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Dynamic modelling of PEM fuel cell of power electric bicycle system

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ABSTRACT

Fuel cells eliminate pollution caused by burning fossil fuels; hence, a proton exchange membrane fuel cell (PEMFC) is one of the promising technological advances for the future of the transportation industry. The key existing challenges for fuel cell commercialization are performance, design and vehicle efficiency. Since the analytical model expressing fuel cells' characteristics is not accurate in comparison with the real system's performance a robust and dynamic model for fuel cells is of great importance. This study aims to introduce an optimized model for PEMFC using an electric bicycle that consists of a 250 W fuel cell, battery pack, DC/DC convertor, electric motor and electric control unit (ECU). In the first phase of this multi-fold study, the analytical model of PEMFC's efficiency has been compared with the experimental results obtained from the electric bicycle. The result of this phase showed an overall system efficiency of 35.4% and a maximum fuel cell efficiency of 63%. This confirms that fuel cell performance is least efficient when functioning under maximum output power conditions. In the second phase of this research, the collected data was used for developing linear and nonlinear regression models. The resulting model was compared with an artificial neural network used for the same purpose, and their prediction efficiencies compared. Results show that neural network modelling improves accuracy and provides promising performance for the electric bicycle system.

Introduction

In recent decades, factors like awareness of health problems related to high air pollution levels and dwindling oil fuel reserves have highlighted the need for a replacement for the internal combustion engine (ICE) [1,2] with green energy resources even though ICE vehicles have high efficiency, near zero emissions, and recyclability [3]. Among the development of new energy technologies, fuel cells with sufficient efficiency and low emissions are considered as one of the most promising vehicular power sources [4,5]. A fuel cell (FC) is an electrochemical energy conversion device that generates electricity by mixing hydrogen and oxygen in electrolyte [6]. In FC systems, hydrogen and oxygen atoms undergo an electrochemical reaction; they release a considerable amount of power in the form of electrical current with water molecules as a by-product.

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Among various FC systems, a proton exchange membrane fuel cell (PEMFC) is a promising FC system for vehicular transport due to its quick start-up, high efficiency, high power density and low emissions [7,8]. However, the efficiency of PEMFC systems is strongly related to environmental factors and the combined-system's performance [9]. The actual efficiency of PEMFC was calculated from the experimental values of PEMFC variables [7] based on generated electric energy versus the energy of the consumed hydrogen. Evaluation of PEMFC efficiency confirmed its association with hydrogen flow rate and system output voltage [10].

Improving power density performance and PEMFC efficiency in various operating conditions is considered challenging issues in this field [11,12]. Modelling and optimization of model are helpful for the efficiency, viability and robustness of PEMFC. Therefore, modeling the efficiency and performance of PEMFC is of great value for both controlling and improving the performance of these systems. Studies which aimed to optimize PEMFC system models have used two different approaches, analytical models [13–16] and empirical models [17–19]. The main complication inherent to analytical models is their dependency on specific knowledge based on electrochemical phenomena [13–16]. Empirical models benefit from the regression of system variables without considering the electrochemical phenomena of fuel cell [17–19].

Among various suggested empirical models [20–33] linear regressions (LR) and artificial neural networks (ANN) have shown promising results due to their simplicity compared to other analytical models in recent studies. Zhi-Dan Zhong et al. predicted the performance of a PEMFC by using a support vector machine to model the behavior of PEMF under different operating conditions [30]. Dong'an Liu et al. proposed a least squares-support vector machine for simulating PEMFC to investigate the effect of an assembly error of the bipolar plate (BPP) [31]. Puranik et al. presented a neural network model for 500-W PEMFC and analyzed the dynamic behavior of fuel cell [20]. Ou et al. tested various neural network models for cell voltage and developed two novel hybrid neural networks with greater accuracy [24]. Cheng presented a RBFNN for estimating PEMFC parameters and applied an effective and economical genetic algorithm for optimizing the performance of the design factors [25]. Meiler et al. investigated multilayer perceptron neural networks to identify the parameters of the model from limited experimental data [27]. Bhagavatula et al. investigated neural networks to estimate the performance of a PEMFC single cell with predictions closely matching experimental data [28]. Chang proposed a radial basis function RBF neural network for estimating PEMFC parameters and applied particle swarm optimization to minimize errors and achieve reliable and accurate estimations [32]. Hasikos et al. applied an ANN with a radial basis function to simulate a PEMFC system for minimizing the consumption of hydrogen, showing that a dynamic behavior model can successfully minimize the consumption of hydrogen [33].

Although recent studies have used various algorithms to model the PEMFC stack, to the best of the authors' knowledge a whole PEMFC system integrated with an electric vehicle such as an electric bicycle has not yet been modelled. Optimizing the performance of a whole system is challenged by the conventional usage of these systems when adjusting the optimization of the whole vehicle with auxiliary components. It is notable that designing a reliable model of PEMFC is an essential step toward providing effective control and system analysis. Therefore, this study aims to explore both optimized linear and non-linear models for predicting fuel cell system variables integrated with an electric bicycle. This model can be utilized for controlling system optimization while avoiding identification of the internal parameters of the fuel cell. In this study, an optimized ANN model was suggested for predicting the output of a 250-W proton exchange membrane fuel cell system in comparison with classical regression methods. This paper is structured as follows: Section 2 describes PEMFC and its systems with a brief introduction of the data collection and modelling applied to the system. In Section 3 the simulation results are given. Finally the conclusion is stated in Section 4.

Methodology

System description

The system used in this study is a commercial PEMFC assisted 25-Kg bicycle. As shown in Fig. 1(a) a bicycle was assisted by a PEMFC consisting of three parts: a cathode and an anode that act as electrolytes formed by platinum-catalysis and the membrane [7]. Schematics of a single cell fuel cell are shown in Fig. 1(b). PEMFC is in the center of system with auxiliary components like electric control unit (ECU), the cooling and reaction air blower that assist in producing electricity.

At the anode, molecules of hydrogen are split into electron and proton as follows:

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

Electrons are released from hydrogen and move along the external load circuit to the cathode creating the electrical output current. Electrons hit the cathode from the external circuit concurrently reacting with oxygen molecules that are joined with a platinum catalyst and two protons (which have moved through the membrane) to create water molecules; this reduction at the cathode is represented in Eq. (2) [34]:

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

where the overall reaction is:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{3}$$

During the reaction a portion of the energy is expended in the form of heat released as a byproduct from the respective redox reaction. The maximum current that system can produce is 20 A. Table 1 displays the nominal fuel cell specifications.

Data collection

In this study, data was collected using the described stationary bicycle with the tire spinning freely on a traditional kickstand. For connection between Fuel Cell ECU and monitoring software, a system (DAQ) designed by MES S.A has been used. The pressure of hydrogen was set to different ranges based on

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