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Short communication

Design of control systems for portable PEM fuel cells ☆

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Abstract

The current evolution in the design of fuel cell systems, together with the considerable development of integrated control techniques in microprocessor systems allows the development of portable fuel cell applications in which optimized control of the fuel cells performance is possible. Control, in the strict sense, implies a thorough knowledge of both the static and dynamic behaviour of the system comprising the stack, manifold and the compressor that enables oxygen supply. The objective of this control, far from being simply to maintain the stack free from oxygen and hydrogen shortages, is to achieve the necessary values of these gases, minimizing compressor consumption, which is the cause of the greatest inefficiency of fuel cells. This objective is essential when fuel cell systems are involved in situations where the net power of the stack is reduced and any unnecessary consumption lowers the total power available to the user. The design of an efficient control system requires the following steps: (1) modeling of the stack, compressor and other pneumatic elements involved in the system. (2) Calculation of the control equations and simulation of the entire system (including control). (3) Emulation of the stack and other pneumatic elements and simulation utilizing the designed control system. (4) Physical realization of the control system and testing within the fuel cell system. The design of a control system for fuel cell systems is introduced to manage PEMFC stacks. The control system will guarantee the correct performance of the stack around its optimal operation point, in which the net power is maximized. This means that both, the air flow and the stack temperature are controlled to a correct value.

Keywords: PEMFC; Control; Fuel cell; Oxygen excess ratio

1. Introduction

The automatic control of PEM fuel cells is a process where the actuation on at least two families of variables: hydraulic (gas flows) and electric (electron flow). The main task that a control strategy must fulfill is to maintain the chemical kinetic of the redox reaction [1]:

$$\begin{aligned} &\text{Cathode}: \ \tfrac{1}{2}O_2\,(g) + H_2O + 2e^- \rightarrow 2OH^-\,(aq) \\ &\text{Anode}: \ H_2\,(g) + 2OH^-\,(aq) \rightarrow 2H_2O + 2e^- \end{aligned} \quad (1)$$

The load or electric impedance that is connected to the stack unbalances the electron equilibrium thus forcing the control systems to dynamically adapt the reactants quantities (oxygen and hydrogen). It is also necessary the use of ambient controller in order to ensure the optimum reaction conditions.

2. Control systems

The work that is presented implements an electronic controller that handles the entire system (Fig. 5). The controller system includes three control loops assigned to the control of oxygen flow, hydrogen flow and environment control (temperature). The oxygen flow is modified actuating on the air flow entering the cathode of the fuel cell stack (FCS). The hydrogen flow is also controlled through the hydrogen output. Finally, the temperature is kept within the limits that guarantee an optimum reaction performance actuating on a fan. In the case of hydrogen flow control, proportional regulation valves are used. These valves ensure a flow that is proportional to the pressure difference between the hydrogen storage unit and the stack anode input. This automatically solves the problem of the control of hydrogen flow ($W_{\text{anode, in}}$) when using a stack with closed anode

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Nomenclature

aq	aqueous
cp	compressor
I	current
P	pressure
st	stack
sFFB	static feed-forward/feed-back
V	voltage
W	gas flow

Greek symbols

δ	duty-cycle
λ_{O_2}	oxygen excess ratio

circuit. In this case, the hydrogen flow is determined by Eq. (2).

$$W_{\text{anode, in}} = K_1(K_2 P_{\text{storage}} - P_{\text{anode}}) \quad (2)$$

The electronic controller performs a feed-forward control of the compressor (air flow) and a proportional feedback for the temperature. The control inputs are the temperature and current signals. Two pulse width modulated (PWM) signals are the controllers outputs: fan control signal and compressor motor control signal. The PWM signals are generated using a 20 kHz carrier and a 12 V amplitude. The electronic controller is implemented using a digital signal processor (DSP) dsPIC30F6014. A Hall effect sensor enables the transduction of the current generated by the stack into a voltage signal that can be measured by the controller. A type K thermocouple is used to sense stack temperature. The user interface is done with a four-button keyboard and a 32 character alphanumeric display. An additional serial communications line enables the system to be monitored using a PC platform. The feed-forward controller calculates the value of the motor input voltage $v_{\text{cp}} = h(I_{\text{st}}; \lambda_{O_2})$, that provides a desired air flow needed to obtain the current drawn to the load I_{st}. The parameter λ_{O_2} establishes the oxygen excess ratio demanded to achieve the demanded net power P_{net}. In reference [4], it is shown that the compressor control voltage can be expressed as:

$$v_{\text{cp}} = h(I_{\text{st}}; \lambda_{O_2}) = \alpha(\lambda_{O_2}) I_{\text{st}} + \beta(\lambda_{O_2}) \quad (3)$$

The general scheme of the electronic control for the air flow and temperature is shown in Fig. 1. The design of the hydrogen flow electronic controller has been implemented assuming that the hydrogen flow will always be determined by the proportional pressure valve.

The oxygen flow control is achieved actuating on the output air flow of the compressor. The ideal air flows in order to comply with the stoichiometric conditions have been calculated following the study of the redox reactions that take place in the PEM stack [1,4]. The oxygen control strategy considers the current amplitude that is demanded by the electric load as an electron flow perturbation. The demanded current is measured and the perturbation is corrected using a feed-forward compensator loop (Fig. 1). The compensator control order is translated to an air flow at the output of a centrifuge compressor that is connected to the stack cathode.

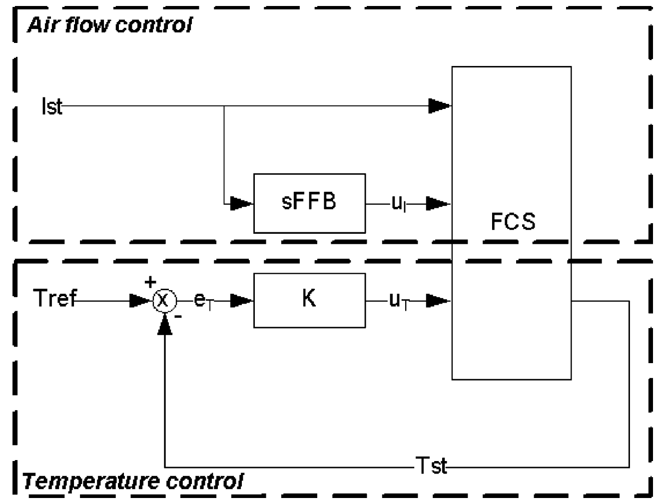

Fig. 1. General control scheme.

3. Temperature control

Every fuel cell stack presents an optimal working temperature at which the reaction occurs with an optimum efficiency. On the other hand, the reaction itself generates heat changing the stack temperature and, thus, forcing the control system to refrigerate it and bring it back to the optimum temperature point.

The fundamental control scheme that is used is based in the classical proportional stack temperature control [2]. The objective of this control is to maintain the stack as close as possible from the optimum temperature point T_{ref}. The process begins with the measure of the stack temperature T_{st}. The control error e_{T} is the input to the control law. The output of the control stage is a PWM signal which information component (modulating signal) responds to the proportional control process. The PWM signal is fed directly on the fan motor [3].

The processes that are performed for the temperature control are described in Fig. 2. The stack temperature $T_{\text{st}}(t)$, is measured at every sampling period k using a K type thermocouple conditioning devices that provides a temperature sample $T_i(k)$. This sample is processed with an averaging filter (Eq. (4)).

$$T(k) = \frac{1}{2}(T_i(k) + T(k-1)) \rightarrow F(z) = \frac{1}{2 - z^{-1}} \quad (4)$$

Using the averaging filter, the high frequency noise in the temperature measurements are reduced. The filtered temperature value, $T(k)$, is the real temperature stack temperature in the kth sampling period. This value is compared with the reference temperature T_{ref}. The difference between the actual temperature value and the reference value is the error signal e_{T}, which is the target of the control law. The actuator that is used is an axial fan that is driven with an electric DC motor. The air flow that the fan is able to impulse to the stack is proportional to the motor speed which is in turn dependent on the torque on the rotor. The torque is finally proportional to the voltage applied to the fan input. It

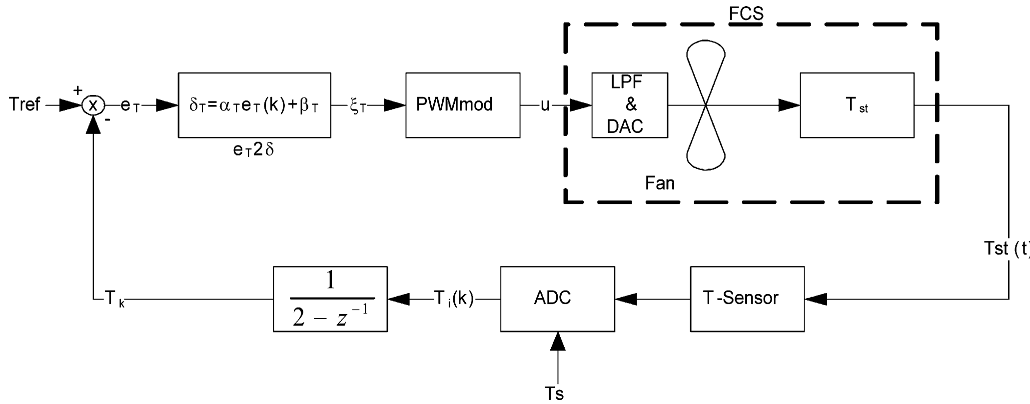

Fig. 2. Scheme of the temperature control process.

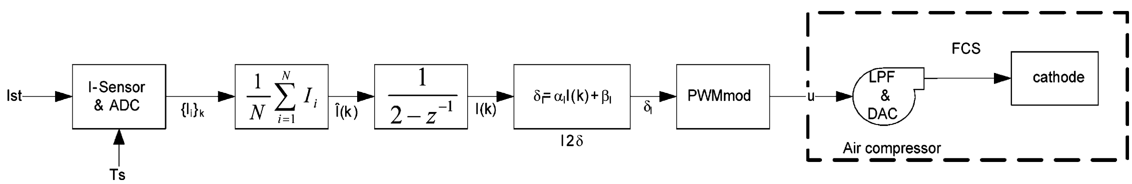

Fig. 3. Air flow control process scheme.

is necessary to adapt the signal to enable the fan control. This signal is a PWM applied to the fan power supply. The control law will calculate the duty-cycle, δ, that best regulates the fan speed, and thus, the air given to the radiator. From Eq. (5):

$$\delta_T = \alpha_T e_T + \beta_T \tag{5}$$

4. Air flow control

The reaction that makes possible the electric current generation in a fuel cell needs an appropriate gas oxygen supply. In reference [4] is demonstrated that the oxygen supply is directly proportional to the current that is drawn from the stack. The objective of the air flow control is to supply the stack with enough oxygen proportionally to the instantaneous current drown from the system. This will guarantee that the oxygen levels in the cathode enable the stack to operate in its optimum operation point.

The stack output current will be considered, in terms of the control structure, a perturbation to the system. A priori, the nature of the current demand is unknown since it depends on the load connected to the FCS. Moreover, in order to make more flexible the design of the control system, no supposition is made about the constitution of the load. Since there is no reference to follow (the load current is a stochastic variable) the control has the task of pre-compensating the air flow to the cathode as a function of the current demand trying to maintain a constant value of oxygen excess ration in the cathode. The pre-compensating or static feed-forward/feed-back, sFFB in Fig. 1, is in charge of actuating on the air supply to guarantee the oxygen supply.

4.1. Processes in the air flow control

The processes that take place in the air flow control can be summarized in three functional blocks: the first one is involved in the acquisition of the perturbation signal I_{st}. The second block calculates the control signal. Finally, the third control block deals with the control signal shaping. The measurement of the perturbation signal is a sensitive process. Due to its high sensitivity, a double filter scheme was chosen. At every sampling period, k, the arithmetic mean value is obtained from N consecutive samples from the current. The obtained mean value is used as the current at sampling instant k and is fed into the second filter, an average filter (Figs. 3 and 4).

From the mathematics point of view, in the kth sampling instant, N consecutive samples are taken from the current I_i. This process will take a period T_m which must be lower than the sampling period T_s. Once the samples are obtained $\{I_i\}k$, the sampling mean value is calculated $\hat{I}(k)$ for the time instant k.

$$\hat{I}(k) = \frac{1}{N}\sum_{i=1}^{N} I_i \bigg|_k \tag{6}$$

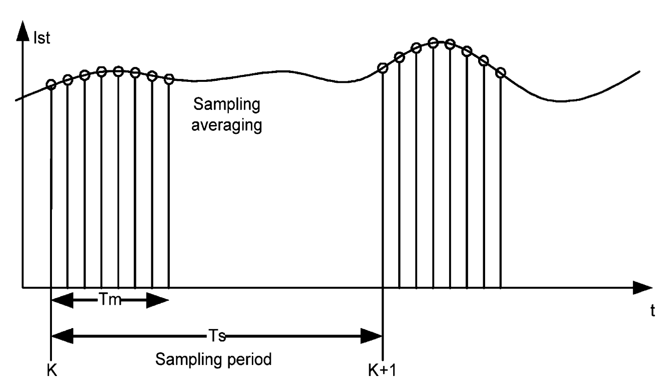

Fig. 4. Sampling average and time steps.

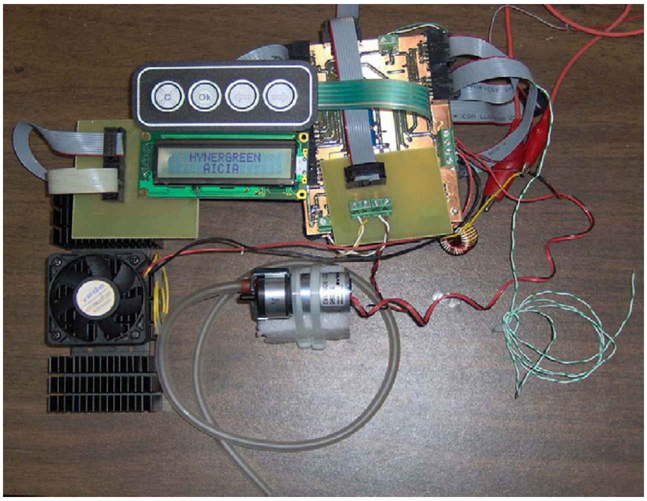

Fig. 5. Implementation of the controller with fan and compressor.

This sampling mean value $\hat{I}(k)$ will be used as an input to the averaging filter (Eq. (7)).

$$I(k) = \frac{1}{2}(\hat{I}(k) + I(k-1)) \rightarrow F(z) = \frac{1}{2 - z^{-1}} \tag{7}$$

This way, the system considers that in the time instant k the stack current value is $I(k)$ to which is applied the control law. As occurred with the fan, it is necessary to shape an appropriate control signal to this motor (compressor). The discussion about the compressor motor is analogous to the one about the fan motor. Once the sample is obtained, the duty-cycle for the PWM modulated control signal δ_I is calculated (Eq. (8)).

$$\delta_I = \alpha_I I(k) + \beta_I \tag{8}$$

That can be deduced [4] considering Eqs. (3) and (9):

$$v_{\text{cp}} = \frac{1}{T}\int_0^T v_{\text{PWM,cp}}(t)\,\mathrm{d}t = \delta V_d \tag{9}$$

The last phase in the control process chain of the air compressor consists in the shaping of the PWM signal that drives the compressor motor using a signal modulator and a buffer.

5. Conclusions

This paper has presented the methodology that is to be followed in order to achieve the control of a fuel cell system using a PEM stack. The control takes care of the system temperature values as well as the cathode air flow that is needed for an optimal performance reaching the highest efficiency in terms of net power generated by the stack, minimizing the power of auxiliary systems. In Fig. 5, a physical implementation of the controller is shown.

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