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Fuzzy PID control of a stand-alone system based on PEM fuel cell

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ABSTRACT

Fuel cell (FC) systems are appropriate candidates as alternative energy sources for use in stand-alone applications. However, the FC generates an unregulated voltage, which is not suitable in stand-alone application usage solely. This paper presents the control of stand-alone application based on fuzzy PID (FPID) controller. The aim of this paper is designing and controlling a suitable power conditioning unit (PCU) that consists of two DC/DC converter stages and DC/AC inverter. In addition, an analysis of cascade structure based on fuzzy PID controller for a single phase inverter is done and also two feedback control loops are comprised. Inductor current and capacitor voltage are measured and sent through feedback to the inner loop and the outer loop, respectively. Besides, to evaluate the proposed controller robustness, the PCU is considered under step loads as disturbance. Finally, it is shown that the proposed controller has a robust behavior and good transient response.

Introduction

In last decades, traditional methods of producing electricity such as burning fossil fuels have destructive environmental impacts. For example, it causes increase in greenhouse-gas emissions contributing to global warming [1,2]. Nowadays, fuel cell technology is considered as a suitable alternative to several applications. Polymer exchange membrane fuel cell (PEMFC) has many advantages such as low temperature, high-power density, and fast response compared with other types of fuel cells. However, high cost despicable reliability and short-term of PEMFCs still limit their widespread use in real practical [3,4]. A large number of fuel cell systems installed for power stations around the world for use in hospitals, hotels, office buildings, schools, power plants and even airport terminals. PEM fuel cells are a good source of energy for supply stationary-state power, but they cannot answer load changes as fast as it will be taken. The main disadvantages of fuel cells are load current variations and extreme load fluctuations causing voltage fluctuations and power problems at the time. This problem can be solved by using proper power converters and control strategies.

Fuel cells have numerous applications such as stand-alone and grid-connected. Therefore, the power conditioning unit is needed to process the raw power output of fuel cell in order to make it usable. The purpose of conditioners is to adapt the fuel cell electric power to suit the electrical needs through application. Recently, several control strategies were excl presented for PEMFC systems application such as feedback linearization [5], sliding-mode control [6]. However, some observer strategies were presented for estimation of key states of PEMFC systems with exclusive application such as HOSM observer [7]. Also, for all of the above methods, fuel cell was controlled and observed as an exclusive application.

The power conditioning unit may have a DC/DC converter to increase the DC output voltage or DC/DC converter stages and DC/AC single-phase inverter. DC/DC converters are used in applications which an average output voltage is required. It can be higher or lower than the input voltage.

Single-phase inverter of the stationary fuel cell systems has been installed around the world. Inverter is widely used in backup electricity generation for critical loads such as computers and life-support systems in hospitals, hotels, office buildings, schools, power plants, and even in airport terminals, and communications systems [8]. Previous research summary about the invertors controls are listed below:

In 2012, a fuzzy self-tuning PID controller for single phase sine inverter with high-frequency links for small wind power systems were offered and designed by Liu et al. in order to improve the reliability and efficiency of energy conversion [8].

In previous researches, there are many control techniques for producing pure sinusoidal output voltage with low total harmonic distortion (THD) and fast dynamic response. Initially, a PID conventional controller for single-phase inverter was presented [9]. Many low-cost methods for discrete time by microcontrollers such as [10], sliding mode control, and [11–13] deadbeat-based control are designed in order to increase the inverter system features. In

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addition, various methods have been reported for inverter control systems including control based on neural networks [14], and fuzzy logic [15].

Discrete methods such as sliding mode, sliding mode control and deadbeat-based control have been implemented to deal with the lack of uncertainty, but problem occurs during hardware implement.

However, the previous research has examined DC/DC converters, it can be noted that ON–OFF procedure allowed them to have power converters. Since ON–OFF is the only admissible operation mode for power converters, therefore, from discrete control points of view, sliding mode is a convenient tool for monitoring current and voltage. The main obstacle to the implementation of sliding mode control is a phenomenon known as chattering in control literature [16] caused heat losses at high switching frequency in power converters [17]. Another method of control, deadbeat control which has been proposed can be used in digital systems. Some writers take this approach as a way to extend the sliding mode in discrete-time systems.

Conventional PI and PID methods are now used in approximately 90% of industrial control loops worldwide to facilitate the implementation of the method. However, conventional PID controllers are insufficient to control processes with complexities such as time delay, significant oscillatory behavior, parameter uncertainty and disturbances. The necessary conditionings for implementation of the conventional PI and PID controllers are the tuning parameters and additional functionalities including anti-windup, feed forward action, and set-point filtering [18].

Fuzzy control is an intelligent, cost-effective nonlinear control. The combination of a PID with a fuzzy control strategy means that PID control has nonlinear characteristics. Fuzzy control strategy makes more sense to enhance conventional PID's performance by making up the areas in which the PID gains do not do so well. The fuzzy self-organizing controller readjusts the PID gains in real-time to improve the process output response and act as adaptive PID, during system operation under parameter uncertainty and disturbances [18].

This study aims to model a stand-alone application consists of a PEMFC as the primary energy source, DC/DC boost converter and voltage source DC/AC inverter. The output voltage of PEMFC is unregulated DC voltage, which fluctuate with load variations. At no load, the output voltage of fuel cells is the highest and with the increase in current, the output voltage decreases. The fuel cell is modeled as the main and unregulated input source with 150 V DC and the boost DC/DC converter is used to regulate an output voltage of the PEM fuel cell system to 215 V. The boost DC/DC converter is controlled by a feedback controller, which is boosted voltage, based on a fuzzy PID. The DC/DC boost converter output voltage is fed to the DC side of the inverter in order to produce an AC current and voltage for grid connection.

The control structure of single phase inverter is consisted of two loops and has been arranged in a cascaded structure. The control structure is comprised of two loops such as inductor current as the inner loop and output voltage as the outer feedback loop as cascade controller. Control law is based on the design of current mode fuzzy PID controller.

The fuzzy PID control strategy is designed for two systems of DC/DC converter and DC/AC inverter in this research. The fuzzy PID control is an intelligent, nonlinear and robust control which improves traditional PID's performance by readjusting the PID gains in on-line and real-time. The fuzzy self-organizing controller (as fuzzy PID) is a robust controller improving the process output response in system operation with parameter variations and load disturbances. The proposed fuzzy PID controller automatically changes the gains of K_p, K_i and K_d with any load variations.

In this paper, a stand-alone system based on fuel cell as the primary energy source and voltage source inverter is proposed using fuzzy PID controller to produce a quality sinusoidal output voltage. And also a control strategy using fuzzy PID controller is presented for DC/DC boost converter. The proposed single-phase inverter is suitable for residential power generation, especially for stand-alone applications. The control technique also has strong robustness, excellent dynamic, and static characteristics.

The paper is organized as follows: Section 'PEM fuel cell dynamic model' presents dynamic modeling of PEM. Section 'Power Conditioning Unit (PCU)' introduces structure of power conditioning unit (PCU). The DC/DC converter design and control process is introduced in Section 'DC/DC boost converter'. The AC/DC inverter design and control are presented in Section 'Single-phase inverter DC/AC'. Section 'Fuzzy logic control' presents fuzzy control design and implementation. The simulation results that validate the developments are shown in Section 'Simulation'. Finally, Section ' Conclusion' some conclusions are presented.

PEM fuel cell dynamic model

The PEMFC model proposed in [19–21] is modified for this research. The presented PEMFC model is made using the relationship between output voltage and partial pressure of oxygen, hydrogen, and water. q_{H_2} is hydrogen molar flow (mol/s). The relationship between the molar flow of hydrogen gas through the valve with its partial pressure is expressed as [19]:

$$\frac{q_{H_2}}{P_{H_2}} = k_{H_2} = \frac{k_{an}}{\sqrt{M_{H_2}}} \tag{1}$$

where k_{an} and M_{H_2} represent valve constant of anode and hydrogen molar mass, respectively. There are three important factors for hydrogen molar flow such as: hydrogen input flow, hydrogen output flow, and the reaction hydrogen flow [20,21]. The relationship between these factors is presented in the following equations:

$$\frac{d}{dt}P_{H_2} = \frac{RT}{V_{an}}\left(q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r}\right) \tag{2}$$

where V_{an} is volume of the anode side. The relationship between hydrogen reacted flow rate and the fuel cell current according to the basic electrochemical relationship is given by [19,20]:

$$q_{H_2}^{r} = \frac{NI_{fc}}{2F} = 2K_r I_{fc} \tag{3}$$

where K_r is a modeling constant. The s domain of the hydrogen partial pressure is attended by applying Laplace's transform, Eqs. (1) and (3) in the following [19,20]:

$$P_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2}s}\left(q_{H_2}^{in} - 2K_r I_{fc}\right) \tag{4}$$

where

$$\tau_{H_2} = \frac{V_{an}}{K_{H_2}RT} \tag{5}$$

Similarly, the oxygen partial pressure and water partial pressure can be calculated.

The ideal standard potential of a PEM fuel cell is 1.229 V (25 °C and 1 atm) with liquid water product. The actual fuel cell potential is decreased from its equilibrium point because of irreversible voltage losses occurring in fuel cell systems. Several sources contribute to irreversible losses in a practical fuel cell. The losses, which are often called polarization over voltage, originate from three sources such as activation polarization, ohmic polarization and