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Power Control for Efficient Operation of a PEM Fuel Cell System by Nonlinear Model Predictive Control

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Abstract: Efficiency of polymer electrolyte membrane (PEM) fuel cells depends directly on anode and cathode gas pressures, and stack temperature. For an efficient chemical reaction and a safe operation for both stationary and dynamic loads all values must fall within specific ranges. This paper deals with real-time nonlinear model predictive control (NMPC) of electrical power for a PEM fuel cell system. The NMPC is split into three nonlinear optimization problems to calculate the optimal stack current and the supply of anode and cathode with hydrogen and oxygen. For real-time application the predictive control algorithm is matched to the sampling time of the system. This NMPC handles all kinds of dynamic load changes, while maximizing power efficiency without a steady state error. Modeling of relevant anode and cathode site fuel cell peripherals is shown. Experimental results on a test bench with a 4.4kW PEM fuel cell are presented.

Keywords: fuel cell, identification, nonlinear model predictive control

1. INTRODUCTION

PEM fuel cell (FC) systems convert chemical energy from hydrogen into electrical power via a reaction with oxygen from the ambient air. The reaction also produces heat, water and oxygen depleted air. The typical use of PEMFC is in producing electrical power for vehicles or in combined heat and power systems in residential buildings. Research in the last few years has shown the possibility for use in autonomous robots, aircrafts , and in rural landscapes. However, regardless of the application, particular conditions of operation influence the FC power and have to be observed. For efficient working, special ranges for stack temperature T_{stack}, partial anode pressure p_{AN} and partial cathode pressure p_{CA}, and excess ratio are necessary. All parameters have more or less influence on the efficiency of the stack and the stack voltage.

$$U = f\left(I, p_{\text{O2}}, p_{\text{AN}}, T_{\text{stack}}\right) \tag{1}$$

where p_{O2} is the partial cathode oxygen pressure. The active power of a FC follows the ohmic law and the efficiency is dependent to the shown parameters in (1). In this case, the definition of a high efficiency of a FC is a high output of electrical energy due to chemical reaction.

$$4\text{H}^{+} + \text{O}_2 + 4\text{e}^{-} = 2\text{H}_2\text{O} \tag{2}$$

The aim is the setting of the input variables for fast power reference following during stationary and dynamic loads and, especially, in stationary case without steady state error. The main inputs are the stack current I, the exhaust valve position reference of the cathode site and mass flow rate reference of the anode site. The inlet valve reference of cathode site depends directly on the active current, the following consumption, and excess ratio. The exhaust valve of the anode has no influence in this scenario because a recirculation operation mode is realized. The inlet cooling temperature and the mass flow rate reference of the cooling pump are controlled by separate low-level controllers in this case. This stems from the chemical reaction rate, which is much faster than the relatively slow transient heat behavior. All settings for partial pressures and temperatures depend on the active stack current. The focus of safe operation is on the partial pressure of anode and cathode and on the fuel supply to the hydrogen and air sites. Two nonlinear optimization problems are resulting. For operation without the risk of starvation, the hydrogen and air supply have to be observed. Modeling and control strategies in an explicit way for prevention of starvation on the cathode site in connection with controlling the oxygen excess ratio have already been considered in the last few years, Arce et al (2007), Danzer et al (2008), Danzer et al (2009), Pukrushpan et al (2004), Vahidi et al (2006). Going along with the prevention of oxygen starvation, strategies for load or current management in use with fuel cells are shown in Vahidi et al (2006) and Sun and Kolmanovsky (2004). But for an efficient and exact operation over complete ranges of power, the focus has to be on all the dependent relationships, those between partial pressures, power and power effectiveness. The third nonlinear optimization problem is shown. The control strategy has to deal with the flow phenomena inside the fuel cell system, the nonlinear characteristic of the cathode exhaust valve, the nonlinear relationship between partial pressures and power, and the limitations of the stack current gradient. A nonlinear model predictive control (NMPC), split into three parts, respects all constraints and sets the FC power to set point with the focus of power efficient operation.

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The system model is described in section II. The control structure with NMPC is presented in section III. The fuel cell stack, which is used as the test device, and experimental results are presented in section IV.

2. FUEL CELL SYSTEM AND MOLDING

This section discusses the *modeling* of the *fuel cell system* and the test bench. The model is based on the physical relationships between the components and focuses on the pressure, transient mass flows between all components and the relationship between stack voltage, partial pressures and stack temperature. The result of the modeling is a nonlinear model containing all states of mass flow rates, partial pressures, temperatures and stack voltages. Table I. shows the description of (3).

$$\begin{aligned} \underline{x} = & \begin{bmatrix} I & U & W_{\mathrm{CA}} & p_{\mathrm{CA}} & h & \dots \\ \dots & W_{\mathrm{AN}} & p_{\mathrm{AN}} & T_{\mathrm{stack}} & T_{\mathrm{cool,in}} & T_{\mathrm{cool,out}} \end{bmatrix}^{\mathrm{T}} \\ \underline{u} = & \begin{bmatrix} I & u_{\mathrm{AN,MFC}} & h_{\mathrm{d}} \end{bmatrix}^{\mathrm{T}} \\ y = & P \end{aligned} \tag{3}$$

Table 1. States and Inputs

W_{CA}	mass flow rate in cathode volume	T_{stack}	stack core temperature
p_{CA}	pressure in cathode site	$T_{\mathrm{cool,in}}$	FC stack inlet temperature
h	exhaust valve position (estimated)	$T_{\mathrm{cool,out}}$	FC stack outlet temperature
W_{AN}	mass flow rate in anode volume	$u_{\mathrm{AN,MFC}}$	anode mass flow rate reference
p_{AN}	pressure in anode site	h_{d}	exhaust valve position reference

Fig. 1 shows the schematic of the used fuel cell system configuration with all relevant peripheral devices for the experiments in this paper.

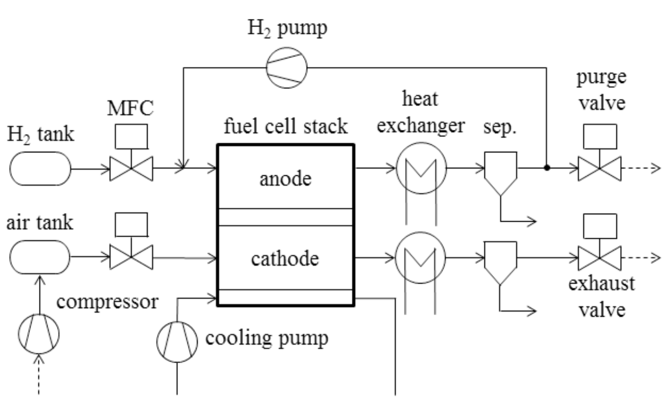

Fig. 1. Schematic of the fuel cell system comprising compressor, H_2 tank, air tank, mass flow controllers (MFC), fuel cell stack, exhaust heat exchanger, water separation (sep.), H_2 pump (circulation), purge valve and exhaust valve

The model is split into three parts to solve the nonlinear optimization problem. The models for the cathode site and the FC voltage are parts of (3b). The model of the anode site is reduced to a time discrete second order time behavior in state space model.

Stack voltage depends on stack current, anode and cathode partial pressure and stack temperature, Schultze et al (2014). Eq. (4) shows the relationship of cell voltage U_{cell} and the shown parameters within the startup and operation range of a PEMFC.

$$\begin{aligned} U &= n_{\mathrm{cells}}\left(U_{\mathrm{rev}} - U_{\mathrm{act}} - U_{\mathrm{ohm}}\right) \\ U_{\mathrm{rev}} &= 1.229 - 8.5\cdot 10^{-2}\left(T_{\mathrm{stack}} - T_0\right) \\ &\quad + 4.3\cdot 10^{-5} T_{\mathrm{stack}}\left(\ln\frac{p_{\mathrm{AN}}}{p_0} + \frac{1}{2}\ln\frac{p_{\mathrm{O2}}}{p_0}\right) \\ U_{\mathrm{act}} &= \zeta_1 + \zeta_2 T_{\mathrm{stack}} + \zeta_3 T_{\mathrm{stack}}\ln(I) \\ &\quad + \zeta_4 T_{\mathrm{stack}}\ln\left(p_{\mathrm{O2}} e^{(498/T_{\mathrm{stack}})} / 5.08\cdot 10^{-6}\right) \\ U_{\mathrm{ohm}} &= R_{\mathrm{ohm}} I \end{aligned} \tag{4}$$

where U is the sum of all cell voltages U_{cell}, n_{cells} is the number of cells of the stack, T_0 is the standard temperature and p_0 is the standard pressure.

$$\begin{aligned} N_{\mathrm{O2}} &= x_{\mathrm{O2}}\frac{W_{\mathrm{CA}}}{\mathrm{M}_{\mathrm{O2}}} - \frac{I}{4\mathrm{F}} n_{\mathrm{cells}} \\ N_{\mathrm{N2}} &= \left(1 - x_{\mathrm{O2}}\right)\frac{W_{\mathrm{CA}}}{\mathrm{M}_{\mathrm{N2}}} \\ p_{\mathrm{O2}} &= \left(\frac{N_{\mathrm{O2}}}{N_{\mathrm{O2}} + N_{\mathrm{N2}}}\right) p_{\mathrm{CA}} \end{aligned} \tag{5}$$

where N_{O2} and N_{N2} are the molar flows, M_{O2} and M_{N2} are the molar masses of O_2 and N_2. x_{O2} is the O_2 mass fraction of air. The identification of the parameters was made by using the method of least squares error minimization using experimental data varying all partial pressures and temperatures up to the maximum stack current, Proton Motor (2011). The membrane is assumed perfectly hydrated. All single cells are assumed identical. Subsequently all variables, influencing the system, are shown.

The mass flow controller (MFC) of the hydrogen supply and the hydrogen tanks are reduced to a first-order delay element with $\tau_{\mathrm{MFC,AN}}$. The operation range of MFC is saturated.

$$W_{\mathrm{MFC,min}} \le W_{\mathrm{MFC}} \le W_{\mathrm{MFC,max}} \tag{6}$$

During the experiments the whole anode system is closed. The unused hydrogen behind the stack is recycled and brought up in front of the stack again. The advantage of this recirculation is an optimal supply with higher mass flow rates inside the stack. The recirculation rate is dependent to the active stack current and monitored by a feedback controller. The model of the anode site is shown in (7) and (8).