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Reduced-order Robust Control of a Fuel Cell Air Supply System ⋆

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Abstract: This paper presents the design of several reduced order robust control strategies for the air supply of a hybrid fuel cell power generator. The management of the air dynamic entering the fuel cell is assured by the control of the air flow of a compressor. The air supply sub-system is controlled to keep a desired oxygen excess ratio, thus improving the fuel cell dynamic performance. Robustness analysis studies are performed, these robust properties are contrasted with classic control strategies, demonstrating the advantage of the multivariable reduced order robust methodologies.

Keywords: Robust control, multivariable control, fuel cells, hybrid power generators, air compressor.

1. INTRODUCTION

Fuel cells (FC) are electro-chemical devices that convert chemical energy into electrical energy by means of an electrode pair, an electrolyte and a catalyzer.

A fuel cell may not operate alone. When referring to a FC *system*, all the auxiliary systems, needed for operation, are included. This makes the complete system a rather complex structure to control. The auxiliary elements can be divided into two groups: electrical and thermo-dynamical management sub-systems. The first ensures the safe connection of the FC to the electrical application (load) and the second sub-system ensures the gas, water, air and thermal management of the FC. A complete robust control solution was presented by the authors in Hernandez-Torres et al. (2011). Of course, these sub-systems are both highly dependent, as the gas flow in the stack directly depends on the load current demand, then the electrical sub-system is influenced by the flow dynamics. In terms of the FC efficiency, the stack will have a better performance at higher flow pressures, but this means higher compression ratios, higher energy consumption of the compressor-motor sub-system and a degraded overall system efficiency. An efficient control is necessary to guarantee an optimal management of hydrogen and air in the system, avoiding stack membrane degradation (and output voltage degradation) for a more reliable and efficient operation.

Within the context, a need is identified for a robust multivariable reduced order control approach to manage the thermo-dynamical sub-systems on the FC. The disturbance rejection approach is considered in this article, since, as a general proposition, this will have an influence on the cells life-span, avoiding non-desired high energy transients. It should be noted that limitations on the FC performance are due not only to material characteristics, but also on the optimization of the thermo-dynamical operating variables as, for example, the flow rate of reactant streams (Gasser, 2006). As a central part of the FC dynamic behaviour, the control of the compressor-motor and the supply air flow are considered. Several articles can be found in the literature addressing these problems. An interesting study on the air compressor control influence on the FC efficiency is presented in Tekin et al. (2006). Linear control of the thermo-dynamical system on a FC is studied using model-based control in Grujicic et al. (2004). Multivariable robust $\mathcal{H}_\infty$ and low order PID's controls are proposed in Wang et al. (2008) and Wang and Ko (2010) respectively. An LPV control approach for the FC air supply was presented in Hernandez-Torres et al. (2012). Non-linear control has also been used with good results using feed-back linearization and passivity in Na and Gou (2008) and Talj et al. (2009) respectively. Model predictive optimal control has also been used for this type of systems in Chang and Moura (2009).

In this work some assumptions are made to obtain simplified control-oriented models. The fuel flow control, the air humidification and the stack temperature controls are assumed to be perfect. Robust control is of special interest, aiming to achieve robust stability and performance for systems subject to uncertainties. In this paper we demonstrate the advantage of a multivariable reducer or-

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der control approach over the classical decoupled control methodologies and the validation with complete closed-loop robustness analysis.

2. SYSTEM MODEL AND PARAMETER IDENTIFICATION

2.1 Test bench setup for system model identification

A test-bench fuel cell setup available in LEPMI laboratory (http://lepmi.grenoble-inp.fr/) is used for model identification of the fuel cell air supply system. The test-bench is composed by different elements that allow to efficiently control, operate and visualize several parameters of the FCS such as: fluid dynamics (pressure, gas flow rates, reactant stoichiometric values, etc.), thermo-dynamic parameters (stack temperature, humidification rates, etc.), or even electrical parameters (single cell voltage, stack current and power).

The stack considered in this work is a PEMFC from French company Paxitech© and mounted on a UBzM© frame with a nominal power of 475W. The arrangement is composed by a 16-cell/100 cm^2 effective area stack. The air channel entering at the FC stack input is controlled by air flow and pressure regulators. For air flow control the setup is equipped with *Smart* series *5800S* models from *Brooks Instruments*©, with reading/regulation capabilities using $0-5$V control signals. For pressure reading purposes the test-bench is provided by series 21 *Keller*© piezoresistive transmitters. For the pressure reading/regulation option, a *VP50* proportional control valve from *Norgren*© was installed for air back-pressure control.

According to the requirements of the FCS in the test-bench, an air compressor was chosen to guarantee at least an air flow of 60 slpm[1] and a pressure range of $1-2$ bars (absolute). With these characteristics and allowing an over-sizing factor for future stack expansion in the test-bench, the Vairex© *VV-0520.08 INT* model dry fixed vane air compressor was chosen. The compressor has an operating range of $24-40$V and nominal power of $900-1200$W. The air flow ranges from $0.2-10$g/s at compression pressures of $1.1-2$ bars (abs). The compressor layout and the compressor map as given by manufacturer are given in Figure 1.

2.2 Air supply model

Compressor modeling is somehow considered as the core of the fuel cell model. Two proposed models are presented in the following sections. First, the non-linear model proposed by Pukrushpan et al. (2004), and secondly, a linear model is proposed by Gasser (2006).

The first compressor model presented here is a non-linear compressor model proposed by Pukrushpan et al. (2004). The block diagram representation of this model is shown in Figure 2.

The compressor model is composed by a static compressor map, used to determinate the air flow rate through the compressor, and by a dynamic model of the system inertia, which determines the compressor speed used to find the

[1] Standard liters per minute

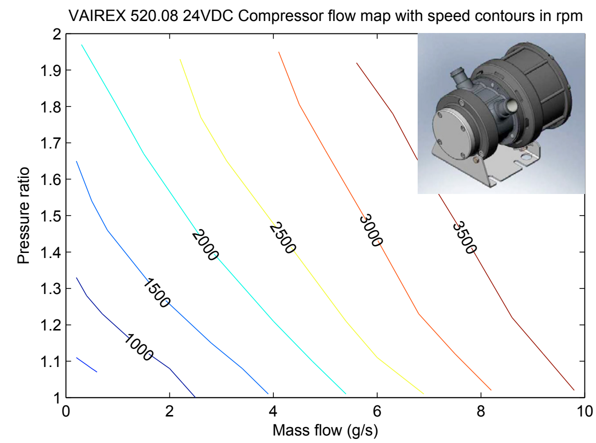

Fig. 1. Compressor operation map.

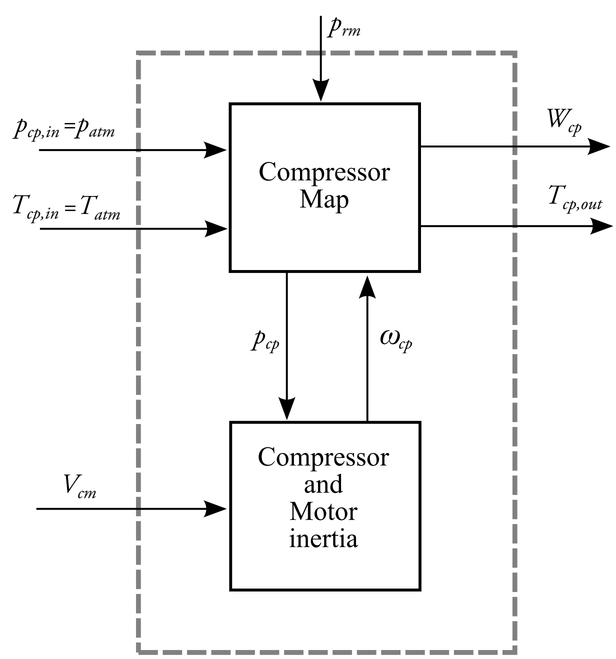

Fig. 2. Compressor model block diagram (Pukrushpan et al., 2004).

air flow rate. The state in the model is the compressor speed ω_{cp}. The inputs to the model are the air pressure p_{atm} and temperature T_{atm} (atmospheric), the supply manifold pressure p_{sm} (downstream pressure) and the voltage command of the compressor voltage v_{cm}.

The compressor flow map can be normally found in the device manufacturer data-sheet. In Pukrushpan et al. (2004) the Jensen & Kristensen map regression method is presented to compute the compressor air flow rate, avoiding the use of look-up tables (not suitable for simulations). This method is presented with details in Pukrushpan et al. (2004) and the air flow rate W_{cp} is computed using a regression algorithm on the compressor map and the compressor diameter d_c in m, the air density ρ_a in kg/m^3, and the air gas constant $\mathcal{R}_a$.

A look-up table is used to obtain the compressor efficiency η_{cp}. Then the temperature of the air leaving the compressor is computed by: