Fuzzy Logic Based Constant Voltage Control of Fuel Cells

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Abstract
Proton exchange membrane fuel cells have been receiving more and more attention these recent years. Maintaining a fuel cell system in correct operating conditions requires good controller. Based on the mathematical model of proton exchange membrane fuel cells described in this paper, the fuzzy logic controllers was designed for the proton exchange membrane fuel cell to make it possible to output constant voltage. Simulation results show that the proposed fuzzy controllers can give good control effects.

Keywords: constant voltage, fuel cell, fuzzy control

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1. Introduction
The world is facing an energy crisis as well as significant environmental problems. It is known that fossil fuels such as petroleum, natural gas and coal are the main resources for generating electricity. But they also have been major contributors to environmental problems. Renewable bio energy is viewed as one of the ways to alleviate the current global warming crisis. Major efforts are devoted to developing alternative electricity production methods [1], [2].

Fuel cells are promising energy sources that produce electrical currents with almost null pollutant emissions [3]. Fuel cell technology plays an important role in the development of alternative energy converters for mobile, portable and stationary applications. In the recent years there was an increasing interest in fuel cell technology. One of the most interesting fuel cells types is the proton exchange membrane fuel cell (PEMFC) due to its low operating temperature, high efficiency, and low electrolyte corrosion [4]. PEMFC, as the most popular kind of fuel cells in the residential and vehicular applications, when is compared with the other fuel cells, is able to efficiently generate high power densities [5]. PEMFC can be used as emergency and small mobile power supply for outdoors power supply and high reliable and high stable power supply. Besides, on the contrast of centralized power supply, PEMFC can be considered as distribution power supply and be gridded into power supply system for peak modulation.

The performance of PEMFC, being important and getting more and more attention in recent years, is known to be influenced by many parameters such as operating temperatures both fuel cell and humidifiers, pressure, flow rates and relative humidity of fuel and oxidant gases [6]. Significant improvements in proton exchange membrane (PEM) fuel cell technology have been achieved over the past decade. However, the performance, stability, reliability, and cost for the present fuel cell technology are not enough to replace internal combustion engines. The fundamental problems must be overcome to improve their performance and reduce their cost [7].
Maintaining a fuel cell system in correct operating conditions when subjected to fast load changes requires good system control. Fuzzy logic can capture the continuous nature of human decision processes and as such is a definite improvement over methods based on binary logic [8]. Fuzzy control using linguistic information possesses several advantages such as robustness, model-free, universal approximation theorem and rule-based algorithm [9]. Fuzzy logic control is considered to be a useful tool for control system design [10]. The techniques of fuzzy logic control have been used in many applications successfully [11-12]. It is an effective method to solve complex industrial process control.

A constant voltage source is designed to provide a constant voltage over a wide range of load conditions, and this is the most common kind of sources in the applications. A single proton exchange membrane fuel cell model is described in this paper and fuzzy logic controllers for PEMFC are designed to realize constant voltage output. This paper is organized as follows. The mathematical model and a brief description of designing fuzzy logic controllers for PEMFC are described in Section 2. Results and discussion are presented in section 3. Finally, our work of this paper is summarized in Section 4.

2. Research Method
2.1. Modelling the PEM Fuel Cell

Fuel cells are electrochemical devices that convert the chemical energy of a fuel (hydrogen) and an oxidizer (oxygen) directly into electricity. The fuel cell consists of an electrolyte between two electrodes. The electrolyte allows the positive ions (protons) to pass through while blocking the electrons. Hydrogen gas passes over one electrode (anode), and with the help of a catalyst, separates into electrons and hydrogen protons. A graphic representation of a PEM fuel cell structure is given in Figure 1 [13].

Mathematical models and simulation are needed as tools for design optimization of fuel cells. In system studies, it is important to have an adequate model to estimate overall performance of a PEM fuel cell in terms of operating conditions without extensive calculations [14].

PEM fuel cell electrochemical process starts on the anode side where H₂ molecules are brought by flow plate channels. Anode catalyst divides hydrogen on protons H⁺ that travel to cathode through membrane and electrons e⁻ that travel to cathode over external electrical circuit. At the cathode hydrogen protons H⁺ and electrons e⁻ combine with oxygen O₂ by use of catalyst, to form water H₂O and heat. Described reactions can be expressed by the following equations [15-16]:

\[
H_2 \rightarrow 2H^+ + 2e^- \quad \text{(Anode)}
\]

\[
\frac{1}{2}O_2 + H^+ + 2e^- \rightarrow H_2O \quad \text{(Cathode)}
\]
The output voltage \( V_{fc} \) of a single cell can be defined as the result of the following expression

\[
V_{fc} = E_{\text{therm}} - V_{\text{act}} - V_{\text{ohmic}} - V_{\text{con}}
\]  

(3)

in which \( E_{\text{therm}} \) is the thermodynamic potential of the cell representing its reversible voltage, and

\[
E_{\text{therm}} = 1.229 - 0.85 \times 10^{-3} (T_{fc} - 298.15) + 4.31 \times 10^{-5} T_{fc} \left[ \ln(P_{H_2}) + \frac{1}{2} \ln(P_{O_2}) \right]
\]  

(4)

where \( P_{H_2} \) and \( P_{O_2} \) (atm) are the hydrogen and oxygen pressures, respectively, and \( T_{fc} \) (K) is the operating temperature. \( V_{\text{act}} \) is the voltage drop due to the activation of the anode and the cathode:

\[
V_{\text{act}} = 0.9514 - 3.12 \times 10^{-3} T_{fc} - 7.4 \times 10^{-5} T_{fc} \ln(C_{O_2}) + 1.87 \times 10^{-4} T_{fc} \ln(i)
\]  

(5)

where \( i \) (A) is the electrical current, and \( C_{O_2} \) is the oxygen concentration. \( V_{\text{ohmic}} \) is the ohmic voltage drop associated with the conduction of protons through the solid electrolyte, and electrons through the internal electronic resistance:

\[
V_{\text{ohmic}} = i(R_M + R_C)
\]  

(6)

where \( R_C \) (\( \Omega \)) is the contact resistance to electron flow, and \( R_M \) (\( \Omega \)) is the resistance to proton transfer through the membrane, which can be described as

\[
R_M = \frac{\rho_M \cdot l}{A}
\]  

(7)

\[
\rho_M = \frac{181.6 \left[ 1 + 0.03 \left( \frac{i}{A} \right) + 0.062 \left( \frac{T_{fc}}{303} \right)^2 \left( \frac{i}{A} \right)^{2.5} \right]}{y - 0.634 - 3 \left( \frac{i}{A} \right) \exp \left[ 4.18 \left( \frac{T_{fc}}{303} \right) \right]}
\]

where \( \rho_M \) (\( \Omega \cdot \text{cm} \)) is the membrane specific resistivity, \( l \) (cm) is the membrane thickness, \( A \) (cm\(^2\)) is the membrane active area, and \( y \) is a specific coefficient for every type of membrane; \( V_{\text{con}} \) represents the voltage drop resulting from the mass transportation effects, which affects the concentration of the reacting gases and can be described by the following expression:

\[
V_{\text{con}} = -B \ln(1 - \frac{i}{i_{\text{max}}})
\]  

(8)

where \( B \) (V) is a constant depending on the type of fuel cell, \( i_{\text{max}} \) is the maximum electrical current. The output power of the single fuel cell is

\[
P_{fc} = V_{fc} i
\]  

(9)

A generally accepted dynamic model of the PEM fuel cell is modified and shown in Figure 2, in which \( q_{H_2} \) is the input molar flow of hydrogen, \( q_{O_2} \) is the input molar flow of oxygen, \( K_{H_2} \) is the hydrogen valve molar constant, and \( K_{O_2} \) is oxygen valve molar constant [17-18]. Based on the above described mathematical model, a Matlab/Simulink simulation model of the
PEMFC can be set up [19]. Parameters of the Ballard Mark V fuel cell [20] are used in the simulation model.

Figure 2. PEMFC dynamic model

Figure 3. The closed-loop fuzzy control system

2.2. Design of Fuzzy Logic Controllers

On many occasions, constant voltage source are needed. So, control a fuel cell output a constant voltage is necessary. In order to make the PEM fuel cell keep constant voltage output, fuzzy logic controllers for constant voltage output are designed. Fuzzy control (FC) using linguistic information possesses several advantages such as robustness, model-free, universal approximation theorem and rule-based algorithm [21-22]. Figure 3 shows the structure of the closed-loop fuzzy control system.

A fuzzy control system with dual inputs is used to control the output voltage of the fuel cell, where $V_f^c$ is the set point of the output voltage. The error $e(k)$, the change in error $e_c(k)$ and the control output $u(k)$ of the fuzzy controller are given as follows:

$$e(k) = V_f^c - V_f$$  \hspace{1cm} (10)
$$e_c(k) = e(k) - e(k-1)$$  \hspace{1cm} (11)
$$u(k) = u(k-1) + \Delta u(k)$$  \hspace{1cm} (12)

where $\Delta u(k)$ is the inferred change of duty ratio by fuzzy controller.

The triangular type membership function is chosen for error $e$, change of error $e_c$, and change of control variable $\Delta u$. In order to receive good control effect, Z-shaped curve membership function is used for NB of $e$ and S-shaped curve membership function is used for PB of $e$. The fuzzy domain for $e$, $e_c$ and $\Delta u$ is [-1, 1]. The fuzzy set for $e$ is (NB, NS, ZE, PS, PB), and for $e_c$ and $\Delta u$ is (NB, NM, NS, ZE, PS, PM, PB). Fuzzy control rule base is shown in Table 1. The membership functions for input error $e$, change of error $e_c$ and output control $\Delta u$ are shown in Figure 4 to Figure 6. To calculate the output $\Delta u$, the type of fuzzy inference engine is Mamdani. The centroid method is used for defuzzification.

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Fuzzy Logic Based Constant Voltage Control of Fuel Cells (Liping Fan)
In order to find an appropriate control method, two fuzzy control schemes are designed and compared in this paper. One is designed to control the output voltage by adjusting the hydrogen flow, and the other is designed to control the voltage by adjusting the oxygen flow. The fuzzy controller is designed as same as each other, and the satisfied control effects are attained by chosen appropriate quantifying factors. The 3-dimensional representation of the change of control variable $\Delta u$ for fuzzy variables ($e$, $ec$) is shown in Figure 7.

3. Results and Discussion

Simulations are done in the Matlab/Simulink platform. The main parameters used in the simulation are: $A=50.6 \text{cm}^2$, $B=0.016 \text{V}$, $I_{\text{max}}=75.9 \text{A}$, $T_c=343 \text{k}$, $R_c=0.0003 \text{\Omega}$, $l=0.0178 \text{cm}$, $\psi=23$. When controlled by adjusting oxygen hydrogen flow, $P_{O_2}=1\text{atm}$; and when controlled by adjusting oxygen flow, $P_{O_2}=1\text{atm}$.

The reference output voltage of the fuel cell is set at 1.5V. In order to test the anti-disturbance capability of the controllers, the load perturbation is considered by setting the load change from 5\(\Omega\) to 10\(\Omega\) at the time of 5s. Two controllers are designed separately to control the output voltage of the fuel cell by adjusting oxygen flow or hydrogen flow. Simulation results of the output voltage and output power of the fuel cell controlled by the two fuzzy controllers are shown in Figure 8 to Figure 9.

It can be seen from Figure 8 to Figure 9 that all the two fuzzy controllers, either adjusting oxygen flow or adjusting hydrogen flow, can receive good control effects on maintaining constant output voltage even though there appears a load disturbance; while a fuel cell without control output a transilient voltage when disturbance appears. Fuzzy control can make the fuel cell track setting voltage well and realize constant voltage output, even though load changing has arisen. Both oxygen flow and hydrogen flow can be used as operating variable, and the control effects are similar, but the tracking time spent by adjusting oxygen flow is a bit shorter than that of hydrogen flow.
To improve the running performance of PEMFC by advanced control is an effective method, but there is not enough achievement by now. Moreover, it can be found from research literature that all the methods for controlling the output of PEMFC system are with the aid of adjusting the converter linked behind the PEMFC, and this cannot improve and steady the performance of PEMFC itself. Compared with other researches which are reported in public up to now, the fuzzy controllers proposed in this paper can improve the running performance of PEMFC itself and make a single PEMFC or a stack of PEMFC in a steady operation state of constant voltage output, and thus make the PEMFC can be used in a real system directly.

4. Conclusions
Proton exchange membrane fuel cells which need to keep the invariable output voltage require good control systems. By using fuzzy logic controller, the fuel cell can not only have fast response characteristic, but also have good steady-state behavior and strong robustness. The suitable fuzzy logic control schemes can get satisfactory results in tracking a given voltage and guarantee that the fuel cells have constant voltage outputs.

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