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Modelling and explicit model predictive control for PEM fuel cell systems

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ABSTRACT

We present an analytical dynamic model and a general framework for the optima control design of a PEM fuel cell system. The mathematical model consists of a detailed model for the PEM fuel cell stack and simplified models for the compressor, humidifier and cooling system. The framework features (i) a detailed dynamic process model, (ii) a reduced order approximating model obtained by performing dynamic simulations of the system and (iii) the design of an explicit/multi-parametric model predictive controller. The derived explicit/multi-parametric controller is tested and validated off-line on several operating conditions.

1. Introduction

Fuel cells are a promising technology for electrical power generation, widely regarded as a potential alternative for stationary and mobile applications. Fuel cells are electrochemical devices that convert the chemical energy of a fuel to electrical energy (Del Real et.al., 2007). The electrical efficiency of the fuel cells is higher than the most conventional devices for power generation, since they avoid intermediate steps of production of mechanical energy. The transport sector is one of the major contributors to global fossil fuel consumption and carbon emissions (Adamson, 2004). Alternative power devices for automotive applications have been actively studied over the last few years with great emphasis on fuel cells (Dyer, 2002). The primary type of fuel cells for automotive industry application is Proton Exchange Membrane (PEM) fuel cells, due to their suitable properties for vehicle applications such as low sensitivity to orientation favourable power to weight ratio and fast and easy start-up.

In order to use a fuel cell in an effective way, mathematical models are necessary to be able to analyse the system behaviour depending on the system design and operating conditions. The models developed in the literature can be classified into three main categories, namely, detailed fuel cell models based on partial differential equations (Fuller and Newman, 1993; Dutta et al., 2001; Wang and Wang, 2005; Wang et al., 2005a,b), steady-state fuel cell system based on experimental maps (Al-Baghadi, 2004) and dynamic fuel cell system models that neglect spatial variations (Springer et al., 1991; Ramousse et al., 2005). Most of the publications on fuel cell modelling were developed at the cell level and included spatial variations of the fuel cell parameters. Membrane-electrode assembly (MEA) modelling is indeed the base of the entire PEM fuel cell system modelling (Pathapati et al., 2005; Shan and Choe, 2005). Complex electrochemical, thermodynamic and fluid dynamics principle were used to describe mathematically the entire physical environment of electrochemical reaction, the transport phenomena of gases, water, proton and electron and as well as the relationships among fuel cell current, voltage, temperature, pressure and materials (electrode, membrane and catalyst). The performance of the fuel cell under different steady-state operating conditions can be determined with those models. Some models are based on two-dimensional, steady-state fuel cell modelling (Golbert and Lewin, 2004, 2007). More complex approaches in 3D modelling have also been developed (Al-Baghdadi and Al-Janabi, 2007), and the main purposes of those detailed models are to design the fuel cell components and to choose the fuel cell operating conditions, but they are computationally expensive and are not suitable for control studies. However, they establish the fundamental effects of operating parameters such as pressure and temperature on the fuel cell voltage.

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Most of the models predict fuel cell polarisation characteristics at different operating conditions. Amphlett et al. (1996) attempted to integrate together mechanistic model and empirical relation to derive advantages from both of them. They developed a dynamic model for a PEM fuel cell stack, which predicts fuel cell voltage and stack temperature for a given set of gas feed and operating conditions. Moreover, many publications addressed the water and thermal management of the fuel cell in order to describe the water, thermal and reactant utilisation of fuel cell by means of two or three-dimensional models (Fuller and Newman, 1993). Fronk et al. (2000) demonstrated the importance of thermal management while trying to maximise the performance of fuel cell stack used within a vehicle. The system-level modelling is even more complicate than the MEA modelling and most of the models in the literature are based upon steady-state conditions. Steady-state models are typically used for component sizing, static trade-off analysis or cumulative fuel consumption (Pukrushpan et al., 2005).

Despite the large number of developed models in the past 15 years (Bavarian et al., 2010), there are still open issues regarding the development of models which are suitable for control and real-time estimation purposes. Current models are either too complex or they have not been sufficiently detailed to capture in detail the fuel cell dynamic behaviour. This field is in intense development, since such models are critical for future control development (Pukrushpan et al., 2005; Del Real et al., 2007). The concurrence of the current evolution in design of fuel cell systems and of the advanced integrated control techniques in microprocessor systems would allow the performance improvement of the portable fuel cell units (power regulation, heat management, water management, etc.) (Pukrushpan et al., 2005). The recent literature has established that advanced control techniques have been deemed suitable for resolving the above issues (Bavarian et al., 2010). This challenging control problem, to design a controller for an integrated fuel cell system as shown in Fig. 1, can be implemented mainly using advanced control techniques, such as model-based control.

Model-based control (MPC) strategy is a suitable approach to obtain the optimal operation of the fuel cell system, due to its ability to control multi-input multi-output systems with interactions and disturbances. However, MPC requires an analytical and accurate dynamic mathematical model of the system. The benefits of MPC have long been recognised from the viewpoint of cost and efficiency of operation. Nevertheless, its applications maybe restricted due to increased online computational requirements related to the constrained optimisation. In order to overcome this drawback, explicit or multi-parametric model predictive control mp-MPC was developed (Pistikopoulos et al., 2007b,d) which avoids the need for repetitive online optimisation.

In this paper we focus on the mathematical modelling and control issues of PEM fuel cell systems according to the framework (Pistikopoulos, 2009) presented in Fig. 2, that comprises of the following steps:

1. Development of a high fidelity mathematical modelling—used for detailed simulation and (design and operational) optimisation studies.
2. Development of a reduced order/approximating model, suitable for multi-parametric MPC.
3. Design of multi-parametric MPC controllers.
4. Off-line validation of the controllers.

Step 1 involves the development of a high-fidelity mathematical model, for performing detailed dynamic simulation and design/operational optimisation studies. The model is validated using experimental data in several operation conditions in order to guarantee the accuracy of the simulation results. In step 2, a reduced order approximated model is derived by performing system identification or reduced order techniques on the simulation data. Step 3 corresponds to the design of the multi-parametric/explicit model predictive controllers (mp-MPC), by applying the available theory and tools of multi-parametric programming and control (Pistikopoulos et al., 2007a,b,d). Finally step 4 involves the off-line validation of the derived multi-parametric /explicit controllers.

In this paper we present a systematic framework for the optimal control design of the PEM fuel cell system. A detailed mathematical model is first presented and dynamic simulations are performed based on which a reduced order state space (SS) model, suitable for the design of advanced model-based controllers for temperature and voltage regulation, is derived. Finally, the controller introduced in the process model and its performance is validated.

2. PEM fuel cell mathematical model

The PEM fuel system model is described analytically in this section. The system under consideration is a PEM fuel cell stack, a compressor and a cooling system to maintain the temperature of the stack (Fig. 1). Hydrogen is channelled in the anode side of the fuel cell while air in the cathode side. The compressor

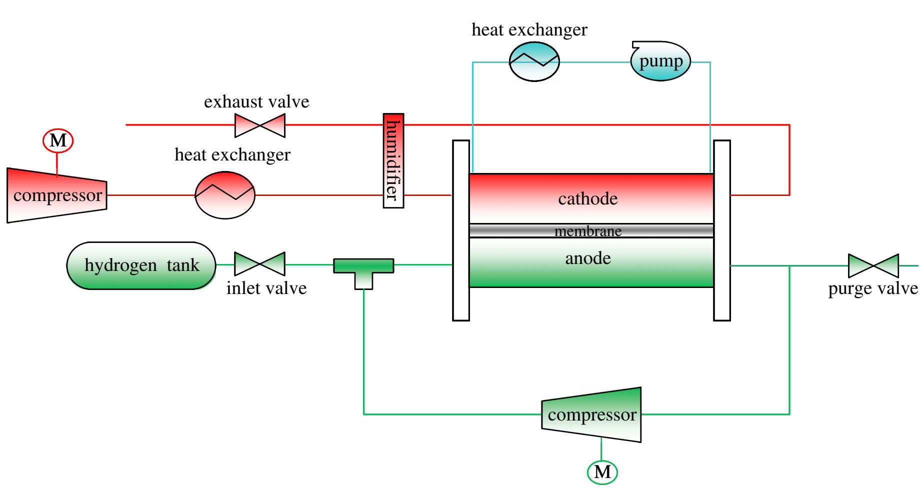

Fig. 1. Overall scheme of the fuel cell system.