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ScienceDirect
Journal of Power Sources 158 (2006) 1317–1323
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Short communication

Performance of diagonal control structures at different operating conditions for polymer electrolyte membrane fuel cells

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Received 5 August 2005; received in revised form 29 September 2005; accepted 26 October 2005
Available online 10 January 2006

Abstract

This work is focused on the selection of operating conditions in polymer electrolyte membrane fuel cells. It analyses efficiency and controllability aspects, which change from one operating point to another. Specifically, several operating points that deliver the same amount of net power are compared, and the comparison is done at different net power levels. The study is based on a complex non-linear model, which has been linearised at the selected operating points. Different linear analysis tools are applied to the linear models and results show important controllability differences between operating points. The performance of diagonal control structures with PI controllers at different operating points is also studied. A method for the tuning of the controllers is proposed and applied. The behaviour of the controlled system is simulated with the non-linear model. Conclusions indicate a possible trade-off between controllability and optimisation of hydrogen consumption.

Keywords: PEMFC; Diagonal control; PI controllers; Operating conditions; Linear analysis; Efficiency

1. Introduction

Compared to other types of fuel cells, polymer electrolyte membrane fuel cells (PEMFC) have many advantages that make them suitable for a large number of applications. Some of these advantages are high power density, compactness, lightweight, low-operating temperature, solid electrolyte, long cell and stack life, low corrosion and high efficiencies [1]. PEMFC are regarded as ideally suited for transportation applications. However, important difficulties remain unsolved and a lot of research is being done in order to make the technology ready to implementation and commercialisation [2].

Advantages of different operating conditions for PEMFC have been described in the literature [3]. However, a comparison of the system controllability at different operating points is not found. A PEMFC can deliver the same amount of net power at different operating conditions. In order to chose the appropriate operating point, control aspects have to be taken into account, as well as efficiency aspects. Some works address the control of PEMFC [4–6], but only the efficiency is considered to determine the operating conditions. The objective of this work is to compare the controllability of a PEMFC operated at different operating conditions. The performance of the control system is evaluated implementing a diagonal structure with PI controllers in the control loops.

2. The model

In their study of the PEMFC flow dynamics, Pukrushpan et al. presented a control oriented model for an automotive application which has been the base for the model used in this work [4,7]. The transient phenomena captured in the model include the flow and inertia dynamics of the compressor, the manifold filling dynamics (both anode and cathode), reactant partial pressures and membrane humidity. On the other hand, the model neglects the extremely fast electrochemical and electrical dynamics, and temperature is treated as a constant parameter because its slow behaviour (time constant of 10^2 s) allows it to be regulated by its own controller. A constant cell temperature of 80 °C is assumed.

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doi:10.1016/j.jpowsour.2005.10.092

Nomenclature

I_{st}	stack current (A)
K_c	proportional constant of the PI controller
p_{ca}	cathode pressure (bar)
P_{net}	net power (W)
T_i	time constant of the PI controller (s)
v_{st}	stack voltage (V)
v_{cm}	compressor voltage (V)
$W_{an,in}$	anode inlet mass flow rate (kg s^{-1})

Greek letters

Δ_p	anode–cathode pressure difference (bar)
λ_{O_2}	oxygen stoichiometry

Mass and energy balance are the basic laws for the different volumes being modelled. Constant properties are assumed in all volumes. Flowrates from one volume to another are calculated as a function of the upstream and downstream pressures. Ideal gases are assumed.

Membrane hydration captures the effect of water transport across the membrane. Water transport is modelled through drag and diffusion effects. Both water content and mass flow are assumed to be uniform over the surface area of the membrane. This surface is of 280 cm^2.

Stack voltage is calculated as a function of stack current, cathode pressure, reactant partial pressures, fuel cell temperature, and membrane water content. Identical behaviour of each cell is assumed and the stack voltage is calculated as the individual cell voltage per the number of cells, in this case 381.

The air entering the cathode is impelled by a compressor the model of which consists of a dynamic part and a static part read from an experimental compressor map. The modelled compressor has the angular velocity limited to 100 krpm, the exit flow limited to 0.1 kg s^{-1}, and the pressure ratio limited to 4. The power consumed by the compressor is the only parasitic power taken into account. The net power, P_{net}, is therefore calculated as the electric power given by the fuel cell minus the power consumed by the compressor. Cooler and humidifier are also included. It is assumed that a static humidifier supplies the air with the desired relative humidity before entering the stack.

At the anode side, entering hydrogen comes from a pressurised tank and the hydrogen flow is assumed to be a manipulated input variable.

Only one modification is introduced, which is the existence of an anode exit flow. This exit is necessary to control the hydrogen pressure along the flow channels and to improve the power demand transient responses [2].

Some of the indexes used for the linear analysis depend on the model scaling. One of the controlled outputs is the difference of pressure between anode and cathode, Δ_p. It has been scaled with a variation of 0.1 bar. To scale the rest of the input and output variables, a maximum variation of 10% has been assumed. Hence, the scaled variables are the non-scaled increments divided by the maximum increments.

SIMULINK linearisation tools have been used to obtain the state space matrices of the system at the studied operating points.

3. Operating conditions

This work is based on the analysis of a set of selected operating points. Their operating conditions are summarised in Table 1. In Fig. 1, the operating points are located on the curves of net power versus stoichiometry at different current values. In a fuel cell, a certain amount of net power can be obtained at different currents. OP1 to OP5 deliver the same net power, P_{net} = 37,400 W, and the same happens with OP6 to OP8, with P_{net} = 30,000 W. OP1 and OP7 have the minimum amount of current for which P_{net} of 37,400 and 30,000 W can be, respectively, obtained. For example, it is not possible to obtain 37,400 W of net power with a current lower than 175 A, at any pressure or stoichiometry. These operating points are specially interesting because minimum current corresponds to the minimum hydrogen consumption if the hydrogen that does not react is recycled. Looking at the different curves of Fig. 1, it can be seen that for small λ_{O_2} P_{net} increases when λ_{O_2} increases, but this trend changes from a certain λ_{O_2} value. This is because when λ_{O_2} is high, to increase λ_{O_2} requires a compressor power increase larger than the electric power increase obtained from the fuel

Table 1
Studied operating points

	P_{net} (W)	I_{st} (A)	λ_{O_2}	v_{st} (V)	p_{ca} (bar)	Efficiency (%)	v_{cm} (V)
OP1	37390	175	2.15	242.7	1.99	42.5	158
OP2		187	1.60	217.8	1.78	40.7	135
OP3			3.20	261.2	2.56	37.4	217
OP4		200	1.41	201.8	1.73	38.3	130
OP5		280	1.29	149.7	1.89	27.3	151
OP6	30000	134	2.37	254.2	1.86	44.9	142
OP7		150	1.25	209.5	1.49	41.4	100
OP8			3.89	273.94	2.55	36.6	214.0

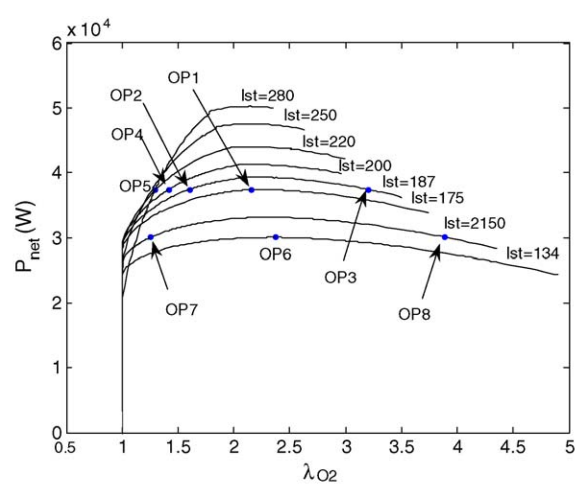

Fig. 1. Different operating points.