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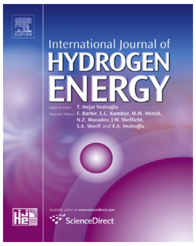

Optimal PID plus fuzzy controller design for a PEM fuel cell air feed system using the self-adaptive differential evolution algorithm

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ABSTRACT

Various control strategies for the air feed to a PEM fuel cell are investigated. Feedback and feedforward control strategies are used simultaneously in order to achieve maximum net power and prevent oxygen starvation. The control objective is to adjust the oxygen excess ratio using compressed air based on external disturbance variations. Maximum power tracking is obtained using the optimal oxygen excess ratio which is also compared to the constant oxygen excess ratio. In the feedforward strategy, a fuzzy logic controller and in the feedback a filtered PID controller is applied. The controller parameters are optimized simultaneously using a self-adaptive differential evolution algorithm. Simulation results show that the proposed technique improves the fuel cell system performance and prevents oxygen starvation by fixing the oxygen ratio at a proper setpoint.

Introduction

The ever-increasing energy demand in industrial societies and the predictable expiration of fossil fuel reserves has led to a constant search toward new energy resources. Besides, due to environmental pollution caused by fossil fuel combustion, new energy sources such as solar, wind, geothermal or hydrogen are considered as inevitable alternatives by energy supervisors. In spite of boundless possibilities for the application of these new energy sources and environmental friendly features the main disadvantage lies in their limited availability in specific situations.

Fuel cells are proposed as one of these alternatives for energy conversion systems during recent decades. Fuel cells are electrochemical systems capable of chemical energy conversion to the electrical form without combustion. High efficiency, low process temperatures, low pollution, high safety factors, flexibility of power generation and short startup times are among the most important advantages of these systems [1]. Hydrogen and oxygen are consumed to produce electricity in a fuel cell and byproducts are discharged as water and heat. However, short lifetime and high expenses has impeded their vast applicability in common systems up to now. As a result, in order to improve the performance, enhance the lifetime and reduce the production costs, the

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optimization of system design, components and materials as well as effective control strategies are essential.

Several control strategies are proposed for PEM fuel cells such as PI [2], LQG [1,3,4], fuzzy sliding mode [5], fuzzy [6,7], time delay [8,9], and neural networks [10,11] which are not validated in real plants. Other studies validated in plant-wide control strategies can also be mentioned as robust [12], gain-scheduled control [13], sliding mode [14,15] and model predictive control [16–18] which are applied for the manipulation of oxygen excess ratio in PEM fuel cells with various degrees of success.

This study is focused on the design and validation of a PIDF (PID with low band filter) and fuzzy controller optimized by the self-adaptive differential evolution (SaDE) algorithm for controlling the oxygen excess ratio in a PEM fuel cell. The main control objectives are preventing oxygen starvation and obtaining the maximum net power output. Oxygen starvation is considered as a critical condition for fuel cell resulting in rapid degradation of the membrane and catalyst layer [19], which is controlled by keeping the oxygen excess ratio higher than a minimum value.

After the introduction of differential evolution (DE) algorithm in 1995 [20], many researchers have paid attention to the issue and as a result many improved algorithms have been under development since then. The SaDE algorithm used in this study is developed by Qin et al. [21] in 2009 and applied in antenna design [22,23], filter design [24] and transforming geocentric Cartesian coordinates [25], thereafter. This algorithm is used in control applications and fuzzy controller optimization for the first time in this study. A feed forward controller uses fuzzy logic which is a representation of human thinking process. Fuzzy logic was introduced by Zadeh [26,27], Mamdani and Assilian [28] identified frameworks for fuzzy control strategy and developed the first industrially applied fuzzy controller and Beirami and Zerafat [29] applied fuzzy control strategy for adaptation of PID controller parameters in a heat exchanger system.

This study is organized as follows: Firstly, the mathematical model of the PEM fuel cell (PEMFC) air feed system and control objective is presented (Section 2). In Section 3, the control scheme of fuzzy logic and PIDF are designed. The self-adaptive differential evolution (SaDE) algorithm and optimization of controller parameters are discussed in Section 4. Simulation results of the fuel cell model are given in Section 5. Finally, main conclusions are presented in Section 6.

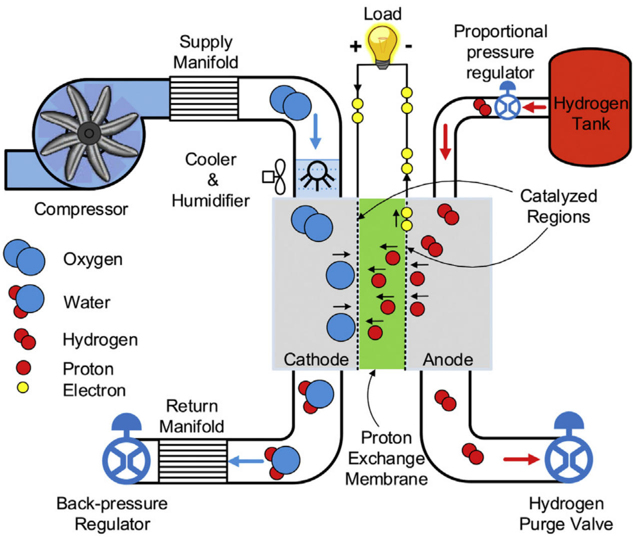

Fig. 1 – Schematic of the PEM fuel cell and ancillary components.

The PEMFC model

The 75 kW PEM fuel cell model used in this study is developed by Pukrushpan et al. [30,31]. The fuel cell stack consists of 381 cells, each with a 280 cm^2 membrane. This model has been widely accepted by researchers as a representative model to indicate real fuel cells for control objectives. The stack is combined with ancillary equipment for power generation. Fig. 1 shows the components of the fuel cell system as well as the chemical reactions involved. Increased pressures improve the reaction rate and enhance the efficiency and the fuel cell power density as well [32]. A cooling system is used to decrease the temperature of compressed air. Upon cooling, air humidity is increased to the desired value in order to prevent electrolyte dehydration. In the anode section, hydrogen is supplied while flow rate and pressure are manipulated using a control valve. Hydrogen molecules are converted to 2H$^+$ and two electrons on the anode catalytic layer:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

Produced protons move toward the cathode catalytic layer through the membrane. Since the membrane is not conductive to electrons, released electrons flow in the external circuit. In the cathode, oxygen passes through the gas layer and reacts with protons and electrons in the catalyst layer resulting in water production:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{2}$$

The general reaction taking place in the fuel cell is a combination of Eqs. (1) and (2) accompanied by heat generation:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{heat} + \text{electrical energy} \tag{3}$$

The PEMFC air feed system model

This section deals with the investigation of dynamic behavior of variables concerning air flow control in order to prevent oxygen starvation. Oxygen, nitrogen and vapor partial pressures in the cathode are calculated using mass conservation combined with ideal gas law:

$$\frac{dP_{O_2}}{dt} = \frac{RT_{fc}}{V_{ca}M_{O_2}}\left(W_{O_2,in} - W_{O_2,out} - W_{O_2,reacted}\right) \tag{4}$$

$$\frac{dP_{N_2}}{dt} = \frac{RT_{fc}}{V_{ca}M_{N_2}}\left(W_{N_2,in} - W_{N_2,out}\right) \tag{5}$$

$$\frac{dP_v}{dt} = \frac{RT_{fc}}{V_{ca}M_v}\left(W_{v,in} - W_{v,out} + W_{v,gen} + W_{v,membr} - W_{l,out}\right) \tag{6}$$

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