



Aging Tolerant Control of Proton Exchange Membrane Fuel Cell: a Model-Based Approach

Mathieu Bressel, Mickaël Hilaret, Daniel Hissel, Belkacem Bouamama

► To cite this version:

Mathieu Bressel, Mickaël Hilaret, Daniel Hissel, Belkacem Bouamama. Aging Tolerant Control of Proton Exchange Membrane Fuel Cell: a Model-Based Approach. International Workshop on Advanced Control and Diagnosis, Nov 2017, Bucharest, Romania. hal-02868309

HAL Id: hal-02868309

<https://hal.science/hal-02868309>

Submitted on 15 Jun 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Aging Tolerant Control of Proton Exchange Membrane Fuel Cell: a Model-Based Approach

Mathieu Bressel^{*‡}, Mickael Hilairt[†], Daniel Hissel[†], and Belkacem Ould Bouamama[‡]

^{*}Hautes Études d'Ingénieur, 13 Rue de Toul, 59000 Lille, France

[†]FEMTO-ST, UMR CNRS 6174, FCLAB, FR CNRS 3539, UBFC, Rue Thierry Mieg, 90000 Belfort, France

[‡]CRISAL, UMR CNRS 9189, Avenue Paul Langevin, 59655 Villeneuve d'Ascq, France

Abstract—Proton Exchange Membrane Fuel Cells are promising energy converters that allow to power vehicles or buildings in a clean manner. Nevertheless, their performance are affected by faults and irreversible degradation mechanisms that are far from being fully understood. Consequently, during the last decade, researches have been conducted on the diagnostic of faults of this promising converter. Nevertheless, aging was never the subject of a particular attention concerning control. As a result, this paper proposes an aging tolerant control strategy for Proton Exchange Membrane Fuel Cells. It aims at generating the load current reference taking the state of health into account. Moreover, using a model inversion of an Energetic Macroscopic Representation with time-varying parameters, the coherent references of input flows of gas can be calculated. Finally, the paper details a Maximum Power Point Tracking algorithm which allows to identify the maximum power the fuel cell is able to provide at each time.

Index Terms—Proton Exchange Membrane Fuel Cell, Fault Tolerant Control, Energetic Macroscopic Representation, Maximum Power Point Tracking

I. INTRODUCTION

In a context of diminishing fossil energy resources, it is imperative to start an energy transition that includes renewable sources. In order to succeed in this transition, the worldwide community needs to tackle the middle and long terms energy storage issue. One of the possible method relies on using hydrogen as an energy vector that is transformed into electricity thanks to a Proton Exchange Membrane Fuel Cell (PEMFC) [1]. Those converters are receiving a growing interest from the scientific and industrial community around the globe due to its high energy density and efficiency, what makes it a suitable solution to replace Internal Combustion Engine for transportation applications. Moreover those converters are able to provide, in a combined manner, electricity and heat to an entire building (μ -CHP) [2].

Among the bottlenecks of the diffusion of this promising technology, the lifespan of a PEMFC is still too limited (2500 hours in average under transportation operating conditions), which is inferior to the transport application prerequisite [3]. Various means of research might lead to overcome this limit: material improvement, optimization of the design, and development of a smart control in order to avoid specific behaviors which degrade this converter. For the last point, it is required to estimate the degradation (i.e. the State of Health) and then to act consequently on the control.

Prognostics and Health Management (PHM) is a maintenance strategy aiming at extending the life of a device thanks to monitoring, diagnosis, prognostic and control. As a consequence, a growing interest emerges among the fuel cell community for this maintenance philosophy [4]. Knowing the State of Health (SoH) of a PEMFC is crucial at the decision step of the PHM cycle. Indeed, it is possible to eliminate or to limit certain faults by the control. For several years the scientists develop Fault Tolerant Control (FTC) of PEMFC systems. Generally, it concerns the power converters [5], the air compressor [6], or the cooling system [7] and aim at eliminating several faults (drying/flooding, defect of the air compressor etc.). However, as far as the authors knowledge, only one paper concerning the aging tolerant control has been identified in the consulted literature [8]. Therefore, the originality of this paper is to propose a law of control which takes into account the SoH of the PEMFC in order to change the objective during the aging.

The structure of this paper follows: first, the PEMFC technology is introduced with, in particular, a brief description of the degradation phenomenon in section II. Then, a time-varying model of PEMFC is presented. It is structured in the Energetic Macroscopic Representation (EMR) formalism, which allows to develop a model-inversion based control in section III. Finally, a control strategy for aging PEMFC is detailed. It allows to regulate the provided power in spite of the loss of performance. When the PEMFC is too much degraded, it becomes impossible to supply a certain amount of power. As a consequence it is interesting to develop an algorithm capable of estimating the maximal power the PEMFC can supply at all time. This algorithm of Maximum Power Point Tracking (MPPT) is presented in section IV.

II. PEMFC DESCRIPTION AND DEGRADATION PHENOMENON

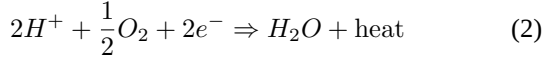
A. PEMFC Description

A PEMFC is an electrochemical converter based on the reverse principle of electrolysis, where at the anode, the hydrogen is diffused to the electrolyte. At this electrode interface, the reaction



occurs. While the electrons flow through an external circuit, the H^+ ions are crossing the Proton Exchange Membrane.

At the cathode, the oxygen reacts with the species described previously in an exothermic manner following:



Between the electrodes is created a difference of potential resulting from the Gibbs free energy G which value depends on the chemical affinity of the species: $E_{rev} = \frac{-\Delta G}{2F}$, where $2F$ is the Faraday constant when there is two of mole of exchanged electrons. The operational temperature and pressure affect this thermodynamical potential as shown by the Nernst equation:

$$E_0 = E_{rev} + \frac{RT}{2F} \left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \right) \quad (3)$$

E_0 is the maximum theoretical potential that can be reached. This theoretical potential is diminished by several losses, namely activation, Ohmic and diffusion [9]. Activation losses are due to the kinetics of reaction and generate an over-voltage, subtracted from the potential above. Ohmic losses are due to the resistivity of the assembly (dependend on the water content) and decrease the potential following the Ohm law. Finally, one can observe a local loss of pressure as the species are consumed leading to a drop on the Nernst potential. This phenomenon is named concentration losses.

Thus, the static voltage of the PEMFC can be described with the following equation:

$$V_{FC} = n \left(E_0 - AT \ln \left(\frac{i}{i_0} \right) - Ri - BT \ln \left(1 - \frac{i}{i_L} \right) \right) \quad (4)$$

where n is the number of cells, i is the input current density ($A.cm^{-1}$), T represents the operational temperature (in kelvin), A and B are respectively the activation and concentration constants, R stands for the global resistance (membranes, electrodes and connectors), i_0 is the exchange current density and i_L is the limiting current density. This relation is also used to model the so called polarization curve $V_{stack} = f(i)$.

During current transients, electrons accumulate along the membrane electrode interface acting as a capacitor. This phenomena is called double layer effect. Moreover, to be operated correctly, a PEMFC requires several auxiliaries. Among them, a cooling system aims at evacuating the heat produced by the losses and chemical reactions. It is important to specify that most phenomenon are coupled (e.g. the voltage drop depends on the temperature and the generated heat is a function of the losses). To overcome this issue, one can decompose functionally the model for the analysis and control [10].

B. Degradation Phenomenon

In a previous work, a study on the effect of aging on the parameters value of Equ. 4 is carried out using experimental data from a long duration test under variable load. An 8 cell stack, provided by the French "Commissariat à l'Energie atomique et aux énergies alternatives" (CEA), was subjected to a μ -CHP power profile during 1000 hours as the polarization curve was recorded periodically. From these curves, a set of model parameters is extracted using a fitting technique. It is

observed that only two parameters evolve significantly. Based on this long duration test, the resistance value R increases by more than 70% and the limiting current i_L decreases of 60%. It is noted that similar behavior was found in an other study [11]. A bad water management, causing dehydration, is the main factor affecting R , while the limiting current value depends on the apparent surface of exchange (related with the catalyst layer) [12]. The reader is invited to refer to [13] for more details on the degradation analysis. Nevertheless, it should be noted that by measuring only the PEMFC voltage, it is impossible to discern the impact of those losses separately (see Equ. 4).

In the same paper, based on the above considerations, an empirical degradation model is developed and is described as follow:

$$R(t) = R_0(1 + \alpha(t)), I_L(t) = I_{L0}(1 - \alpha(t)), \quad (5)$$

$$\alpha(t) = \int_0^t \beta(\tau) d\tau \quad (6)$$

where the speed of parameters deviation is β and α is the State of Health indicator and it is responsible of coupling the two parametric deviations. R_0 and i_{L0} are the initial resistance and limiting current density extracted from the first polarization curve.

Despite the fact that the proposed model has some limitations (i.e. the speed of degradation is not a function of the operating conditions), it was successfully used for PEMFC's prognostics which motivated its use in the present work.

III. TIME VARYING EMR MODEL FOR PEMFC CONTROL

A. Time Varying EMR Model of PEMFC

1) *EMR for modeling*: Among the several graphical formalisms to model a multi-physical system, the Energetic Macroscopic Representation (EMR) aims at representing the transfer of energy in a macroscopic manner. It is shown by two arrows connecting subsystems representing the effort e (potential variable) and the flow f (kinetic variable). The product of these dual variables gives the power $P = e f$. Moreover, two of the strong concept of the formalism are the principle of action-reaction and the representation of the phenomenon in the integral causality (given by the direction of the arrows) [14].

A set of four graphical elements forms the EMR language:

- Sources (green oval): provide or receive an effort or a flow.
- Energy storage elements (rectangle with an orange diagonal): show the energy accumulation with or without losses and impose the causality to the others elements.
- Energy conversion elements (yellow square and circle for mono and multiphysical conversion respectively): are responsible of the transfer of energy without loss nor accumulation. The conversion can be modulated using a tuning vector.
- Energy distribution elements (several squares or circles which intersect for mono and multiphysical distribution): exhibit a similar function as the conversion elements when a common physical resource is shared.

Those graphical elements are presented in the appendix.

Moreover, an extension to this formalism called Practical Control Structure (PCS) allows to design a model-inversion based control [15]. Since, the integral causality is always preferred, a direct inversion would lead to a derivative causality. Thus, correctors (or observers) are used to estimate variables. In PCS, the unrealistic or costly measurement are replaced and the limitation of the model is included in the control design. The control structure shows the required sensors and is implementable in real time. As a result, EMR and its associated PCS are successfully used for PEMFC modeling and control [16].

2) *Stationary model of PEMFC*: The developed time-varying EMR model used in this work is based on the quasi-static model presented in Hissel et al. [10] for which the electric dynamics (related with the double layer effect) has been ignored. This hypothesis can be done once that the gas dynamics is predominating.

This dynamical model includes the hydraulic dynamics with pressure losses and it is represented by a pair of converters (for the input and output) and an accumulation element. Through a distribution element, the partial pressure on the membrane can be computed at both anode and cathode. A converter computes the electrical potential E_{rev} which is diminished following the Nernst law in a multi-physical coupling element (using the partial pressures). One coupling element is responsible for cal-

culating the voltage drop causes by the activation, ohmic and concentration losses. Moreover, this model is able to predict the flow of entropy produced by the PEMFC. The generated heat is evacuated by a cooling system which is modeled as a first order system (accumulation element associated with a conversion element, controlled with the volumetric flow of water cooling). A source element is imposing the temperature of the cooling water. In [10], the model is also validated using data from a 20 cells PEMFC.

For the needs of this work, the parameters of this model (see Fig. 1) has been identified using data from a 8-cell stack as detailed in [17].

3) *Time varying parameters*: In this section, the parametric evolution seen in section II.B is included in the PEMFC model in order to develop a control structure. Indeed, this parameter deviation has a slow dynamic compared with the transient of the PEMFC, i.e. about an hour. Nevertheless, it has a strong impact on the control performance [18]. It is reminded that the resistance and the limiting current evolve for more than 60% compared to the initial values, affecting significantly the model accuracy.

In order to take into account the aging in the model, the PEMFC is now modeled as a time varying parameter system in the EMR formalism, following the methodology proposed by Wankam et al. [19] which is shown in Fig. 2.

This extension of the EMR formalism to non-stationary systems allows to model a non-linearity (dependent on state variables), a variation due to the environment or a parameter evolution that depends on the process. It is represented by a classic fixed parameter EMR model (the yellow rectangle of Fig. 2). Then a block of orange color is in charge of calculating the variation of the parameters and it is injected directly on the fixed parameters EMR model.

In our study case, the resistance and the limiting current of the multi-physical conversion element are now functions of the SoH of the PEMFC such as described in Equ. 5.

The variant nature of the parameters is graphically represented by the arrow which crosses the block of conversion as shown in Fig. 1. The law of evolution of the SoH (Equ.6) is included in the crossed orange block (the relation is time dependent). It should be noted that the degradation profile is coming from [13] and was accelerated for the needs of the simulation. In a concern of generality, it was chosen to represent the block of parameters variation as a function of the input current even if the model of degradation does not reveal

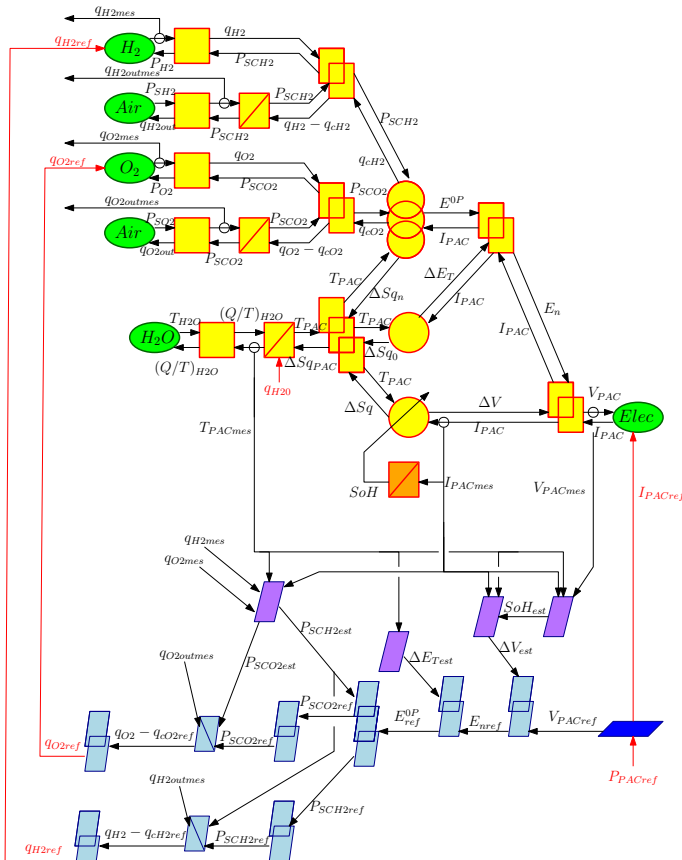


Fig. 1. Time varying parameters EMR model of PEMFC and associated control

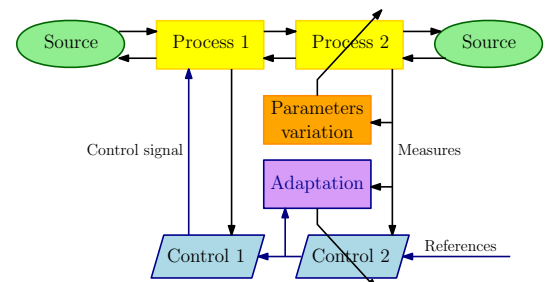


Fig. 2. EMR model structure for adaptive control

it explicitly. Indeed, it is experimentally shown that the speed of degradation depends on the current value and dynamics but a law of evolution could not be clearly established.

In order to control the power, it is necessary to act simultaneously on the load current I_{FC} , on the flows of gas q_{H2ref} , q_{O2ref} , and also on the flow of cooling water q_{H2O} . The latter is only used for the regulation of the temperature of the PEMFC and not to act on the output power. The volumetric flows q_{H2ref} and q_{O2ref} allow the correct feeding in reactives to obtain the requested power. On the EMR model of Fig. 1, it can be noticed that the phenomena are strongly coupled. However, because there is no action on the flow of cooling water q_{H2O} for the power regulation and because the EMR rules allow the decoupling, it is possible to invert the model for the design of a Practical Control Structure [15].

B. Control by model inversion

By following the procedure of adaptive control introduced by [19], the PCS is defined by the rules of inversion of the EMR model with fixed parameters (rectangle of blue color on Fig. 2). Then, the measures that are not easy to access could be replaced by observers such as described in Boulon et al. [16] and seen in Fig. 1.

To this nominal parameters control is added a block of adaptation (represented by a purple rectangle) which allows the on-line identification of the variants parameters. In our case, this identification is performed by an Extended Kalman Filter (EKF) developed in a previous work. It allows the joint estimation of the health indicator at each instant k α_k and the associated derivative β_k . It is based on the discrete non-linear state-space system:

$$x_k = Ax_{k-1} + w_{k-1} \quad (7)$$

$$y_k = g(x_k, u_k) + v_k \quad (8)$$

The state vector x_k represents the variables to estimate (α_k β_k). The inputs (current and temperature) are included in the vector u_k while the output voltage is described with y_k . The state and the output are tainted with process and observation noises considered gaussian with zero-mean [20].

From the EMR model of Fig. 1, one can notice that the voltage drop ΔV which is due to the losses of ohm, activation and concentration is not physically reachable. As a consequence, it is chosen to estimate the state from the measured output voltage V_{FC} . This voltage can be described by the state of health dependent expression:

$$g(x_k, u_k) = n \left(E_0 - AT \ln \left(\frac{i_k}{i_0} \right) - R_0 (1 + \alpha_k) i_k - BT \ln \left(1 - \frac{i_k}{i_{LO}(1 - \alpha_k)} \right) \right) \quad (9)$$

which is based on Equ. 4 expressed in discrete form for a sampling period fixed of $T_s = 1$ sample per second.

Supposing the speed of degradation β being quasi-constant on a period, one can deduce the matrix of transition:

$$A = \begin{bmatrix} 1 & T_s \\ 0 & 1 \end{bmatrix} \quad (10)$$

Therefore the algorithm of state estimation can be expressed as [20]:

Algorithm 1 Extended Kalman Filter

```

1: procedure
2:   Initialization
3:    $x_{0|0} = E[x(t_0)]$ 
4:    $P_{0|0} = Var[x(t_0)]$ 

5:   Prediction
6:    $x_{k|k-1} = Ax_{k-1|k-1}$ 
7:    $P_{k|k-1} = AP_{k-1|k-1}A^T + Q$ 

8:   Correction
9:    $K_k = P_{k|k-1}H_k^T(H_kP_{k|k-1}H_k^T + R)^{-1}$ 
10:  with  $H_k = \frac{\partial g(x_k, u_k)}{\partial x_k}$ 
11:   $P_{k|k} = (I - K_kH_k)P_{k|k-1}$ 
12:   $x_{k|k} = x_{k|k-1} + K_k(V_{stk} - g(x_k, u_k))$ 

```

The chosen degradation profile $\alpha(t)$ and its estimation by the EKF can be found in Fig. 3. This time evolution used for this simulation comes from the analysis of real data on a 8-cell PEMFC under a μ -CHP profile of current as found in [13]. Nevertheless, for computational consideration the degradation has been accelerated sixty times. The variation of the slope is related with the change of current profile (the simulated seasons). For a more detailed description of the estimation of the SoH using an EKF, the reader is invited to refer to [13].

Fig. 1 shows the global time varying parameter PCS of a PEMFC, where, the dark blue parallelogram represents the control strategy which is presented in the following section. It allows defining the current reference in order to regulate the power the PEMFC has to provide. In practice, this reference current is given to the controller of the DC-DC converter (symbolized by a controlled source in the model), nevertheless the presented study is limited to the fuel cell core.

C. Model limitation

It is advised to remind the limitations of the fixed parameters model. In particular, all the parameters of the model are identified for certain operating conditions, what limits the domain of validity (temperature lower than 80 degrees, pressure and

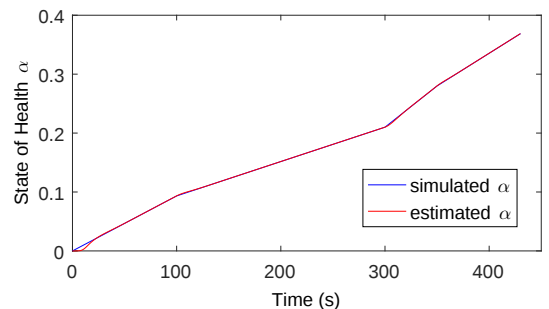


Fig. 3. Estimation of the SoH $\alpha_{k|k}$ by an EKF

relative humidity close to the nominal, stoichiometries of 1,5 and 2 for the anode and the cathode respectively). However, since our control structure implies the use of estimators, the lack of accuracy on certain parameters value of the model is compensated in the control loop.

Besides, in the original work the objective is the regulation of the PEMFC's voltage for a constant value of power, what can turn out as a over-consumption of hydrogen. This problem is by-passed here by the Degradation Tolerant Control strategy which allows the deduction of relevant reference of current and voltage during the aging.

It is also necessary to remind that towards the original model, the electric dynamics due to the double layer capacitance is ignored in this work. This has a direct impact on the inversion-based control. Indeed, this unknown dynamics is seen by the control as a disturbance. Therefore, it becomes necessary to add an estimator in the control strategy in order to compensate this model simplification.

The authors of the nominal parameters model specify that an experimental validation of the control is necessary and that the range of validity must be widened to other operating conditions. Nevertheless this model allows the control of the output voltage of a PEMFC for the studied domain of validity. In [10], it is intended to rely on this control to maximize the efficiency of the PEMFC system or to optimize its life expectancy. These issues are partially treated in the following section.

IV. AGING TOLERANT CONTROL OF PEMFC

A. Degradation Tolerant Control framework

This section describes a strategy aiming at controlling a PEMFC in spite of the aging. First, a strategy of constant power regulation is presented. It allows generating the current and voltage references for the PCS in order to obtain the desired power.

Secondly, once the performances of the PEMFC diminish with the aging, the converter will not be able, at a moment, to supply the desired power. Therefore, an estimator of the maximal power the fuel cell can provide is also presented.

In order to design a FTC, two steps must be carried out [21]:

- First, a diagnostic module allowing the detection and isolation of faults is designed. When a fault occurs, a signal is sent to a supervisor.
- The supervisor is responsible of taking decisions in order to cancel or diminish the effect of the fault. This can be done by reconfiguring the system architecture or by adapting the requested load current (changing the objective).

Blanke and al. [21] proposes to schematize the FTC in a three levels architecture (see Fig. 4).

B. Power regulation of an aging PEMFC

The control by model inversion presented in section III.B. allows to compute the reference of gazes flow for a given current and voltage. Nevertheless it is required to define those

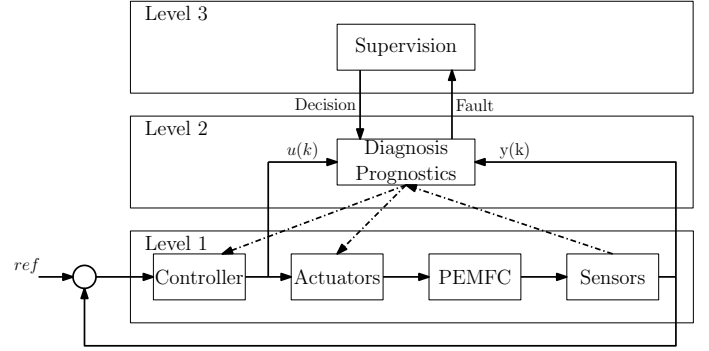


Fig. 4. Fault Tolerant Control architecture scheme

references in the strategy block (purple parallelogram in Fig.1) for a requested power. The resultant power of a PEMFC depends strongly on the load current in a non-linear manner as Equ. 4 shows. Therefore, to deduce the voltage and the current for a reference power is not a trivial task. It is proposed in this work, to approximate the current reference based on the initial characterization. Indeed, thanks to the polarization curve $V_{FC}(i)$, one can deduce the power as a function of the current $P_{FC}(i) = V_{FC}(i)i$. By inverting this curve (in the form of a table), the nominal current is estimated. Nevertheless, due to the loss of performance, a reference adjustment is required in order to maintain the power P_{mes} to the desired level P_{ref} . This step is realized with a PI corrector as shown in Fig. 5. The voltage reference is calculated for a given current using Equ.9 and the SoH estimation of the EKF.

It is noted that other control scheme could be used such as passivity-based control. Fig. 6 shows the reference current generated for a power demand of 550W, and Fig. 7 shows the real power the PEMFC provides.

One can notice on Fig. 7 that the control strategy is able to regulate efficiently the PEMFC power in spite of the aging. It is also noted at $t = 420s$ that the PEMFC is not anymore able of providing the requested power (with our accelerated aging). It shows that a high level of degradation impacts the safety of the system and thus, must be avoided. This is the reason it is interesting to know the power the PEMFC is able to provide at each instant as presented in the next section.

C. MPPT for an aging PEMFC

A Maximum Power Point Tracking algorithm (MPPT) is an estimator able to predict the maximal power a device is able to provide. It was historically developed for photo-voltaic panels and windmill but it can be generalized to every non-linear source of energy [22]. It usually requires a relation expressing the power as a function of several input variable.

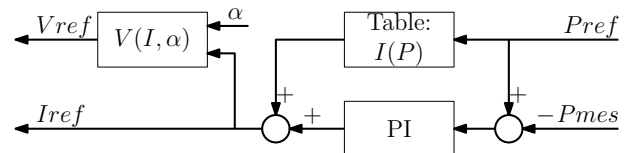


Fig. 5. Current and voltage reference generation scheme

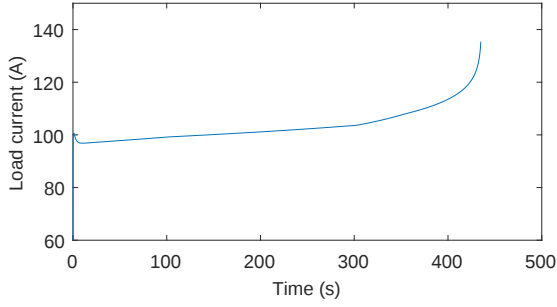


Fig. 6. Reference current I_{ref} for a power demand of 550W

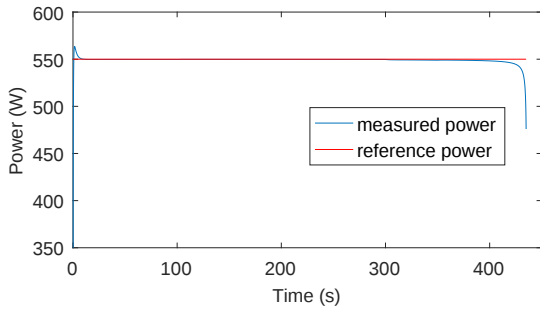


Fig. 7. Simulated PEMFC power P_{mes} for a power reference of 550W

When an input is considered unknown (i.e. direction of the sun or speed of the wind), the MPPT is implemented using a "Perturb and Observe" method for instance [23]. Otherwise, a classical optimization techniques, as a gradient descent, can be used.

Under the assumption that the estimation of the SoH estimation $\alpha_{k|k}$ can be obtained by the EKF in real-time (see Fig. 3), it is possible to forecast the power the PEMFC can provide as a function of the load current at each instant following:

$$P_{pac}(i_k) = ni_k \left(E_0 - AT \ln\left(\frac{i_k}{i_0}\right) - R_0(1 + \alpha_{k|k})i_k - BT \ln\left(1 - \frac{i_k}{i_{L0}(1 - \alpha_{k|k})}\right) \right) \quad (11)$$

From the equation above, it is possible to estimate the maximal power point of the aging PEMFC as shown on Fig. 8.

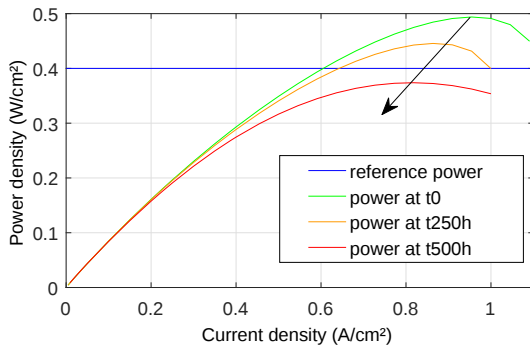


Fig. 8. Power density through aging

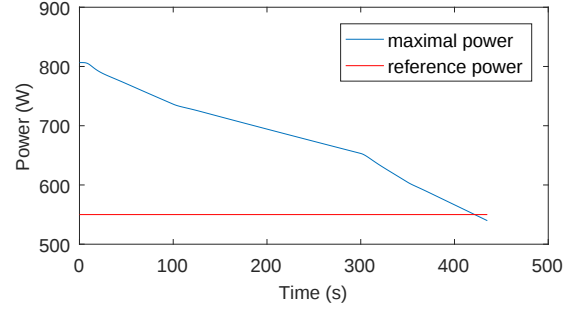


Fig. 9. Maximal power the PEMFC is able to provide through aging

In this paper, the load current x corresponding to the maximal power is given by an iterative gradient descent as shown in Algorithm 2.

Algorithm 2 Maximum Power Point Tracking

```

1: procedure
2:   Initialization
3:    $j = 0$ 
4:    $x_j = i_{start}$ 

5:   Estimation
6:   while  $j < N_{max}$  or  $|x_{j+1} - x_j| < \delta$  do
7:      $G_j = \frac{\partial P_{pac}(x_j)}{\partial i_k}$ 
8:      $x_{j+1} = x_j - \nu G_j$ 
9:      $j = j + 1$ 

```

Where j is the counter, i_{start} is the initial guess, G_j is the gradient of the PEMFC power and ν is the learning step.

The convergence for which the maximum power and associated load reference are obtained is given by the tolerance δ ($|x_{j+1} - x_j| < \delta$) or a maximum number of iteration $j < N_{max}$. Fig. 9 depicts the maximum power estimation in our simulation case. It can be noted that at time $t = 420s$, the PEMFC is no longer able to provide the requested power of 550W and should be put to safety as predicted on Fig. 7.

As a drawback, the accuracy of the maximum power estimation is strongly dependent on the performance of the EKF estimation of $\alpha_{k|k}$. Nevertheless, this algorithm of MPPT for aging PEMFC can be applied in a multi-source system where the individual and overall power can be estimated, allowing to modulate the requested power to each sources (in particular for the most damaged).

V. CONCLUSION

The FTC of PEMFC system is a very young research subject which allows to eliminate or to limit diverse faults. The work proposed in this paper aims at taking into account the aging in the control loop. First of all, a time varying parameters multi-physical model of PEMFC in the EMR formalism is presented. The degradation which affects the electrochemical parameters is integrated in this model to take into account the aging.

A PCS is then developed by inversion of the EMR model where the not reasonable measures are replaced by estimators.

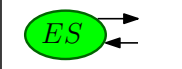
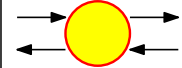
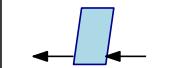
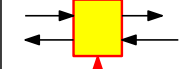
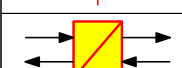
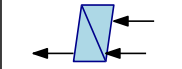
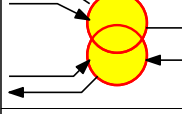
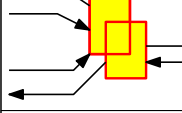
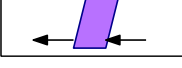
An EKF estimates the SoH in order to adjust the parameters of the control. Furthermore, a strategy of aging tolerant control for a given power reference is proposed. It allows the regulation of the power the PEMFC provides in spite of a performance degradation.

When the degradation is too important, the maximal power the PEMFC can provide becomes lower than the reference power. This motivated the development of an algorithm of MPPT by using the SoH estimated by the EKF. This algorithm is based on a descent of gradient.

These algorithms were not able to be experimentally validated but we can already imagine that their performances could be improved before implementing it on a real system. Indeed, the reference current has a direct impact on the degradation speed of the fuel cell and thus should be taken into account in the control. Improving the performances of the SoH estimation will allow to obtain better performances for the FTC. Moreover, it could be interesting to develop a multi-sources strategy to modulate the requested power to the most degraded sources in order to extend the availability of the system. Nevertheless, this paper puts the bases for future works.

APPENDIX

ELEMENTS OF THE EMR AND PCS FORMALISM

	Source of energy
	Multi physical domain converter
	Control block without controller
	Mono physical domain converter
	Element with energy accumulation
	Control block with controller
	Multi physical domain coupling device (energy distribution)
	Mono physical domain coupling device (energy distribution)
	Observer

REFERENCES

- [1] S. Vazquez, S. Lukic, E. Galvan, L. Franquelo, and J. Carrasco, "Energy storage systems for transport and grid applications," *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp. 3881–3895, 2010.
- [2] S.-D. Oh, K.-Y. Kim, S.-B. Oh, and H.-Y. Kwak, "Optimal operation of a 1-kw pemfc-based micro-chp system for residential applications," *Appl. Energy*, vol. 96, pp. 93–101, 2012.
- [3] U. D. of Energy, "The department of energy hydrogen and fuel cells program plan," U. D. of Energy, <http://www.hydrogen.energy.gov/roadmapsvision.html>, Tech. Rep., 2011.
- [4] M. Jouin, R. Gouriveau, D. Hissel, M. C. Pera, and N. Zerhouni, "Prognostics and health management of pemfc - state of the art and remaining challenges," *Int J Hydrogen Energy*, 2013.
- [5] D. Guilbert, A. Gaillard, A. NDiaye, and A. Djerdir, "Fault-tolerant control for pemfc and its dc/dc converter," *proc. of IYCE'15, Pisa, Italy*, 27-30 May, 2015.
- [6] V. Puig, D. Feroldi, M. Serra, J. Quevedo, and J. Riera, "Fault-tolerant mpc control of pem fuel cells," *proc. of IFAC'08, Seoul, Korea*, July 6-11,, 2008.
- [7] L. Xu, J. Li, M. Ouyang, J. Hua, and X. Li, "Active fault tolerance control system of fuel cell hybrid city bus," *Int J Hydrogen Energy*, vol. 35, pp. 12 510–12 520, 2010.
- [8] R. Mezzi, N. Steiner, M.-C. Pera, and D. Hissel, "Optimisation des conditions de fonctionnement en vue d'augmenter la durée de vie de la pemfc," in *Congrès National de la Recherche des IUT (CNRIUT2017)*, may 2017.
- [9] F. Barbir, *PEM fuel cells theory and practice*. Academic Press, 2012.
- [10] D. Hissel, M. C. Pera, A. Bouscayrol, and D. Chrenko, "Representation energetique macroscopique d'une pile a combustible," *Revue Internationale de Genie Electrique*, vol. 11, pp. 4–5, 2008.
- [11] M. Jouin, R. Gouriveau, D. Hissel, M.-C. Pera, and N. Zerhouni, "Degradations analysis and aging modeling for health assessment and prognostics of pemfc," *Reliab. Eng. Syst. Saf.*, vol. 148, pp. 78–95, April 2016.
- [12] W. Schmittinger and A. Vahidi, "A review of the main parameters influencing long-term performance and durability of pem fuel cells," *JPS*, vol. 19, pp. 291–312, 2008.
- [13] M. Bressel, M. Hilaret, D. Hissel, and B. O. Bouamama, "Remaining useful life prediction and uncertainty quantification of proton exchange membrane fuel cell under variable load," *IEEE Trans. Ind. Electron.*, vol. 63, no. 4, pp. 2569–2577, 2016.
- [14] A. Bouscayrol, X. Guillaud, J. P. Hautier, and P. Delarue, "Macromodeling for electro-mechanical conversions: application to electrical machine control (from the french: Macromodelisation pour les conversions electromecaniques : application a la commande des machines electriques)," *Revue Internationale de Genie Electrique*, vol. 3, pp. 257–282, 2000.
- [15] L. Boulon, D. Hissel, A. Bouscayrol, M.-C. Pera, and P. Delarue, "Maximal and practical control structure of a pem fuel cell system based on energetic macroscopic representation," *proc. Of FDFC'08*, p. 11p, 2008.
- [16] L. Boulon, D. Hissel, A. Bouscayrol, and M. Pera, "From modeling to control of a pem fuel cell using energetic macroscopic representation," *IEEE Trans. Ind. Electron.*, vol. 57, no. 6, pp. 1882–1891, June 2010.
- [17] M. Bressel, M. Hilaret, D. Hissel, and B. Ould-Bouamama, "Dynamical modeling of proton exchange membrane fuel cell and parameters identification," *proc. of FDFC'15, Toulouse, France*, 2015.
- [18] J. T. Pukrushpan, A. G. Stefanopoulou, , and H. Peng., *Control of fuel cell power systems*. Springer, 2005.
- [19] Y. Wankam, P. Sicard, and A. Bouscayrol, "Extension of energetic macroscopic representation to time-varying systems - application to winder tension control," *IEEE ISIE 2006, July 9-12, Montreal, Quebec, Canada*, 2006.
- [20] M. Grewal and A. Andrews, *Kalman filtering: Theory and Practice using Matlab*. John Wiley & Sons, 2008.
- [21] M. Blanke, M. Kinnaert, J. Lunze, and M. Staroswiecki, *Diagnosis and Fault-Tolerant Control*. Springer-Verlag Berlin Heidelberg, 2003.
- [22] F. Paz and M. Ordonez, "High-performance solar mppt using switching ripple identification based on a lock-in amplifier," *IEEE Trans. Ind. Electron.*, vol. 63, no. 6, pp. 3595–3604, June 2016.
- [23] M. Killi and S. Samanta, "Modified perturb and observe mppt algorithm for drift avoidance in photovoltaic systems," *IEEE Trans. Ind. Electron.*, vol. 62, no. 9, pp. 5549–5559, September 2015.