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Sliding Mode Control of a Hybrid Fuel cell-Battery Power System

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Abstract: This paper presents the analysis and design of sliding mode control (SMC) for a hybrid power system, which consists of a fuel cell, a battery, a unidirectional converter, and a bidirectional converter. The fuel cell and the battery are connected to the same voltage bus through a unidirectional converter and bidirectional converter, respectively. Fuel cell has a slow start and a large time delay to respond the transient. Therefore, the battery as an auxiliary energy source provides the power during the system's start and absorbs the dynamic power when the load varies. A SMC is proposed to control a unidirectional converter for fuel cell and a bidirectional dc/dc converter for a battery. The SMC used in the paper has a capability of robustness to control properly under all operating conditions.

Keywords: sliding mode control, bidirectional converter, fuel cell, battery, power management.

1. INTRODUCTION

Fuel Cells (FCs) are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. They are attractive power sources in the distributed generation power system, electrical vehicles, and naval ship system because of their high reliability, high efficiency and cleanness (Jin et al., 2009; Blaabjerg et al., 2006; Yang et al., 2010).

Two types of fuel cells are usually used for utility grade power plants which are called solid-oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC). What is common between the two types of fuel cell is that they both operate at high temperature to generate electricity. Various SOFC dynamic models have been proposed by researchers, and a comprehensive simplified dynamic model of SOFC with thermal dynamics was proposed (Sedghistigarchi and Feliachi, 2004) and a modified thermal dynamic block of SOFC was reported (Goel, Mishra, and Jha, 2006).

When fuel cell power plant is connected to the power grid through converter and inverter, it needs an auxiliary energy source to compensate for the following several shortcomings of the fuel cell: 1) slow response; 2) no capability of energy storage; and 3) difficulty in cold start. Therefore, an auxiliary energy source such as battery or ultra-capacitor should be added to the FC power system to improve the dynamic characteristics, enhance the peak power capacity, and power the load during cold start (Jin, Ruan, Yang, and Xu, 2009).

The charging and discharging current cannot be controlled when an auxiliary source is in parallel directly with the DC bus. Therefore, a bidirectional converter needs to be inserted between the dc bus and the auxiliary source to control the charging and discharging current.

The dc-dc converters are non-linear in nature. A great deal of effort has been directed in developing modelling and control techniques of various dc-dc converters. However, these methods cannot ensure stability under large variations of state conditions. They often perform unacceptably in large load and input voltage variations (He and Luo, 2006).

This paper proposes a sliding mode control (SMC) strategy for a dc-dc converter for the FC and an auxiliary energy source, which is a battery used here. The SMC (Itkis, 1976; Edwards et al., 1998; Utkin, Guldner and Shi, 1999; Khalil, 2002) for variable structure systems is an effective non-linear approach for the control of dc-dc converters. The sliding mode theory offers the robustness and flexibility to easily get different operational modes (Tan, Lai, Cheung, and Tse, 2005; Inthamoussou, Pegueroles-Queralt, and Bianchi, 2013). Thus, SMC proposed in the paper can provide a robustness control strategy and make the overall hybrid system work properly under the different operation modes.

The paper is organized as follows: Section II introduces the hybrid fuel cell power system which consists of the dynamic model of SOFC, battery, the unidirectional converter and the bidirectional converter. The sliding mode control of unidirectional converter and bidirectional converter is described in Section III. Section IV presents the power management between fuel cells and battery, and the simulation results are presented in Section V. Finally the conclusion is provided in Section VI.

2. HYBRID FUEL CELL POWER SYSTEM

2.1 Overall Architecture of Hybrid Fuel Cell Power System

The hybrid Fuel Cell system used in this paper is shown in Fig. 1. The power system consists of an FC, a battery, a

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unidirectional dc-dc converter (UDC), a bidirectional converter (BDC) and a load.

The hybrid power system can improve the system efficiency as the following cases: 1) The battery provides the power to the load so that the FC cold starts easily during the start of the system; 2) When the load steps down or up, the battery will absorb or provide the power; 3) The battery can provide the peak power, so that the total cost of FC can be reduced.

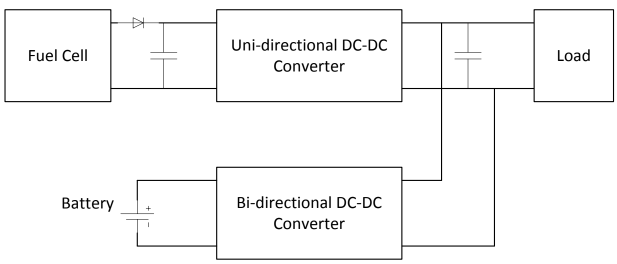

Fig. 1. Hybrid fuel cell power system.

2.2 Dynamic Model of SOFC

The dynamic model of SOFC consists of three components: electrochemical model, thermal model, and Nernst's voltage equation.

Padulles, Ault and McDonald (2000) introduced a model for the SOFC plant, where the derivative of the partial pressure was calculated using the perfect gas equation for hydrogen as follows:

$$\frac{d}{dt} p_{H_2} = \frac{RT}{V_{an}} (q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r}) \tag{1}$$

where p_{H_2} is the partial pressures of hydrogen (atm), R the universal gas constant ((1atm)(kmol K)$^{-1}$), T the absolute temperature (K), V_{an} the volume of the anode, $q_{H_2}^{in}$ the hydrogen input flow (kmol s^{-1}), $q_{H_2}^{out}$ the hydrogen output flow (kmol s^{-1}), $q_{H_2}^{r} = 2K_r I$ the hydrogen flow that reacts (kmol s^{-1}), I the stack current (A), and K_r a constant defined for modelling purpose (kmol/(s A).

If it could be considered that the molar flow of any gas through the valve is proportional to its partial pressure inside the channel, then the relationship can be expressed as:

$$\frac{q_{H_2}}{p_{H_2}} = K_{H_2} \tag{2}$$

where q_{H2} is the molar flows of hydrogen through the anode valve (kmol s^{-1}), p_{H2} the partial pressure of hydrogen (atm), and K_{H2} the valve molar constants for hydrogen (kmol/(s atm)). Taking the Laplace transform of (1), replacing the output flow by (2), and isolating the hydrogen partial pressure yields the following expression:

$$p_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2} s} (q_{H_2}^{in} - 2K_r I) \tag{3}$$

where

$$\tau_{H_2} = \frac{V_{an}}{K_{H_2} RT} \tag{4}$$

In a similar manner, the equations for the partial pressure of water and oxygen are derived as follows:

$$p_{H_2O} = \frac{1/K_{H_2O}}{1+\tau_{H_2O} s} \cdot 2K_r I \tag{5}$$

$$p_{O_2} = \frac{1/K_{O_2}}{1+\tau_{O_2} s} (q_{O_2}^{in} - K_r I) \tag{6}$$

The fuel cell voltage is given as the summation of four terms, the Nernst reversible voltage, the activation drop, the concentration drop, and the ohmic drop:

$$V_{cell} = E - V_{act} - V_{con} - V_{ohmic} \tag{7}$$

where E is Nernst reversible voltage, V_{act} the activation loss, V_{con} the concentration loss, and V_{ohmic} the ohmic loss. The expressions of the Nernst reversible voltage, and three voltage drops are given by (Gebregergis and Pillay, 2010).

The temperature either increases or decreases with respect to the instantaneous energy loss in the fuel cell. Researchers presented the modified thermal dynamic block in (Gelen and Yalcinoz, 2013). The amount of increase in temperature can be calculated as follows:

$$T_o = T + \left(\frac{T_{in} + \Delta T - T}{t} \right) dt \tag{8}$$

where T_o is the output temperature, T_{in} the initial temperature, ΔT the rise in temperature from T_{in} that will occur after a laps of the relaxation time, T the present temperature of the fuel cell under load, t the relaxation time, which is around 200 seconds, and dt the Simulink time step.

The output voltage of fuel cell varies with respect to the current of fuel cell as shown in Fig. 2. The output voltage is given by (7), and the voltage drop is presented as the current of fuel cell increases.

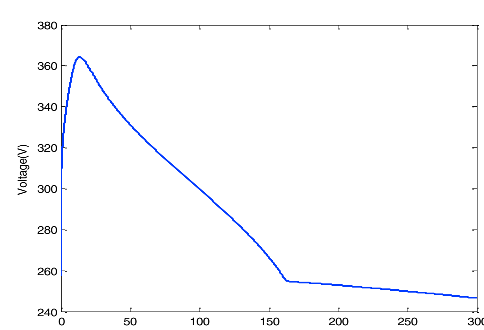

Fig. 2. Output voltage vs. current of fuel cell.