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MODEL PREDICTIVE CONTROL BASED HYDROGEN EXCESS RATIO REGULATION WITH CIRCULATING PUMP FOR POLYMER ELECTROLYTE MEMBRANE FUEL CELL

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ABSTRACT

Polymer electrolyte membrane fuel cells have been considered as the potential solution for vehicle energy. Hydrogen is supplied to the anode of the fuel cell and electrochemically reacted with the oxygen of the cathode through the proton exchange membrane. The output current of the fuel cell varies under different vehicle operating conditions. Therefore, it is necessary to regulate the anode hydrogen excess ratio to maintain the high efficiency of the fuel cell. In this paper, a fuel cell anode hydrogen supply system is proposed based on a multiple-input multiple-output model predictive control (MPC) approach. The flow control valve and the hydrogen circulating pump via the proposed MPC are used to regulate the anode pressure and hydrogen excess ratio to meet the power demand of the vehicle. Comparing with the proportional-integral control result, the great control precision and transient response characteristics of the MPC can be achieved.

Keywords: Polymer electrolyte membrane fuel cell, hydrogen excess ratio, hydrogen supply, hydrogen circulating pump, model predictive control

1. INTRODUCTION

Proton exchange membrane (PEM) fuel cells have the advantages of pollution-free, high efficiency and low noise which have significant development potential and broad application prospect in the automotive field. A PEM fuel cell is a power generation device in which the hydrogen and oxygen react electrochemically to generate electrical energy. Therefore, the amount of hydrogen and oxygen delivered has a great influence on the output capacity of the fuel cell. As the vehicle's operating conditions change, the demand for hydrogen in the fuel cell is also changing. If the hydrogen supply is not timely, the fuel cell will cause fuel starvation, resulting in a decrease in fuel cell output power and remaining useful lifetime which is disadvantageous for the safety and economy of fuel cells and the vehicles [1-2]. Therefore, it is significant to have fast and accurate control of the hydrogen supply system to ensure the output capacity and service life of the fuel cell. At present, many studies have been conducted in the modeling and control of the fuel cell hydrogen supply system. Pukrushpan et al. [3] proposed a typical model of fuel cells which discussed the balance of oxygen, nitrogen and water in the fuel cell channel. Steinberger et al. [4] introduced two purge strategies to remove the inert gases which can achieve the theoretical maximum fuel efficient. Chen et al. [5] proposed a segmented anode model based on a high order sliding mode observer to estimate the unmeasurable and partial pressure in fuel delivery system. Tsai et al. [6] proposed a mathematical model which can capture the variation of the gas composition along anode flow channel to study the effect of the purge strategy on energy efficiency. In this work, a hydrogen supply system of PEM fuel cell was proposed which contains a high-pressure hydrogen tank, a flow control valve, a supply manifold, a return manifold, a purge valve, a fuel cell anode flow channel and a hydrogen circulating pump. The high-pressure hydrogen tank stores hydrogen gas, and outputs a certain flow rate and pressure of hydrogen through the flow control valve which is introduced into the anode flow channel of the fuel cell. However, the hydrogen in the anode cannot be completely reacted, and it is necessary to recirculate unreacted hydrogen through a hydrogen circulating pump to improve fuel utilization rate. In this paper, a multiple-input multiple-output MPC controller based on the linearized state space model is designed to regulate the pressure and hydrogen excess ratio of the anode. The anode pressure is controlled by the flow control valve to make a quickly tracking of the pressure change in the fuel cell cathode. The anode hydrogen excess ratio of the fuel cell is regulated by the hydrogen circulating pump to ensure the working efficiency. In Section 2, the model of hydrogen excess ratio is developed. The design and results of hydrogen excess ratio MPC controller is introduced in Section 3. Finally, the conclusion is drawn in Section 4.

2. HYDROGEN EXCESS RATIO MODELING

The modeling process of the hydrogen excess ratio can be divided into two parts: the hydrogen supply system and the hydrogen circulating pump.

2.1 Hydrogen supply system

The model of hydrogen supply system consists of a flow control valve, a supply manifold, a return manifold, a purge valve and a fuel cell anode flow channel.

The flow control valve completes flow and pressure control of hydrogen. The steady-state characteristics of flow control valve can be described as a linear function:

$$W_{fcv} = u_{fcv} W_{fcv,rated} \tag{1}$$

where u_{fcv} is the control voltage signal of the flow control valve, and the value is 0-1. $W_{fcv,rated}$ is the output flow when the flow control valve is fully open.

The supply manifold and the return manifold direct the flow of hydrogen throughout the hydrogen supply system which will cause pressure loss and humidity change along the pipeline. The dynamics of the hydrogen pressure and the humidity in these manifolds can be described:

$$\frac{dp_{H_2}}{dt} = \frac{R_{H_2} T_{mf}}{V_{mf}} \left(W_{H_2,mf,in} - W_{H_2,mf,out} \right) \tag{2}$$

$$\frac{d\phi_{mf}}{dt} = \frac{R_{H_2O} T_{mf}}{P_{sat} V_{mf}} \left(W_{v,mf,in} - W_{v,mf,out} \right) \tag{3}$$

where $W_{H2,mf,in}$ is the mass flow rate of hydrogen flowing into the manifolds, $W_{H2,mf,out}$ is the mass flow rate of hydrogen flowing out of the manifolds, $W_{v,mf,in}$ is the mass flow rate of water vapor flowing into the manifolds and $W_{v,mf,out}$ is the mass flow of water vapor flowing out of the manifolds. The P_{sat} is the saturation pressure of water vapor which is a function of the manifold temperature.

In the anode flow channel, the hydrogen is reacted by electrochemical reaction and the water vapor diffuses through the polymer electrolyte membrane with the proton which will also cause the pressure drop and humidity change in anode:

$$\frac{dp_{H_2}}{dt} = \frac{R_{H_2} T_{an}}{V_{an}} \left(W_{H_2,an,in} - W_{H_2,an,out} - W_{H_2,react} \right) \tag{4}$$

$$W_{H_2,react} = N_{cell} \frac{I_{st} M_{H_2}}{2F} \tag{5}$$

where $W_{H2,an,in}$ is the mass flow rate of hydrogen flowing into the anode flow channel, $W_{H2,an,out}$ is the mass flow rate of hydrogen flowing out the anode flow channel, $W_{H2,react}$ is the reaction mass flow rate of hydrogen in the fuel cell anode, and N_{cell} is the number of the fuel cell units. The dynamics of the humidity in anode flow channel can be described:

$$\frac{d\phi_{an}}{dt} = \frac{R_{H_2O} T_{an}}{P_{sat} V_{an}} \left(W_{v,an,in} - W_{v,an,out} - W_{v,m,diff} \right) \tag{6}$$

$$W_{v,m,diff} = \alpha_{net} N_{cell} \frac{I_{st} M_{H_2O}}{F} \tag{7}$$

where $W_{v,an,in}$ is the mass flow rate of water vapor flowing into the anode flow channel, $W_{v,an,out}$ is the mass flow rate of water vapor flowing out the anode flow channel, $W_{v,m,diff}$ is the reaction mass flow rate of water vapor in the fuel cell anode, and α_{net} is the water transport coefficient which is a function of current and the humidity of the cathode and anode.

The purge valve is set to maintain the hydrogen concentration and remove liquid water of the anode channel, which is due to nitrogen and water diffusion form cathode. The purge frequency is a function of the current that the higher of the current, the more frequent of the purge.

2.2 Hydrogen circulating pump

Hydrogen circulating pump is a low power compressor which recirculates the unreacted hydrogen from anode flow channel to the supply manifold. The mass flow rate of circulating can be obtained:

$$\Phi = \frac{W_{pu} \sqrt{\lambda_T}}{\lambda_P \rho_{rm} d_{pu}^2 U_{pu} \pi / 4} \tag{8}$$

$$\frac{d\omega_{pu}}{dt} = \frac{1}{J_{pu}} \left(\tau_{pm} - \tau_{pu} \right) \tag{9}$$

$$\tau_{pu} = \frac{c_{p,rm} T_{rp} \sqrt{\lambda_T}}{\omega_{pu} \eta_c} \left[\left(\frac{P_{sm}}{P_{rm}} \right)^{\frac{\gamma_{g,rm}-1}{\gamma_{g,rm}}} - 1 \right] W_{pu} \qquad (10)$$

$$\tau_{pm} = \eta_{pm} \frac{k_t}{R_{pm}} \left(u_{pu} - k_v \omega_{pu} \right) \qquad (11)$$

where Φ and η_c are the scaled flow rate and efficiency of the circulating pump which are the function of the dimensionless parameter and the Mach number at the tip of the blade. λ_T and is λ_P the temperature and pressure ratio of the return manifold and the reference. U_{pu} is the pump tip velocity of the rotating blade which is calculated by the blade diameter d_{pu} and the angle velocity ω_{pu}. The angle velocity is calculated by the integral of difference between driving torque τ_{pm} and the resistance torque τ_{pu}. k_t, R_{pm}, η_{pm}, k_v are the performance parameters of the pump motor, and u_{pu} is the driving voltage of the hydrogen circulating pump.

2.3 Hydrogen Excess Ratio

Hydrogen excess ratio is the ratio between the hydrogen flowing into the anode floe channel and the reaction of the hydrogen based on real-time current:

$$\lambda_{H_2} = \frac{W_{fcv} + W_{H_2,pu}}{W_{H_2,react}} \qquad (12)$$

The proper hydrogen excess ratio ensures sufficient hydrogen supply and high fuel cell efficiency which should be regulated as the current change.

3. MPC-BASED HYDROGEN EXCESS RATIO REGULATION

A MPC controller was designed to regulate the hydrogen excess ratio and the pressure of fuel cell anode. The fuel cell hydrogen supply system is a complex nonlinear model which should be linearized at a rate operating point. The continuous-time state space model is described as follow:

$$\begin{cases} \dot{X}(t) = AX(t) + B_u U(t) + B_d d(t) + B_w W(t) \\ Y(t) = CX(t) + D_u U(t) + D_d d(t) \end{cases} \qquad (13)$$

where

$$\begin{cases} X = \left[P_{sm\_H}, P_{an\_H}, P_{rm\_H}, \phi_{sm}, \phi_{an}, \phi_{rm}, \omega_{pu} \right]^T \\ Y = \left[P_{an}, \lambda_{H_2} \right]^T \\ U = \left[u_{fcv}, u_{pu} \right]^T \\ d = I_{st} \end{cases} \qquad (14)$$

where ***X*** is the state vector of the hydrogen supply system model which consist of the angle velocity of hydrogen circulating pump and the pressure of hydrogen and humidity in two manifolds and anode flow channel. ***Y*** is the controlled output vector, which is the total pressure and the hydrogen excess ratio of the anode. ***U*** is the control input vector that is the driving voltage of the flow control valve and the driving voltage of the hydrogen circulating pump. ***d*** is the measured disturbance which is set to current, ***W*** is the unmeasured disturbance. And ***A***, ***Bu***, ***Bd***, ***Bw***, ***C***, ***Du***, ***Dd*** are the matrices of the state space model.

After linearization, a linearized MPC controller can be designed based on the linearized model which can be divided into three steps: predictive equation, optimization problem, application and recalculation. By establishing prediction equation and solving the optimization problem, an optimal control sequence was obtained and the first component of which was applied into the linearized model to recalculate optimal control sequence of the next time. The MPC controller structure is illustrated in Fig.1. By controlling the control variable, the MPC controller keep the output variable at a reference value.

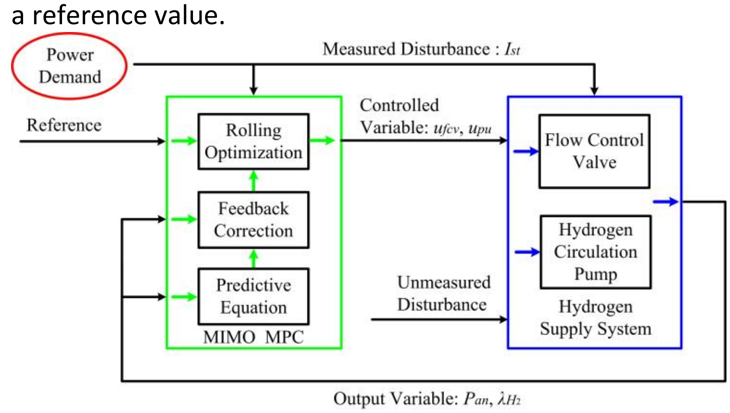
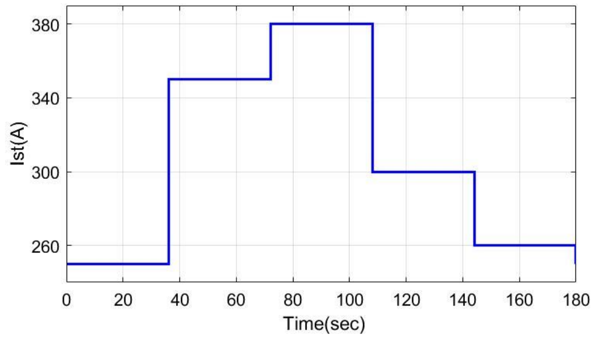


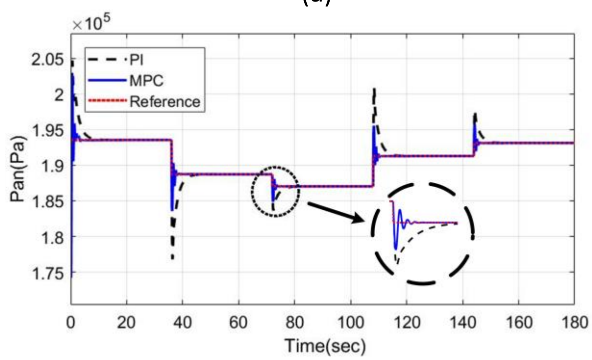
Fig 1 MPC controller structure

3.1 Hydrogen Supply System Control

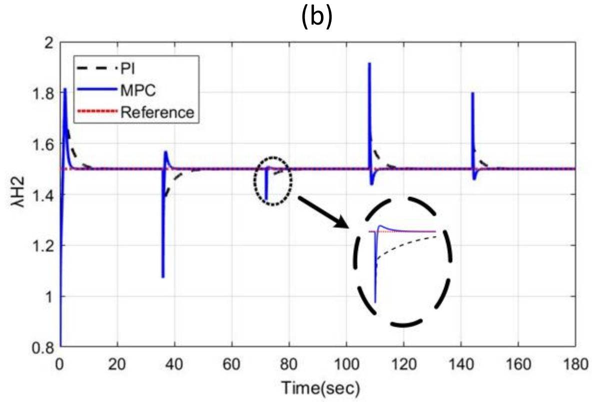
The MPC controller collects the anode pressure output of the model, and outputs the driving voltage of the flow control valve to the model, to maintain the anode pressure as the given pressure reference value. When the vehicles are driving under frequently changing conditions, the demand for oxygen mass flow in fuel cell cathode will change, which will cause fluctuations in the pressure of the cathode. Due to the pressure difference the polymer electrolyte membrane can sustain within a certain range, the pressure of anode should track the pressure of cathode which is a function of the current. Fig 2 (a) shows the step change of current which simulates the change in power demand of the vehicle. Fig 2 (b) shows the MPC tracking result of pressure in anode which compares with a proportional integral (PI) controller. The overshot of MPC is smaller to keep the pressure difference and prevent membrane damage.



(a)



(b)



(c)

Fig 2 Control results (a) Step change of current (b) pressure of anode (c) hydrogen excess ratio

3.2 Hydrogen Circulating Pump Control

Hydrogen circulating pump recirculates the unreacted hydrogen in anode and delivers to the anode along with the flow control valve output hydrogen to maintain the hydrogen excess ratio. In this work, the reference of hydrogen excess ratio is set to 1.5 which can make a fine-tuning with the change of vehicle power demand. Fig 2 (c) shows the regulation results of hydrogen excess ratio. It is obviously that MPC has a shorter settling time and quicker response characteristics which shows a better regulation of hydrogen excess ratio than PI.

4. CONCLUSION

In this work, an anode hydrogen supply system is proposed based on MPC to make a regulation of pressure and hydrogen excess ratio in the anode of polymer electrolyte membrane fuel cell system. The change of humidity and purge flow are taken into considered in the modeling process of the hydrogen supply system. The multiple-input multiple-output MPC is designed based on the linearized state equation of the close-loop system. The simulation shows that the regulation based on MPC approach shows faster transient dynamics as well as smaller overshoots than PI control. However, this model does not consider the water changes between liquid and gaseous which should be conducted in the future research.

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