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Disturbance rejection control of a fuel cell power plant in a grid-connected system

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ABSTRACT

Interface of a fuel cell plant to power grid is challenging because of the high nonlinearities of the fuel cell plant and the power conditioning system (PCS). This paper focuses on the control of grid-connected solid-oxide fuel cell (SOFC) power plant that is subject to varying load and uncertain network parameters. To this end, Active Disturbance Rejection Control (ADRC) is utilized to improve the performance of the PCS consisting of a dc-dc converter and a dc-ac inverter. ADRC is used in the dc-dc converter to stabilize the dc link voltage and yield a robust performance against the nonlinearity. Used in the dc-ac inverter, ADRC eliminates the steady-state error and is insensitive to the high-frequency noise. Simulation results show that, for grid current control, ADRC achieves a more robust performance than the conventional proportional-integral (PI) controller. Moreover, the total harmonic distortions (THDs) of the output current controlled by ADRC are always below 5% in spite of the variation in the load demand and network parameters.

1. Introduction

The increasing awareness of environmental concerns is making a rapid transformation of the electric power system to an intelligent electric grid. Distributed generators (DGs), such as wind, solar, biofuel, micro-turbines and fuel cells, are becoming attractive due to less gas emissions and improvement in efficiency and reliability (Blaabjerg, Teodorescu, Liserre, & Timbus, 2006; Wojszczyk, Uluski, & Katiraei, 2008). Nevertheless, due to the intermittency of wind and solar in power outputs, it results in power systems under constant stress in maintaining power balance and voltage and frequency regulation. Compared to them, fuel cells can provide reliable power since the input fuel is controllable. Moreover, fuel cells are highly-efficient and environmentally-friendly energy conversion devices. Therefore, it will play an important role in the microgrid as an ultra-battery to supply the power continuously as long as the fuel is available.

The output power of solid-oxide fuel cell (SOFC) is of dc type; hence, a power conditioning system (PCS) is required to interface between SOFC and the power grid to convert dc power into ac power. The PCS consists of a dc-dc boost converter and a dc-ac inverter. The dc-dc converter is to boost and regulate the output voltage of SOFC into a higher voltage in the dc link, and the dc-ac inverter is to convert dc voltage into ac voltage to supply the power to load and the power grid.

The dc link voltage is required to be maintained at a constant voltage via the boost converter, and the current of inverter is controlled to generate a smooth ac waveform with fewer harmonics to provide high-quality power to the load and the grid. However, since the voltage of SOFC changes over a wide range as load demand changes, the dc link voltage is fluctuating and the inverter current contains harmonics (Figueres, Garcerá, Sandia, González-Espín, & Rubio, 2009; Hajizadeh, Golkar, & Feliachi, 2010; Yang, Lei, Peng, & Qian, 2011). Moreover, the network parameter changes not only affect the power quality of the inverter, but also challenge the control of grid-connected inverter and the grid filter design in terms of stability.

The current practice is to use a conventional proportional-integral (PI) controller to control the dc link voltage and the inverter current due to its simple structure, which gives satisfactory performances under steady-state and nominal operating conditions (Jin, Ruan, Yang, & Xu, 2009; Taher & Mansouri, 2014; Wu, Lee, & Yang, 2013). The power quality is measured by the Total Harmonic Distortions (THDs) of the output current of the inverter. According to the IEEE 519 standard (IEEE, 2014), the THDs of the current are to be less than 5% over every ten cycles. However, PI controller cannot guarantee that it can work properly in every operating condition. It is important to mitigate the THDs because the unwanted flow of harmonic currents may lead to increased losses and heating in numerous electromagnetic devices and can shorten the life of electronic equipment and cause damage to power systems. Therefore, a proper control is necessary to

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meet the requirement under all operating conditions.

The main contribution of this paper is to use a robust controller which is independent of the system model and has simple features (i) to make the SOFC power plant supply the high-quality power with low THDs to load and the power grid and (ii) to guarantee to have a stable system under a wide range of load variations and network disturbances. For this purpose, a novel concept of active disturbance rejection control (ADRC) is applied in this paper to maintain low THDs in meeting the standard and to achieve a stable system with various working conditions.

The ADRC is an advanced PID controller which has a strong robustness, stability, and adaptability against external disturbances and parameter perturbation (Chang, Li, Zhang, Wang, & Xue, 2015; Han, 2009; Sun, 2007). The main idea of ADRC is that both the internal dynamics and the external disturbances can be estimated and compensated in real time (Chang et al., 2015). Therefore, ADRC improves the PID controller, while enjoying the advantages of the simple structure and strong robustness at the same time (Sun, 2007).

This paper is organized as follows: In Section 2, modeling of grid-connected SOFC is described. Control topology of ADRC is introduced in Section 3, and analysis of the controlled system is shown in Section 4. Simulation results are presented in Section 5 and conclusions are drawn in Section 6.

2. Modeling of grid-connected SOFC

A brief overview of the modeling of SOFC and power conditioning system is presented in this section along with the problem formulation.

2.1. Modeling of SOFC

The FC converts the chemical energy from fuel into electricity through a chemical reaction, and can produce electricity continuously for as long as fuel is supplied. The modeling of SOFC power plant used in this paper is based on the model developed in (Achenbach, 1995; Gebregergis, Pillay, Bhattacharyya, & Rengaswemy, 2009; Sedghisigarchi & Feliachi, 2004) which considered both the electrochemical and the thermal dynamic aspects of chemical reactions.

The voltage of SOFC is given as the summation of the Nernst's equation and Ohm's law, and it can be expressed as follows (Gebregergis et al., 2009; Sedghisigarchi & Feliachi, 2004):

$$V_{fc} = V_0 - V_{act} - V_{ohm} - V_{conc} \tag{1}$$

where V_0 is the Nernst reversible voltage, V_{act} is the activation loss, V_{ohm} is the ohmic loss, and V_{conc} is the concentration loss. The Nernst reversible voltage and each loss can be written with respect to the temperature as following:

$$V_0 = N_0\left[E_0 + \frac{RT}{2F}\ln\frac{p_{H_2}p_{O_2}^{0.5}}{p_{H_2O}}\right] \tag{2}$$

$$V_{act} = \tfrac{RT}{F}(z + \sqrt{1+z^2})$$
$$z = I_{fc}/2I_0$$
$$I_0 = A\exp(-E_{act}/RT) \tag{3}$$

$$V_{ohm} = \alpha\exp\left[\beta\left(\frac{1}{T_o} - \frac{1}{T}\right)\right]I_{fc} \tag{4}$$

$$V_{conc} = \frac{RT}{2F}\ln\left(1 - \frac{I_{fc}}{i_L}\right) \tag{5}$$

where T is the fuel cell stack temperature, p_{H_2}, p_{O_2}, and p_{H_2O} are the reactant partial pressures of hydrogen, oxygen and water, respectively, and other parameters are listed in Table 1.

To achieve the Nernst voltage in (2), the partial pressure for each species can be found according to the electrochemical relationships (Padulles, Ault, & McDonald, 2000). They can be expressed as the following transfer functions:

$$p_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2}s}\left(\frac{1}{1+\tau_f s}q_f - 2K_r I_{fc}\right) \tag{6}$$

$$p_{O_2} = \frac{1/K_{O_2}}{1+\tau_{O_2}s}\left(\frac{1/r_{HO}}{1+\tau_f s}q_f - K_r I_{fc}\right) \tag{7}$$

$$p_{H_2O} = \frac{1/K_{H_2O}}{1+\tau_{H_2O}s}2K_r I_{fc} \tag{8}$$

The disturbance mainly comes from the external current load; furthermore, it shows that the relaxation time of the output voltage is highly related to the effect of temperature dynamics (Achenbach, 1995). Thus, the modified thermal dynamic block is presented in (Gebregergis et al., 2009; Sedghisigarchi & Feliachi, 2004) according to (Achenbach, 1995). Thermal equations are introduced in a dimensionless form based on two major parameters which are the Fourier number (F_0) and the source term number (S_0) (Achenbach, 1995):

$$F_0 = \frac{\lambda_s \cdot t}{(\rho C_P)h_{eff}^2} \tag{9}$$

$$S_0 = \frac{1-\eta}{\eta}\cdot\frac{V_{fc}I_{fc}}{\lambda_s \Delta T/h_{eff}} \tag{10}$$

where t is the relaxation time, which is defined as the period necessary to reach 90% of the new steady-state value, and ΔT is the rise in temperature from the initial temperature at no load that will occur after a laps of the relaxation time. F_0 is a constant and S_0 is a variable governed by fuel cell voltage, current and temperature, and is constrained by

$$F_0 = 0.72 S_0^{-1.1} \tag{11}$$

An approximate equation for the change in the stack temperature ΔT can be derived from (9)–(11), and the output temperature of fuel cell stack can be updated as following (Goel, Mishra, & Jha, 2006):

$$T_{out} = T + \left(\frac{T_{init} + \Delta T - T}{t}\right)dt \tag{12}$$

where T_{out} is the output temperature, T is the present temperature of the fuel cell under load, T_{init} is the initial temperature at no load, and dt is the Simulink time step. The dynamic model of the SOFC plant and the detailed thermal dynamic block are shown in Figs. 1 and 2. Note that the memory blocks used in the clock and T_{out} should be initialized to '0' and T_{init}, respectively.

Fuel utilization factor (u_f) is the ratio between the fuel flow reacted and the input fuel flow and it can be expressed in terms of the fuel cell current I_{fc} as

$$u_f = \frac{q_{H_2}^{in} - q_{H_2}^{o}}{q_{H_2}^{in}} = \frac{q_{H_2}^{r}}{q_{H_2}^{in}} = \frac{2K_r I_{fc}}{q_{H_2}^{in}} \tag{13}$$

where, $q_{H_2}^{in}$, $q_{H_2}^{o}$ and $q_{H_2}^{r}$ are the hydrogen input, output, and reacted flow rates, respectively, and K_r is the reaction constant.

The fuel utilization factor is one of the most important operating variables which may affect the performance of SOFC (Li, Rajakaruna, & Choi, 2007). For instances, the desired range of u_f is 0.7–0.9; however, overused-fuel condition (u_f> 0.9) can cause permanent damages to the cells because of fuel starvations, while it may have unexpectedly high voltages with the under-used condition (u_f< 0.7). Along with the varying load demand, the current of SOFC varies, resulting in the perturbation of u_f. To maintain the fuel utilization factor constant in the safe operation range, the natural gas input to the stack can be calculated by solving (13), yielding a feedforward control