Maximum power point tracking of a proton exchange membrane fuel cell system using PSO-PID controller

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Fuel cells output power depends on the operating conditions, including cell temperature, oxygen partial pressure, hydrogen partial pressure, and membrane water content. In each particular condition, there is only one unique operating point for a fuel cell system with the maximum output. Thus, a maximum power point tracking (MPPT) controller is needed to increase the efficiency of the fuel cell systems. In this paper an efficient method based on the particle swarm optimization (PSO) and PID controller (PSO-PID) is proposed for MPPT of the proton exchange membrane (PEM) fuel cells. The closed loop system includes the PEM fuel cell, boost converter, battery and PSO-PID controller. PSO-PID controller adjusts the operating point of the PEM fuel cell to the maximum power by tuning of the boost converter duty cycle. To demonstrate the performance of the proposed algorithm, simulation results are compared with perturb and observe (P&O) and sliding mode (SM) algorithms under different operating conditions. PSO algorithm with fast convergence, high accuracy and very low power fluctuations tracks the maximum power point of the fuel cell system.

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I N T R O D U C T I O N

A fuel cell is an electrochemical device that combines hydrogen and oxygen to produce electricity, with water and heat as its by-product. Fuel cells have various advantages compared to conventional power sources. They have higher efficiency and reliability, operate silently, and eliminate pollution caused by burning fossil fuels and greenhouse gases. Common types of fuel cells include the alkaline fuel cell, proton exchange membrane fuel cell (PEMFC), direct methanol fuel cell, molten carbonate fuel cell, phosphoric acid fuel cell, and solid oxide fuel cell. Due to the performance characteristics of the PEMFC such as fast start-up, light weight, high power density, and low operating temperature, the PEMFC is the most popular type of fuel cells and the best candidate for residential and vehicular applications.

Output characteristics of fuel cells are nonlinear and influenced by such parameters as the cell temperature, oxygen partial pressure, hydrogen partial pressure, and membrane water content. In each particular condition, there is only one unique operating point for a fuel cell system with the maximum output. Thus, it is important to find the optimal operating voltage (or current) of fuel cell systems in order to increase the efficiency of fuel cells.

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There are different methods for MPPT in the literature such as, perturb and observe (P&O) or hill climbing (H&C), incremental conductance (IC), extremum seeking control, sliding mode control, voltage-based (VMPPPT) and current-based (CMPPT) methods, hysteresis controller, and as well, intelligent computing methods. Most of these methods have been applied to photovoltaic systems MPPT [1] and few researches on fuel cell MPPT have been reported. In Ref. [2] the use of P&O control strategy aimed at extracting the maximum allowable power from a Fuel Cell in a grid connected application is proposed. The P&O MPPT control technique is applied to improve the net output power of a system consisting in a PEMFC with its air motocompressor group in Ref. [3]. Ref. [4] investigates the performances of MPPT-FC generators supplying electric vehicle power train through an interleaved boost DC/DC converter (IBC). The accent is made on forcing the FC generator to operate at its maximum power point by using P&O algorithm integrated to the IBC control. In Ref. [5], P&O and IC methods are simulated and compared in order to identify which one is better for fuel cell system application. A novel Fractional Order Incremental Conductance Algorithm (FOINC) with variable step size control is presented in Ref. [6] for MPPT of fuel cells. Ref. [7] proposes a neural network IC-based variable step size MPPT controller for fuel cell power system. In Ref. [8] a two-loop cascade controller with an intermediate converter is designed to operate fuel cell power plants at their maximum power points (MPPs). The outer loop uses an adaptive extremum seeking algorithm to estimate the real-time MPP, and then gives the estimated value to the inner loop as the set-point, at which the inner loop forces the fuel cell to operate. In Ref. [9] the extremum seeking control performances are analyzed in energy generation system case which uses a fuel cell with proton exchange membrane (PEMFC) as renewable energy source. An extremum seeking algorithm is used in Ref. [10] to track the varying MPP for microbial fuel cells and also a voltage overshoot avoidance algorithm is developed to manage the voltage overshoot conditions. Ref. [11] proposes the sliding mode control approach for MPPT of PEM fuel cells and compares the results with P&O algorithm. Sliding mode algorithms to control electrical variables of fuel cells according to different power management objectives are developed in Ref. [12]. Ref. [13] proposes an integrated photovoltaic (PV) and proton exchange membrane fuel cell (PEMFC) system for continuous energy harvesting under various operating conditions for use with a brushless DC motor. The proposed scheme is based on the incremental conductance algorithm combined with the sliding mode technique.

Ref. [14] proposes VMPPT and CMPPT methods to minimize the fuel consumption of a fuel cell. In Ref. [15], an integrated control system that can perform both real-time MPPT and the maximum available power harvesting has been developed. The system does not utilize charge pumps and was operated under batch conditions with a hysteresis controller based energy harvesting system. The fuzzy controller is proposed in Ref. [16] to keep the direct methanol fuel cell working at the MPP by adjusting the operating conditions followed by the variation of the driven load in real time. In Ref. [17], a dynamic system of PEM fuel cell is modeled and an adaptive fuzzy controller is designed to control the PEMFC system to maintain a constant output voltage.

This paper presents an MPPT approach based on PSO-PID controller for PEMFC systems under different temperature and membrane water content conditions. The proposed method finds the optimal operating voltage of the fuel cell system and adjusts the operating point of the fuel cell system to the maximum power by tuning of boost converter duty cycle. The performance of PSO-PID controller is compared with P&O and sliding mode methods.

The paper is organized as follows: Section Characteristics of Fuel Cell gives the fuel cell characteristics. In this section impact of the cell temperature and the membrane water content on the performance of fuel cell system is investigated. The proposed PSO-PID algorithm, P&O and sliding mode methods are explained in Section MPPT Algorithms. In Section Simulation Results, the simulation results are given, analyzed and discussed. Finally, Section Conclusions gives the conclusions.

### Characteristics of fuel cell

#### Dynamic gas transport model

The proportional relationship between the flow of gas through a valve and the partial pressure can be stated as [8].

\[
\frac{q_{H_2}}{F_{H_2}} = \frac{k_{an}}{\sqrt{M_{H_2}}} = k_{H_2}
\]

and

\[
\frac{q_{O_2}}{F_{O_2}} = \frac{k_{an}}{\sqrt{M_{O_2}}} = k_{O_2}
\]

where \( q_{H_2} \) is molar flow of hydrogen (kmol s\(^{-1}\)), \( p_{H_2} \) hydrogen partial pressure (atm), \( k_{H_2} \) hydrogen valve molar constant (kmol (atm s\(^{-1}\))), \( k_{an} \) anode valve constant (\( \sqrt{k \text{ mol kg}^{-1} \text{ atm}^{-1}}\)), \( M_{H_2} \) molar mass of hydrogen (kg kmol\(^{-1}\)).

For hydrogen, the derivative of the partial pressure can be calculated by using the following perfect gas equation

\[
\frac{d}{dt} p_{H_2} = \frac{RT}{V_{an}} \left( q_{in}^{H_2} - q_{out}^{H_2} - q_{H_2} \right)
\]

where \( R \) is the universal gas constant ((1 atm) (kmol K)\(^{-1}\)), \( T \) absolute temperature (K), \( V_{an} \) anode volume, \( q_{in}^{H_2} \) hydrogen input flow (kmol s\(^{-1}\)), \( q_{out}^{H_2} \) hydrogen output flow (kmol s\(^{-1}\)), \( q_{H_2} \) hydrogen flow that reacts (kmol s\(^{-1}\)).

The amount of hydrogen consumed in the reaction can be calculated from the following electrochemical principle:

\[
q_{H_2} = \frac{N_{EC} I_{FC}}{2F} = 2k_i I_{FC}
\]

where \( N_{EC} \) is the number of the series-wound fuel cells, \( I_{FC} \) the fuel cell current (A), \( F \) Faraday’s constant (C kmol\(^{-1}\)), \( k_i \) modeling constant (kmol (sA\(^{-1}\))\(^{-1}\)).

When the output flow is replaced by Eq. (1) and the first order differential equation (Eq. (3)) is solved, hydrogen partial pressure can be rewritten in the time domain as:
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