from 49 °C to reach 60 °C at that moment the fan acts to supply air and evacuated heat in order to decrease temperature that should not exceed a reference value. In this case, the fan voltage attains its maximum value which is 12V. While, for the same value of stoichiometric coefficient S_C and I_{st} = 20A, it can be notice that the stack temperature reaches a smaller value compared to this reached at I_{st} = 50A. Moreover, the fan voltage is about 3V.

b) Fan voltage and stoichiometric coefficient

The fan voltage V_{fan} is proportional to the stack current I_{st}, the stack temperature T_{st} and the stoichiometric coefficient S_C. Fig.12 shows an increase in stoichiometric coefficient S_C leads to an increase on the fan voltage V_{fan}. So, high value of stoichiometric coefficient S_C relatively requires a high fan voltage V_{fan} in order to provide the demanded airflow. For example at S_C = 30 and I_{st} = 20A, the fan voltage is about 3.2V, yet, at S_C = 50 and by keeping the same stack current value (I_{st} =20 A) the fan voltage V_{fan} is more greater, it reaches a value of about 4.8V. Consequently, for the first considered case the fuel cell temperature is about 52.7 °C, since the fuel cell temperature in the second case is lower and attains 47.75 °C. Indeed, at high stoichiometric coefficient S_C, there is an excess of suppling air within the fuel cell which contribute to improve the cooling process of the stack.

c) Fan voltage and stack current

Based on Fig.12, it can be noticed the strong relation between the stack current I_{st} and the fan voltage V_{fan}, In fact, the increase in the stack current I_{st} engenders an increase the stack temperature T_{st} , which demands the fan voltage V_{fan} increase, simply to ensure both the air supply and the fuel cell cooling. For example at I_{st} = 20 A and S_C = 30, the fan voltage is about 3.2V, yet, at I_{st} = 50 A and by keeping the same stoichiometric value (S_C = 20 A) the fan voltage V_{fan} is more important, it reaches its maximum value which is 12 V, in the same time, it prevent the stack temperature T_{st} to exceed the reference value.

Previous analysis, explains the strong coupling between the stack current I_{st}, the stack temperature T_{st}, the air stoichiometric coefficient S_C and the fan voltage V_{fan}. As a conclusion, there is a good agreement between simulations results and experimental data of the proposed control strategy which confirm subsequently its efficiency.

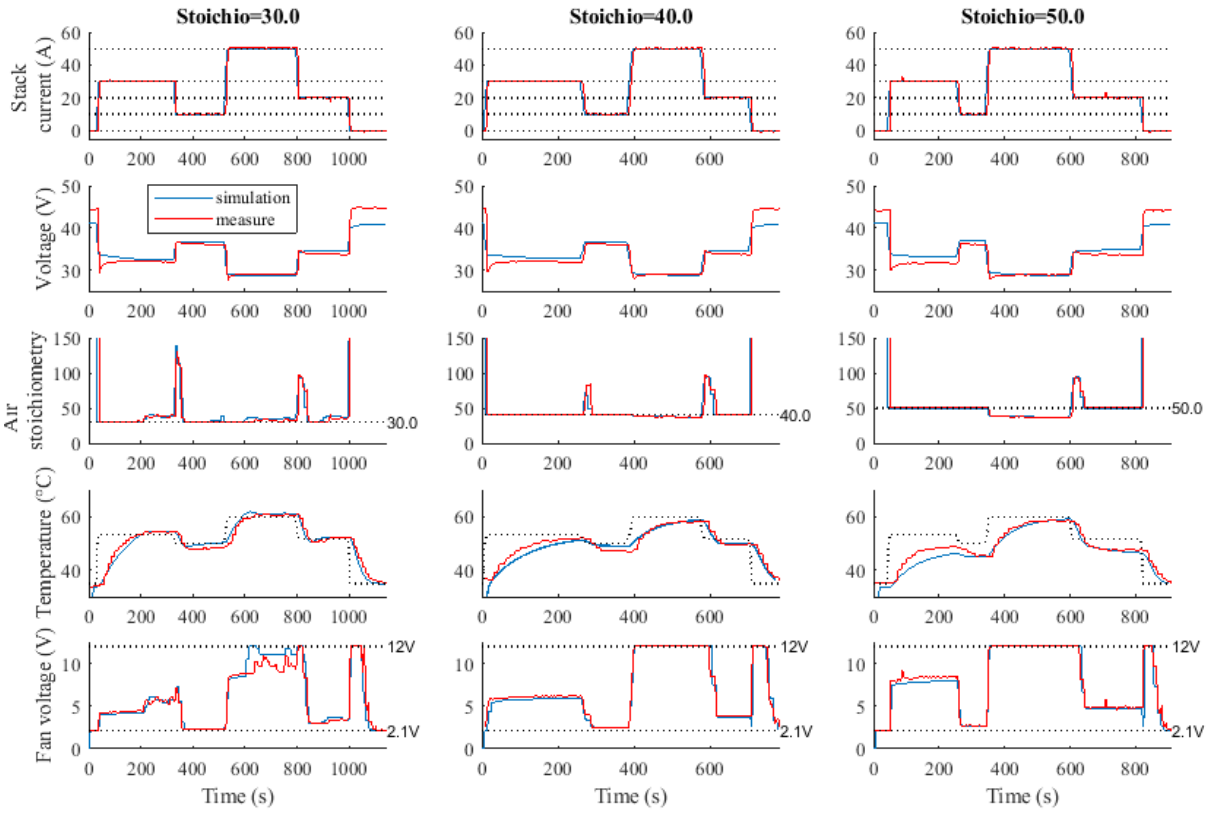

Fig.12. Comparison between the simulation results and the experimental data

Parameters of the used open cathode *PEM* fuel cell are given in Erreur ! Source du renvoi introuvable..

TABLE I FUEL CELL PARAMETERS

Description	Symbol	Value	Unit
Oxygen pressure	PO2	0.5	Bar
Hydrogen pressure	PH2	0.5	Bar
Reversible single cell potential	E0	1.2	V
Exchange current	J0	4e-7	A/m2
Active cell area	Scell	100e-4	m2
Limit current	Imax	90	A
Molar gas constant	R	8.3144	J/(mol.K)
Faraday constant	F	9648	J/(mol.V)
Ohmic resistance	Rohm	2.9	mΩ
Number of elementary cell	N	48	_
Mass	m	10	kg
Air density	rho	1.2	kg/m3
Fuel cell specific heat	Cp	3000	J/(kg.K)
Air specific heat	Cp-air	1000	J/(kg.K)
latent heat of water steam	LH20	2500	kJ.kg-1
Liquid to steam coefficient	kw	0.3	
Atmospheric pressure	P_a	101 300	Pa
Natural convection coefficient	h	3	$W.K^{-1}.m^{-2}$
Equivalent surface of natural convection	S_{eq}	0.15	m^2
Proportional controller gain	K_p	250	$V.K^{-1}$

V. CONCLUSION

The main goal of this work is to design an appropriate control strategy which combining simultaneously the stack temperature regulation and the air stoichiometry adjustment in order to guarantee the performance improvement and the degradation prevention of the studied system. To succeed on designing this control strategy with respect to operating conditions change, an accurate model of fuel cell system is necessary. A multi-physical model is developed in MATLAB/Simscape based on acausal modeling approach. It allows mainly emulating the dynamic behaviour of an open cathode fuel cell system under different operating conditions and controlling stack temperature through the fan voltage input. An experimental part by using 2 kW open cathode fuel cell gives validation of the proposed model. The main innovative aspect of the developed model is its ease of integration with different components from different library. Several domains are integrated in the same bloc independently from each other. Another feature of the designed model is its improvement by inserting more domains in the same bloc already developed, such as ageing domain.

Temperature variations in the fuel cell system are considered as a critical factor as its increase beyond a specific value causes thermal stresses and reduces the system performance and efficiency. As well airflow rate for both supplying and air cooling tasks is an important factor in an open cathode fuel cell system. Therefore, these two parameters have a significant role in the fuel cell thermal management.

System thermal balance was studied for two issues. The first one is to release the fuel cell fans characterization. Knowing that, the fan empirical equation is deduced from experimental results. The second one is to find the best compromise between these two parameters which are the air stoichiometric coefficient S_c and the fuel cell temperature T_{sc} in order to guarantee an optimal fuel cell performance. Through the proposed control strategy, an optimal and safety operating zone is defined in which the fuel cell performance is better. This zone is defined as a constant stoichiometric

air ratio of 40 surrounded by the operating limit of the fan voltage (2.1 and 12V) and the stack temperature. The comparison between experimental and simulation results prove the effectiveness of the appropriate control strategy with different operating conditions. Consequently, a temperature increase caused by the load current increase requires an excess of supplying air in order to ensure the system cooling and to avoid performance degradation.

ACKNOWLEDGMENT

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VI. APPENDIX

TABLE II CODE OF THE MULTI-PHYSIC PEM FUEL CELL MODEL IMPLEMENTED IN MATLAB/SIMSCAPE

```
component MP_FC < foundation.electrical.source  %Multi-Physic FC
inputs
    Vvent     = {0,'V'};  %Vfan:top
end
outputs
    Tfc    = {0,'K'};     %Tst:bottom
    Per    = {0,'W'};     %losses:bottom
    end
parameters
    PO2    = 0.5;                          % Pressure of oxygen
    PH2    = 0.5;                          % Pressure of Hydrogen
    Eo     = {1.2,'V'};                    % Reversible single cell potential,
    Io     = {6e-7,'A/m^2'};               % Exchange current
    Sact   = {100e-4,'m^2'};               % Surface active
    Imax   = {100,'A'};                    % Limit current
    T      = {298.15,'K'};                 % Ambient temperature
    R      = {8.3144,'J/(mol*K)'};         % Molar gas constant
    F      = {96485,'J/(mol*V)'};          % The Faraday's constant
    Alpha  = {0.77,'1'};                   % Transfer coefficient
    Rohm   = {0.0029,'Ohm'};               % Ohmic resistance
    N      = {48,'1'};                     % Number of elementary cells
    m      = {10, 'kg' };                  % Mass
    Cp     = { 300, 'J/(kg*K)' };          % Specific heat of fuel cell
    Cp_air = { 1000, 'J/(kg*K)' };         % Specific heat of air
    rho    = {1.2, 'kg/m^3'};              % Air density
    a      = {600,'m^3/(s*V^0.5)'};
    g      = {1,'A'};
    V0     = {2.0, 'V'};                    % Minimum fan voltage
    LH2O   = {2500e3, 'J*kg^-1'};           % Water latent heat of evaporation
    Pa     = {101300,'kg*m^-1*s^-2'};       % Atmospheric pressure
    rh2o   = {1e3,'kg/m^3'};                % water volume density
    kw     = {0.5,'1'};                     % Wasselynck coefficient
    h      = {3,'W/m^2/K'};                 % Wasselynck coefficient
    Seq    = {0.14,'m^2'};                  % Heat exchange surface
end


variables
    ist  = {0,'A'};                   % Stack current
    Eth    = {0,'V'};                   % Thermodynamic potential
    Vconc  = {0,'V'};                   % Concentration losses
    Vohm   = {0,'V'};                   % Ohmic losses
    Vact   = {0,'V'};                   % Activation losses
    Tst    = {0,'K'};                   % Stack temperature
    Qv     = {0,'m^3/s'};               % Coolant flow rate
end
equations
    v      == N (Eth-Vohm-Vact-Vconc);                                % Stack voltage
    Eth    == Eo+(0.5*(R*Tst/F)*(log(PH2)+0.5*log(PO2)));             %Reversible voltage
    Vconc  == -0.5*(R*Tst/F)*log(1-(ist/Imax));                     %Concentration losses
    Vact   == (0.5*(R*Tst)/(Alpha*F))*(log(max(ist,g)/(Sact*Io))); %Activation losses
    Vohm   == icell*Rohm;                                           %Ohmic losses
    Tst.der==1/(m*Cp)*(Per - (rho*Cp_air*Qv*(Tst-T)) - 1e-3*kw*rh2o*ist*N*R/(4*Pa*F)*Tst*LH2O -
h*Seq*(Tst-T));                                                     %Temperature variation
    Per== N*(Eth-v)* ist;                                           %Dissipated losses
    Qv== a*max(0,(Vvent - V0))^(0.5)/60000;                         %Qv=f(Vfan)

    ist == -I;
    Tfc  == Tst;
end
end
```