CONTROL STRATEGY FOR POLYMER ELECTROLYTE MEMBRANE FUEL CELL SYSTEMS

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Abstract: The polymer electrolyte membrane (PEM) fuel cell is an ideal prime mover to replace the internal combustion engine, but there are two interrelated control problems that must be resolved before it can be accepted widely for automotive power trains. One is the matching of the fuel cell output power to the power required by the application; this involves control over the fuel cell. The second is the matching of the voltage and/or the current to the application requirements which involves the control of a power conditioning unit (PCU). Rapid variations of load that a fuel cell cannot meet because of its inherently low transient response are dealt with by means of an energy storage device (ESD).

The response of fuel cells to transient variations in demand tends to be poor because it depends on the regulation of pressure and flow rates of air and hydrogen. In addition, it is necessary also to manage heat and water produced as a result of the electrochemical reaction. This paper deals with the complex problems of controlling a fuel cell system to deal with the steady state as well as transient variations of load and/or speed and describes a control strategy to deal with these issues.

Keywords: PEM, fuel cell system, control strategy, transient response, power conditioning.

1. INTRODUCTION

Fuel cells are energy devices that directly convert the chemical energy of the fuel (commonly hydrogen gas) to electrical energy. The absence of combustion and moving parts in the process of energy conversion would help energy conservation due to increased efficiency, protection of the environment being pollution free and have noiseless operation. As any engineering system, the fuel cell can be described precisely by a group of variables. These variables may be divided into three categories: geometrical variables, operational variables and performance variables. The geometrical variables of the fuel cell specify machine design in order to produce manufacturing drawings. The operational variables, or operating conditions, include pressures, humidity and flow rates of the reactants (hydrogen and oxygen), the temperature of the fuel cell and the water content in the membrane. The performance variables include the output power (the product of voltage and current), the efficiency and, for transient conditions, the response time.

Geometrical variables of a fuel cell are chosen at the design stage on the basis of analysis to achieve the specified design performance. For control system design, geometrical variables are fixed, and the operational variables are controlled to optimise the performance. In this study, the interest is confined to controlling the operational variables in order to optimise the fuel cell output and response to rapid changes in demand.

2. FUEL CELL THEORY

Literature on all important aspects of the fuel cell is generally confidential because of its commercial significance; nevertheless there are many purely

theoretical, semi-empirical and empirical models available to describe the fuel cell operation. For the purpose of control system design, it would be sufficient to use the simplest model that describes the necessary phenomena in the fuel cell should be controlled. A review of the available models showed that semi-empirical models are simple, easier to implement in simulations, reduce simulation time and are sufficient for control studies and design. A semi-empirical model proposed by Amphlett et al. (1995) has been used in this study for its simplicity and ease of implementation. The relevant theory of this model is given below:

For a reversible fuel cell, the ideal open circuit voltage is given in the following equation, developed in Ref.(Abul-Hawa, 2005):

$$E = 1.229 - 0.85 \times 10^{-3}(T - 298.15)$$
$$+ 4.3085 \times 10^{-5} \times T \left\{ \ln P_{H_2} + \frac{1}{2} \ln P_{O_2} \right\} \quad (1)$$

In a real case, there will be losses of energy due to several causes. The main sources of losses are given below:

Activation losses: These losses occur at the anode as well as at the cathode. They are due to the energy absorbed to push forward the reaction. The equation for these losses is as follows:

$$V_{act} = -\left\{ \zeta_1 + \zeta_2.T + \zeta_3.T\left[\ln\left(c_{O_2}\right)\right] + \zeta_4.T\left[\ln(I)\right] \right\} \quad (2)$$

where c_{O_2} is the concentration of dissolved oxygen in the electrolyte in (mol/cm^3) and ζ's are empirical constants which may vary from one fuel cell to another depending on the geometrical design and the materials used in the construction of the fuel cell. Amphlett's values for ζ's are:

$\zeta_1 = -0.944$ V, $\qquad \zeta_2 = 3.54 \times 10^{-3}$ V/K,
$\zeta_3 = 7.8 \times 10^{-5}$ V/K, $\qquad \zeta_4 = -1.96 \times 10^{-4}$ V/K.

Ohmic losses: These losses, as the name implies are due to internal resistance of the fuel cell components which results from the flow of protons and electrons. Ohmic losses are of two categories: electronic and protonic; they are given by the following equation:

$$V_{ohmic} = I.r$$
$$= I.(r_{electron} + r_{proton}) \quad (3)$$

The value of the electronic resistance is usually found experimentally because it is difficult to determine it analytically due to the fact that the electrons follow different paths in different materials. However, the value of the electronic resistance does not change significantly from 25°C to 90°C, the usual range of operating temperature in PEM fuel cells. Therefore, the use of a constant value for that range would be justified.

The protonic or ionic resistance is the resistance of the electrolyte to the flow of protons. Its value is estimated by using Mann's model (Mann et al., 2000) and is given below:

$$r_{proton} = \frac{r_M.l}{A} \quad (4)$$

where l is the membrane thickness (cm), A is the membrane active area (cm^2) and r_M is the membrane specific resistivity (ohm.cm).
The value of the protonic resistance for a given material of the membrane varies significantly with the temperature of the membrane and its water content. The value of r_M can be found from Mann's equation given below:

$$r_M = \frac{181.6\left[1 + 0.03\left(\frac{I}{A}\right) + 0.062\left(\frac{T}{303}\right)^2 \cdot \left(\frac{I}{A}\right)^{2.5}\right]}{\left[\lambda - 0.634 - 3.\left(\frac{I}{A}\right)\right].\exp\left(4.18\left[\frac{T-303}{T}\right]\right)} \quad (5)$$

where:

$$\lambda = \begin{cases} 0.043 + 17.81a_{H_2O} \\ \quad -39.85a_{H_2O}^{\;2} + 36.0a_{H_2O}^3 & \text{for } 0 < a_{H_2O} \leq 1 \\ 14 + 1.4(a_{H_2O} - 1) & \text{for } 1 \leq a_{H_2O} \leq 3 \end{cases} \quad (6)$$

where a_{H_2O} is the water activity in the membrane and equals (C_wRT/P^{sat}), C_w is the molar concentration of water in the electrolyte membrane

Concentration losses: These losses depend mainly on the physical limitation of the geometrical design of the flow channels, diffusion characteristics of other components such as the gas diffusion layer and the electrodes, the flow rate of the reactants, etc. Several models have been used by researchers to take account of the concentration losses (Larminie and Dicks, 2000; Pukrushpan, 2003) and all have been claimed to work satisfactorily. Therefore, the choice of a model for a particular application is a matter of personal preference. The authors of this paper have used the model of Larminie and Dicks (2000) and the equation for this model is given below:

$$V_{conc} = -\frac{RT}{2F}\ln\left(1 - \frac{i}{i_L}\right) \quad (7)$$

where i_L is the limiting current which may be found experimentally.

It should be noted that Amphlett's analysis considered an over simplified model of the concentration losses, hence, the sharp voltage drop at high current densities was not taken care of in comparison with Larminie's model as shown in Fig. 1.
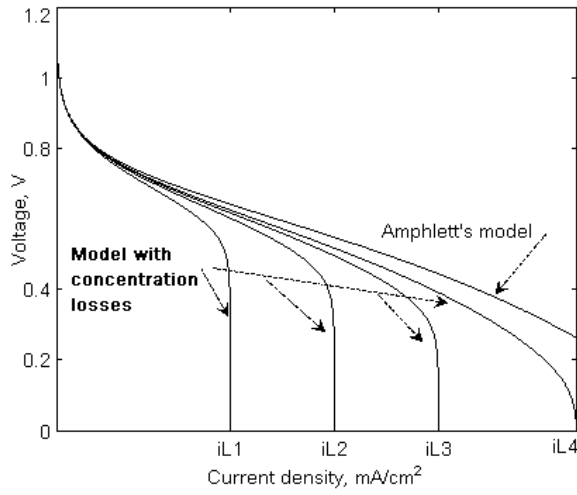
Fig. 1. Typical fuel cell polarization curves at $T = 80°C$, $\lambda = 14$, with different supplied mass flow rates.

Based on this analysis, the fuel cell output voltage, taking account of all three losses, is given by:

$$V_{fc} = E - V_{act} - V_{ohmic} - V_{conc} \quad (8)$$

And the efficiency is given by:

$$\eta_{fc} = \frac{V_{fc}.I}{\text{Calorific value (LHV) x } \dot{m}_{H_2}} \times 100\%$$
$$= \frac{V_{fc}}{1.25} \times 100\% \quad (9)$$

where $\dot{m}_{H_2}$ is mass rate of fuel consumption. Equation (9) shows that the efficiency is a function of the fuel cell voltage.

3. THE FUEL CELL CONTROL REQUIREMENTS

For steady state operation, the fuel cell control would be required to monitor the following variables:

(1) Temperature: the optimum operating temperature for PEM fuel cells is approximately 80°C. This temperature can be controlled using a cooling fluid, such as water, flowing through the cooling plates of the fuel cell. The equation relating the amount of heat produced as a function of the output electrical power is given below:

$$\dot{Q} = \frac{(1-\eta_{fc}) \times I.V_{fc}}{\eta_{fc}}$$
$$= \left(\frac{1}{\eta_{fc}} - 1\right) \times I.V_{fc} \quad (10)$$

Substituting Eq. (9) into Eq. (10) yields:

$$\dot{Q} = \left(\frac{1.25}{V_{fc}} - 1\right) \times I.V_{fc} \quad (11)$$

(2)Pressure: the pressure difference across the membrane should be kept to a minimum, to prevent reactants cross over, and membrane damage, by adjusting the pressure upstream or downstream of the electrodes to satisfy Eqs. (1) to (8).

(3) Water content of the membrane: This can be controlled by humidifying the gas streams of the reactants. The water content in the membrane is not uniform; at the anode it is less than that at the cathode. This is due to the fact that protons drag some water molecules as they move to the cathode. Back-diffusion on the other hand balances this phenomenon. During transients, the electro-osmotic drag takes effect immediately, therefore, drying out the anode side of the membrane until back-diffusion starts to take effect. The estimated time constant for reaching the steady-state of membrane water content depends on the amount of change in current and the final value of the current (Wang and Wang, 2005; Wang and Wang, 2006). Reported results for partially humidified reactants are 6 s for a step change in current density from 0.1 to 0.8 A/cm². The rate of water produced by the reaction at the cathode is given by:

$$\dot{m}_{H_2O} = 18 \times \frac{I}{2.F} \quad \text{g/s} \quad (12)$$

(4) Flow rate of the reactants: This should be controlled according to the current drawn from the fuel cell as shown by the equations below:

$$\dot{m}_{H_2,\text{used}} = 2.016 \times \frac{I}{2.F} \quad \text{g/s} \quad (13)$$

$$\dot{m}_{O_2,\text{used}} = 32 \times \frac{I}{4F} \quad \text{g/s} \quad (14)$$

4. CONTROL REQUIREMENTS FOR FUEL CELL SYSTEM (TRANSIENT OPERATION)

The fuel cell system includes the following components:
  i.   The fuel cell.
  ii.   The energy storage device (ESD).
  iii. The power conditioning unit (PCU).

Fuel cell. For transient operation, the mass flow rate of the reactants is usually greater than that consumed in the reaction to prevent the fuel cell starvation, or short circuit (due to concentration losses), during sudden changes in current demand. The term commonly used in this regard is called the utilisation factor and is defined as the ratio (fuel used/fuel supplied), i.e.:

$$\text{Utilization factor} = \frac{\dot{m}_{H_2,\text{used}}}{\dot{m}_{H_2,\text{supplied}}} \quad (15)$$

The value of the fuel utilization factor depends on the transient behaviour of the application, and the response time of the flow of the reactants through the flow channels and across gas diffusion layers. For large or fast changes in the demand, a smaller utilization factor is needed than that for small or slow

changes. The geometrical design of the fuel cell, properties of the membrane and the porosity of the gas diffusion layer impose a limit on the current that cannot be exceeded even if the flow of reactants was increased. This is due to the fact that when fuel utilization factor is 1, any further increase in the current will cause a sharp drop in voltage due to concentration losses.

The maximum (limiting) current that can be withdrawn from a fuel cell depends on two factors:

a. Geometrical design of the fuel cell: specifically, the porosity of the electrodes or the gas diffusion layer (GDL). Increasing the porosity of the GDL, increases the amount of gas that can flow through it, but on the other hand, this would increase the resistance of the GDL to electrons. The flow of hydrogen in this case is assumed to meet the reaction rate according to Eq. (13).

b. The supplied mass flow rate of hydrogen (or oxygen), assuming the porosity of the GDL allows that flow rate.

In Fig. 2, i_{L4} is the limiting current due to porosity limit, while i_{L1}, i_{L2} and i_{L3} are limiting currents due to insufficient mass flow rate of hydrogen. If operating the load at a certain point, such as (1) as shown in Fig. 2, an increase in the supplied mass flow rate of hydrogen and/or oxygen would change the operating point to (2).
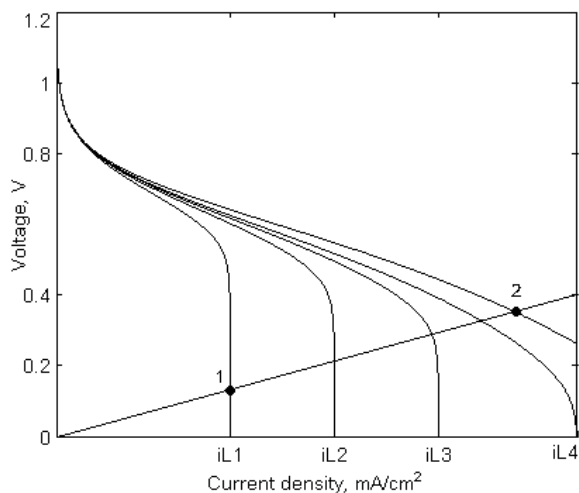

Fig. 2. Operating point changes with mass flow rate of the reactants.

Finding the maximum current that can be taken from a fuel cell under certain operating conditions (flow rate) is necessary in applications where there are load changes. Figure 3 shows the importance of the chosen supplied mass flow rate of hydrogen (or oxygen) when the load changes to a smaller resistance (the straight line with the smaller slope).

In Fig. 3, consider the initial operating point is at point (1). The change in the load moves the operating point to (2a), (2b), (2c) or (2d) according to the mass flow rate of hydrogen (or oxygen) that was supplied during operating at point (1). It is clearly seen that point (2a) is the least efficient operating point, with high losses (concentration losses). When there is a sudden change in the load, the fuel supply control

system will not be able to change the mass flow rate of hydrogen (or oxygen) from point (2a) to point (2d) because the time needed to change the mass flow rate of the reactants is greater than the time needed for the fuel cell to respond to load changes, see Table 1. To ensure a better response to sudden changes in the load, and to reduce the size of the energy storage device (ESD), discussed later, a small fuel utilization factor (U_f) should be used. On the other hand, this would mean more hydrogen not being used in the reaction.
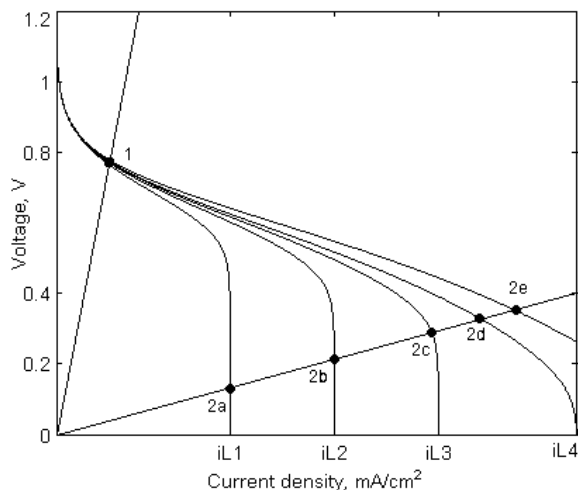

Fig. 3. Operating points due to a sudden load change at different mass flow rates of reactants.

There should be a compromise between the fuel utilization factor and the size of the energy storage device that would reduce the amount of hydrogen used.

In automotive applications, two main strategies for controlling the fuel flow in response to a change in demand are found in the literature (Hauer *et al.*, 2000; Pukrushpan, 2003); one controls the flow according to the load demand, or the current that is being drawn from the fuel cell, while in the second strategy, the drive command, represented by the pedal position, controls both the load and the fuel flow rate.

Energy storage device (ESD). In order to use fuel cells in automotive applications, the response of the fuel cell system to changes in demand must be comparable to that of the internal combustion engine. However, the response of the fuel cell to transient changes in power demand tends to be poor because it depends on management of heat and water content in the membrane, regulation of pressure and flow rate of the reactants. Therefore, an energy storage device, e.g. battery or capacitor, is needed to supply the load with the required power during transients until the fuel cell is able to produce that required power. Estimated time constants reported in Ref. (Pukrushpan, 2003; Wang and Wang, 2005) for significant phenomena in the fuel cell are shown in Table 1. Gas transport includes the flow of gases through flow channels and the gas diffusion layer. These time-constants represent the time needed to reach steady-state after a transient change. According to these time constants and the maximum change of

power required by the load, the size of the ESD can be found.

Table 1 Time constants for some phenomena in the fuel cell

Phenomenon	Scale of time constants
Membrane hydration	10 s
Gas transport	0.01 – 0.1 s
Double layer discharge	0.1 µs
Cell temperature	100 s

Power conditioning unit (PCU). The function of the PCU is to match the fuel cell output with the load demand. The operating point of the fuel cell on the polarization curve depends on the load connected to the fuel cell. Consequently, there will be a single operating point for a certain load. Due to this limitation, a power conditioning unit is required to be connected between the load and the fuel cell. Two examples are presented to demonstrate the matching strategy of the PCU as shown in Fig. 4. The chosen operating point of the load is at 1, which corresponds to the power at 2 on the power curve for the load. Therefore, assuming no losses in the PCU, the fuel cell has to produce the same power as required by the load, which is at point 3. This corresponds to operating point 4 on the polarization curve.
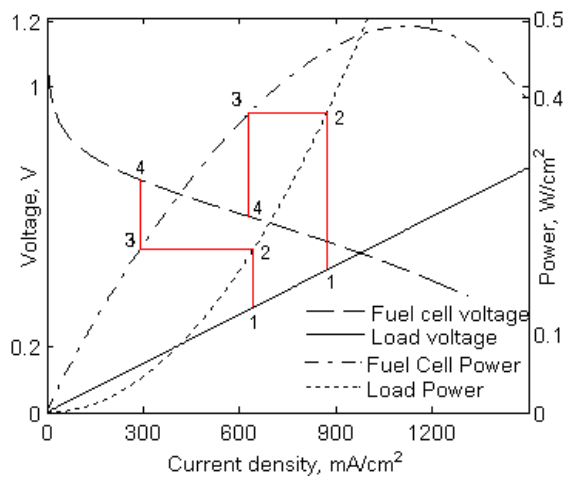

Fig. 4. Matching of load operating point with fuel cell operating point

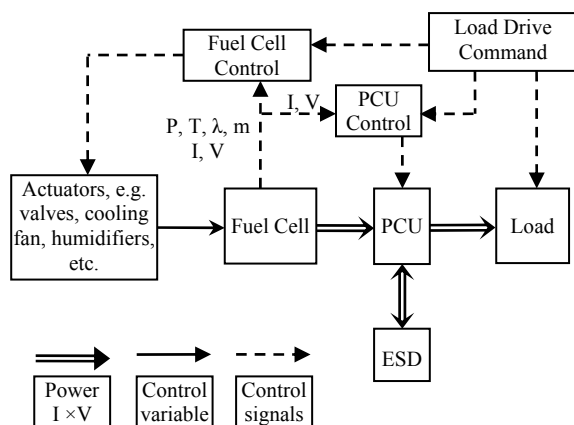A block diagram of the proposed control system is shown in Fig 5.

Fig. 5. Fuel cell system control diagram.

5. SENSITIVITY ANALYSIS

Sensitivity analysis has been used to find the significant control variables that would change the performance variables in the desired manner. In addition, sensitivity analysis is used to draw the specifications such as the resolution and the error range of the measuring devices as an aid for the experimental stage.

Using the models and the corresponding equations relating the performance to the operating variables, three curves are given below to show the effect of a change in pressure, temperature and water content of the membrane on the maximum power output of the fuel cell. All curves were plotted by assuming the following operating conditions:
$P_{anode} = P_{cathode} = 1$ bar; $T = 80$ °C; and water content of the membrane, $\lambda = 14$.

It can be seen from Fig. 6 that the water content in the membrane has the largest effect on the maximum output power; hence, this measurement should be made with great precision. The next important measurements are the temperature and the pressure.
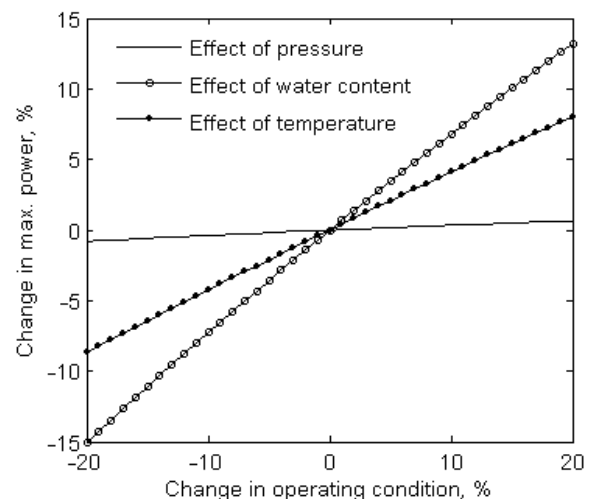

Fig. 6. Effect of percentage change in temperature, pressure and λ on the maximum power

The temperature equals 80°C for a zero percentage change in temperature. If the temperature varies from 80°C to 64°C (i.e. −20%), the output power will change by about −9%

6. CONCLUDING REMARKS

i.   The fuel cell is the future prime mover that can help to minimize pollution and improve energy conservation.
ii. Due to its inherent characteristics, the fuel cell requires control strategies that are different from those normally used for other types of prime movers.
iii. With respect to the transient response, the control system for the fuel cell prime mover should include energy storage device, which is an additional component for the control system to deal with.

iv. In order to maintain the operation of the fuel cell at optimum condition, it is necessary to use additional components, i.e. a power conditioning unit.

v. These issues have been discussed in the paper. In view of the present world wide concern for energy conservation and protection of the environment, the paper is considered to be timely as well as important.

NOMENCLATURE

A	The membrane active area, cm^2.
a_i	Activity of species i.
C_w	The molar concentration of water in the electrolyte membrane, $mol.cm^{-3}$.
c_{O_2}	The concentration of dissolved oxygen in the electrolyte, $mol.cm^{-3}$.
E	The ideal open circuit voltage of the fuel cell, V.
F	Faraday's constant (96485), $C.mol^{-1}$.
i	The fuel cell current density, $mA.cm^{-2}$.
I	The fuel cell current; the current through the external circuit, A.
i_L	Maximum fuel cell current, $mA.cm^{-2}$.
l	The membrane thickness, cm.
LHV	The Lower Heating Value of a fuel, $kJ.g^{-1}$.
$\dot{m}_i$	Mass flow rate of species i, $g.s^{-1}$.
P_i	Partial pressure of species i, atm.
P^{sat}	Saturation pressure of vapour, atm.
$\dot{Q}$	Rate of heat produced by the fuel cell, Watt.
r	The total resistance of the fuel cell, ohm.
R	Universal gas constant (8.314), $J.K^{-1}.mol^{-1}$.
$r_{electron}$	The electron resistance, ohm.
r_M	The membrane specific resistivity, ohm.cm.
r_{proton}	The protonic resistance, ohm.
T	Absolute temperature, K.
V_{act}	Activation loss, V.
V_{conc}	Concentration loss, V.
V_{fc}	Fuel cell voltage, V.
V_{ohmic}	Ohmic loss, V.
ζ_i	Empirical parameters for calculating V_{act}
η_{fc}	The efficiency of a single fuel cell.
λ	Water content of the membrane (H_2O/SO_3^{-1})

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