Electrical Power and Energy Systems 74 (2016) 49–57

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Various control schemes of power management for phosphoric acid fuel cell system

Rupendra Kumar Pachauri *, Yogesh K. Chauhan

Department of Electrical Engineering, School of Engineering, Gautam Buddha University, Greater Noida, India

ARTICLE INFO

Article history:
Received 19 August 2014
Received in revised form 26 May 2015
Accepted 9 July 2015

Keywords:
Fossil fuels
Fuel cell
Green energy
Phosphoric acid fuel cell
Renewable energy

ABSTRACT

In this paper, the analysis of phosphoric acid fuel cell (PAFC) system is presented. Various control schemes of power management e.g. current, voltage, power, reactants flow pressure and temperature based control schemes are proposed with simple and easy to implement PI controller for PAFC operation. These control schemes can be utilized for power management purpose. The proposed model of PAFC along with these control schemes is realized in the MATLAB/Simulink environment. The performance of a PAFC system along with these proposed control schemes is found to be satisfactory even under dynamic conditions.

Introduction

The consumption of electrical energy is escalating due to its various advantageous features. The storage of fossil fuels is limited, so there is urgent need to explore more sustainable energy sources. The renewable energy (RE) sources are suitable options to generate the electrical power [1]. The common and techno-feasible RE sources are such as wind turbine (WT), solar photovoltaic (PV) system, and FC system. Pollution free power generation and other environment issues have been driving an increasing demand of RE sources over the last few years. Recently, a lot of research is going on FC to make suitable it for power generation.

FC is an electrochemical device that converts chemical energy into electrical energy. FC has a very low environment impact and operates silently in practical situations with high efficiency and long life time. So FCs can be represented as a very good option as a distributed generation, since it has high power density in comparison of battery energy storage system (BESS). The PAFC has been considered as a promising power apparatus since more than one decade because of its low operating temperature, compactness and high efficiency [2]. FCs are used in the stand-alone purposes at residential, hospitals, industries as well as electrical vehicles.

Sedghisigarchi and Feliachi [3] proposed a model, which contains the electrochemical equations with thermal expects inside the FC stack but the reactant flow pressure controller is not presented. Malla [4] proposed a concept on FC based distribution generation (DG) with or without DSTATCOM, control active and reactive power. But not discussed on special controller based on advanced fuzzy logic techniques. Hajizadeh et al. [5] presented the controller for hybrid power DG system that includes the dynamic models of a solid oxide fuel cell (SOFC), battery system and power electronics interface is presented, but the power control strategy for the FC system or the design of reactants flow controllers have not been focused. In [6], a controller has been designed for FC power generation system to improve the power quality and active power control, but the dynamic model of FC system and reactant flow controller is not discussed. Hajizadeh and Golkar [7] and Tong et al. [8] gave a concept on reactant flow controller based on fuzzy logic for the fuel cell DG systems. Hence, in this paper novel attempt is made to develop various control schemes for PAFC power management system.

System description

The complete system is divided into four major parts: (a) PAFC system. (b) Control schemes for power management as: (i) Current controller; (ii) Voltage controller; (iii) Power controller; (iv) Reactants flow rate controller; (v) Temperature controller. (c) Power electronics interface using DC/DC converter. (d) Load. The schematic diagram of complete system is shown in Fig. 1. In this system, the FC system is utilized as a power generating source. A resistive load is considered for dynamic analysis.

---

* Corresponding author. Tel.: +91 1202346016.
E-mail addresses: rupendra.gbu@gmail.com (R.K. Pachauri), chauhanyk@yahoo.com (Y.K. Chauhan).

http://dx.doi.org/10.1016/j.ijepes.2015.07.012
0142-0615/

Nomenclature

V_{fc}	fuel cell voltage, V
E	Nernst voltage, V
V_{act}	activation voltage drop, V
V_{conc}	concentric voltage drop, V
V_{ohmic}	ohmic voltage drop, V
E_0	reference Nernst potential, V
R	universal gas constant, J mol^{-1} K^{-1}
T	cell temperature, °C
F	Faraday constant, C mol^{-1}
P_{H_2}	H_2 flow pressure, atm
P_{O_2}	O_2 flow pressure, atm
P_{H_2O}	H_2O flow pressure, atm
m_{H_2}	mass of hydrogen at the anode, kg/mol
R_{H_2}	H_2 gas constant, J/kg K
V_{anode}	anode volume, m^3
$V_{cathode}$	cathode volume, m^3
m_{O_2}	mass of O_2 at the cathode, kg/mol
R_{O_2}	O_2 gas constant, J/kg K
m_{H_2O}	mass of H_2O at the cathode, kg/mol
Q_{H_2O}	molar flow rate of water, mol s^{-1}
$k_{cathode}$	cathode flow constant, mol s^{-1} atm^{-1}
R_{mem}	membrane resistance, ohm
t_m	membrane thickness, cm
V_{stack}	FC stack voltage, V
Greek symbol	
σ	conductivity, S/m

Modeling of PAFC system

PAFC voltage (V_{fc}), can be expressed using Eq. (1) [9,10]. When a cell delivers power to the load, the no load voltage, known as Nernst voltage (E) is reduced by three categories of voltage drop as,

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

The Nernst equation is expressed using Eq. (2), which gives the open circuit cell potential (E) as a function of cell temperature (T) and reactants flow pressure as,

$$E = E_0 + \left(\frac{RT}{nF}\right) \ln\left(\frac{(P_{H_2})(P_{O_2})^{\frac{1}{2}}}{(P_{H_2O})}\right) \tag{2}$$

A FC system mainly consists a dynamic fuel reactant flow processing unit e.g. hydrogen flow pressure (P_{H_2}), oxygen flow pressure (P_{O_2}) and water flow pressure (P_{H_2O}), which can be expressed using Eqs. (3)–(5) [10–12] as,

$$P_{H_2} = \left(\frac{m_{H_2} R_{H_2}}{V_{anode}} T\right) \tag{3}$$

$$P_{O_2} = \left(\frac{m_{O_2} R_{O_2}}{V_{cathode}} T\right) \tag{4}$$

$$P_{H_2O} = \left(\frac{(m_{H_2O})^{\frac{1}{2}} Q_{H_2O}}{k_{cathode}}\right) \tag{5}$$

The activation drop (V_{act}) can be represented by Tafel's equation which gives the activation drop is shown in Eq. (6) as,

$$V_{act} = -\lambda_1 + \lambda_2 T - \lambda_3 T[\ln(I)] + \lambda_4[\ln(\text{conc. } O_2)] \tag{6}$$

where $\lambda_1, \lambda_2, \ldots, \lambda_4$ are constants. The oxygen concentration (conc. O_2) is given as a function of stack temperature as shown in Eq. (7) [13–15] as,

$$\text{conc. } O_2 = \frac{P_{O_2}}{5.08 \times 10^6 \times \exp^{\left(\frac{-498}{T}\right)}} \tag{7}$$

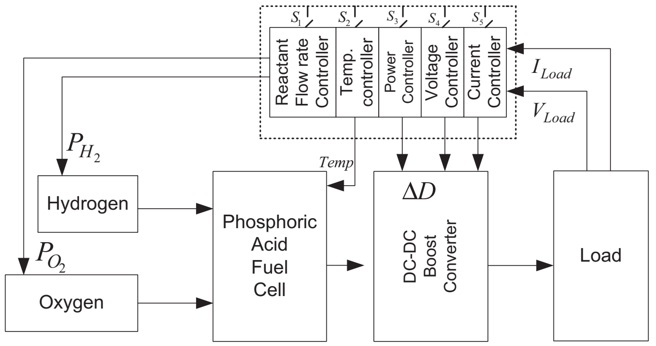

Fig. 1. Schematic diagram of PAFC with proposed control schemes.

The ohmic voltage drop (V_{ohm}) is almost linear in nature and obtained using Eqs. (8) and (9) as,

$$V_{ohm} = \mathrm{IR}_{mem} \tag{8}$$

$$R_{mem} = \frac{t_m}{\sigma} \tag{9}$$

At higher current density, the cell potential decreases rapidly due to mass limitation [16,17]. This linearity is termed as the concentration over potential and shown in Eq. (10) as,

$$V_{conc} = c_1 - c_2(T - 273)e^{(c_3 I)} \tag{10}$$

Here, c_1, c_2 and c_3 are the constants and given as,

$$c_1 = 1.1 \times 10^{-4}, \quad c_2 = 1.2 \times 10^{-6}, \quad c_3 = 8 \times 10^{-3}$$

Eqs. (1)–(10) could be solved for cell potential. If all the FCs are in series, stack output is the product of cell potential and number of cells in the stack (N), the V_{stack} is expressed by Eq. (11) as,

$$V_{stack} = NV_{fc} \tag{11}$$

MATLAB/Simulink model of PAFC and power management schemes

Modeling of PAFC system

The simulation of PAFC has been done in MATLAB/Simulink GUI environment, is shown in Fig. 2. All the operating parameters of PAFC system used in this paper are given in Appendix.

Control schemes of power management

Various control schemes of power management depend upon the generation of reference signal, which is based on current, voltage, power, reactant flow pressure (P_{H_2}, P_{O_2}) and temperature. For all these power control management schemes, the PI controller is used, which is easy to implement and effective.

Current control scheme

The MATLAB/Simulink model of reference current control schemes is shown in Fig. 3. The reference and actual current system are compared and generated error is processed in the PI