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Nonlinear MPC for the airflow in a PEM fuel cell using a Volterra series model

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ABSTRACT

The particular industrial interest in fuel cells is based on the possibility to generate clean energy both for stationary and automotive applications. Performance and safety issues of fuel cells are closely related to the control strategy used for the fuel and oxidant supply. In PEM (polymer electrolyte membrane or proton exchange membrane) fuel cells the oxygen excess ratio expresses the proportion between oxygen reacting in the cells and oxygen entering the stack and represents a decisive variable for the mentioned issues. This work is focused on the design of a nonlinear model predictive control (NMPC) strategy manipulating the air flow rate in order to maintain the oxygen excess ratio in a desired value, both for safety and performance reasons. The designed NMPC, based on a second order Volterra series model, was implemented on a commercial fuel cell. The proposed NMPC strategy is validated in experiments and compared to a linear model predictive controller and to the original built-in controller.

1. Introduction

Fuel cells are electrochemical devices which continuously convert the chemical energy stored in a fuel and an oxidant to electric energy. Nowadays, fuel cell are of great industrial interest as they provide the possibility to generate clean energy, both in stationary and automotive applications. The PEM (polymer electrolyte membrane or proton exchange membrane) fuel cell used in this work runs at low temperatures and can be characterized by its fast dynamical response, high power density, small size, low corrosion and high efficiency, which make it suitable for mobile applications (Rodatz, Paganelli, Sciarretta, & Guzzella, 2005; Stefanopoulou & Suh, 2007). Both the fuel and the oxidant, usually pure hydrogen and ambient air, are supplied continuously to the anode and the cathode, respectively. On the anode side the hydrogen dissociates into protons and electrons of which the protons are conducted through the membrane towards the cathode. Due to the electric isolation of the membrane the electrons cannot pass through the membrane and are forced through an external circuit generating electric energy. In the cathode, the oxygen molecules, the electrons and the protons react and form water as a residual (Pukrushpan, Stefanopoulou, & Peng, 2004b). For an efficient use of fuel cells it is necessary to control the air and hydrogen feed, the flow volumes and pressures as well as the water produced by the chemical reaction. During transitions the feed of the fuel cell has to be controlled to maintain temperatures, hydration of the membrane and partial pressures of the reactants in a suitable level to avoid membrane degradation and to maintain system's efficiency (Gruber, Bordons, & Dorado, 2008).

A continuous air flow is supplied to the cathode by a compressor or a blower and can be considered as the main control variable of a PEM fuel cell. On the anode side, hydrogen, usually stored in a pressurized tank, is fed through a fast opening valve to track a desired ratio of the air flow. During the operation of the fuel cell sufficient oxygen has to be supplied to the cathode channel in order to fulfill some specific stoichiometric requirements to generate the demanded current. An insufficient oxygen supply results in the oxygen starvation phenomenon which implies a fast stack degradation and low power generation (Yousfi-Steiner, Moçotéguy, Candusso, & Hissel, 2009), and the only way to finish it is by stopping the supply of the reactants and the current demand (Bordons, Arce, & del Real, 2006). In several studies controlling the oxygen excess ratio, defined as the ratio between the oxygen supplied to the cathode channel and the oxygen consumed by the electrochemical reaction, is proposed to prevent this undesired phenomenon (Pukrushpan, Stefanopoulou, & Peng, 2004a; Thounthong & Sethakul, 2007). The proposed control strategies include feedforward control (Pukrushpan et al., 2004b; Pukrushpan, Stefanopoulou, Varigonda, Eborn, & Haugstetter, 2006), LQR (Pukrushpan et al., 2004b; Rodatz, Paganelli, & Guzella, 2003), neural networks (Almeida & Simões, 2005) or model predictive control (MPC) (Bordons et al., 2006; Gruber et al., 2008). Nevertheless, only a few control strategies have been validated experimentally, amongst others an adaptive control (Zhang, Liu, Yu, & Ouyang, 2009), a constrained MPC (Gruber, Doll, & Bordons, 2009) and an explicit MPC (Arce, del

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Real, Bordons, & Ramirez, 2010). The fast system dynamics are a challenging task in fuel cell control as they require the development of control strategies with low computational complexities in order to calculate a new input signal within one sampling period.

The proposed strategy is a nonlinear model predictive control (NMPC), that is used to maintain the oxygen excess ratio at a desired level. The NMPC is based on a second order Volterra series model which relates the compressor motor voltage to the oxygen stoichiometry, i.e. the prediction model considers the dynamics of the compressor and the fuel cell stack. The effect of the load current, regarded as the main disturbance of the system, is considered in the control strategy and includes implicitly a feedforward effect. The Volterra series model, representing the logical extension of a convolution model, is linear in the parameters and allows the identification of the model parameters from experimental data by means of least squares estimation. The control strategy is based originally on an efficient iterative optimization algorithm (Doyle, Pearson, & Ogunnaike, 2001; Maner, Doyle, Ogunnaike, & Pearson, 1996), extended in Gruber, Bordons, Bars, and Haber (2010) to include constraints and a weighting of the control effort. The motivation to use the proposed NMPC strategy is based on the possibility to consider the nonlinearities of the fuel cell dynamics in the control scheme and to solve the resulting optimization problem for low sampling times. The designed control was implemented in a real-time framework and validated on a commercial fuel cell.

The paper is organized as follows: Section 2 presents a description of the fuel cell module, the mathematical definition of the oxygen excess ratio, the used real-time system to implement the control strategy and the control objective. Section 3 gives a detailed description of the used Volterra series model and its identification from experimental data as well as the nonlinear model predictive control law based on the identified model. In Section 4 the experimental results obtained with the proposed NMPC are shown and compared to the ones obtained with a linear MPC and the original built-in control of the used fuel cell. Finally, in Section 5 the major conclusions are drawn.

2. System description

This section gives a detailed description of the used fuel cell module and an exact mathematical definition of the oxygen excess ratio. Furthermore, the real-time system to implement the proposed control strategy is presented. Finally, the control objective of the NMPC strategy is specified.

2.1. Fuel cell module

The work has been performed on an 1.2 kW PEM fuel cell module (Ballard Nexa Power Module, Ballard, 2003, see Fig. 1) designed for operation in indoor environments. The mentioned system was the first commercially available fuel cell module and can be considered as a benchmark since it is widely used by many research groups and it is representative of state-of-the-art PEM technology. The stack is composed of 46 cells connected in series with a voltage of 26 V at rated power and a rated current of 46 A. The air supply is auto-humidified before reaching the cells and the fuel cell stack is air-cooled by an integrated small fan (Ballard, 2003). The hydrogen feeding is carried out in dead-end mode, i.e. with a closed anode outlet, supplying hydrogen at the exact rate at which it is consumed (Barbir, 2005). The anode–cathode pressure ratio is controlled to avoid membrane stress or damage, and therefore the hydrogen and oxygen mass flows are correlated. In the original configuration of the fuel cell module the air supply is controlled by the manufacturer's built-in controller. In this work the built-in controller is overridden by an external controller in order to validate the proposed control strategy (see Section 3) in experiments on the fuel cell module. An electric load connected to the fuel cell module allows simulating a variable power demand.

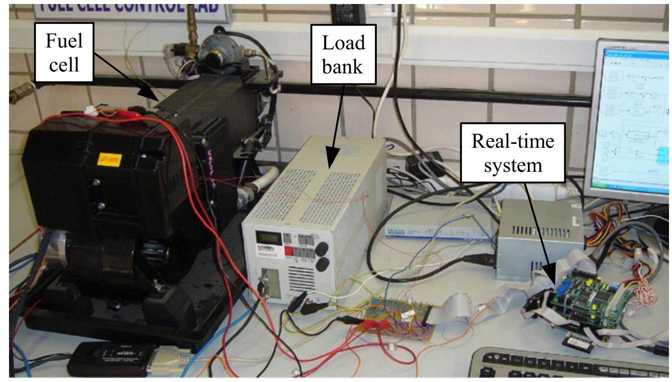

Fig. 1. The used Ballard Nexa fuel cell module in the laboratory.

2.2. Oxygen excess ratio

The general purpose of this work is the design of a control strategy to regulate the oxygen excess ratio λ_{O_2}, defined as the ratio between the oxygen $W_{O_2,ca,in}$ entering the cathode and the oxygen $W_{O_2,reacted}$ reacting in the fuel cell stack. The oxygen excess ratio λ_{O_2} is considered as a performance variable of the system and its regulation is an important issue since this parameter determines the safety of the fuel cell.

The oxygen excess ratio has been defined in Pukrushpan et al. (2004b) as

$$\lambda_{O_2} = \frac{W_{O_2,ca,in}}{W_{O_2,reacted}} \tag{1}$$

where the oxygen consumption rate $W_{O_2,reacted}$ is proportional to the stack current I_{st} and given by (Larminie & Dicks, 2003)

$$W_{O_2,reacted} = M_{O_2}\frac{nI_{st}}{4F} \tag{2}$$

with $n=46$ the number of cells of the used fuel cell stack, M_{O_2} the molar mass of oxygen and F the Faraday constant. The oxygen mass flow rate $W_{O_2,ca,in}$ entering the cathode channel depends on the mass flow rate of dry air $W_{a,ca,in}$ at the cathode inlet:

$$W_{O_2,ca,in} = x_{O_2,ca,in}W_{a,ca,in} \tag{3}$$

The oxygen mass fraction $x_{O_2,ca,in}$ can be calculated by

$$x_{O_2,ca,in} = \frac{y_{O_2,ca,in}M_{O_2}}{y_{O_2,ca,in}M_{O_2}+(1-y_{O_2,ca,in})M_{N_2}} \tag{4}$$

where M_{N_2} denotes the molar mass of nitrogen. For the oxygen mole fraction a value of $y_{O_2,ca,in}=0.21$ is assumed. The mass flow rate of dry air at the cathode inlet is defined as

$$W_{a,ca,in} = \frac{1}{1+\omega_{ca,in}}W_{ca,in} \tag{5}$$

with the humidity ratio:

$$\omega_{ca,in} = \frac{M_v}{M_{a,ca,in}}\frac{p_{v,ca,in}}{p_{a,ca,in}} \tag{6}$$

M_v being the molar mass of vapor and $M_{a,ca,in}$ the molar mass of air at the cathode inlet. The molar mass $M_{a,ca,in}$ is defined generally by

$$M_{a,ca,in} = y_{O_2,ca,in}M_{O_2}+(1-y_{O_2,ca,in})M_{N_2} \tag{7}$$