Performance Analysis and Improvement of a Proton Exchange Membrane Fuel Cell Using Comprehensive Intelligent Control

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Abstract- To analyze and improve the performance of proton exchange membrane fuel cell (PEMFC) stack, this paper conducts research in intelligent comprehensive control of the operational parameters, such as the operating temperature, pressure, mass flows of hydrogen and air for the PEMFC stack, current density, the exhaust emission quantity of reactant gas, and humidity of the hydrogen and air/oxygen. A detailed analysis is presented about the factors which affect the performance of PEMFC stack, including the operating temperature and pressure, the activation polarization loss, Ohmic loss, concentration polarization loss and the influences of the leakage loss, gas crossover, internal current, exchange current density, limiting current density, and internal structures of the stack. An intelligent comprehensive control strategy is proposed and applied to a 500 W PEMFC system for an uninterruptible power system with backup PEMFC and battery power sources. The experimental results show that the current-voltage performance for the PEMFC stack has been improved comparing with the normal performance using the conventional PI control.

I. INTRODUCTION

Due to high efficiency, flexibility with respect to power and capacity, long lifetime and no pollutions, the fuel cells, including the proton exchange membrane (PEM) fuel cell (PEMFC) and the liquid-fed direct methanol fuel cell (DMFC), are rapidly becoming a significant power source in the design and development of the uninterruptible power system (UPS), and their use in a variety of applications is inevitable [1]. The PEMFC converts the chemical energy of hydrogen and oxygen directly and efficiently into electrical energy, so the main characteristics of PEM fuel cells can be summarized as: they produce water in the cathodes as a byproduct, which will not pollute the environment; they have higher efficiency and power density when compared with the heat engines; they operate at low temperatures (<100 °C), which allows a fast start-up; they use a solid polymer as the electrolyte, which reduces concerns related to construction, transportation and safety [2].

To acquire high efficiency of energy conversion and high power density, the PEMFC should be controlled to have low voltage loss when operating at high current density. However, in practical applications, because the output voltage of PEMFC stack depends on the number of unit cells, the stack could have a significant impact on the performance and efficiency, and the heat and water management strategies, which are successful for single cell, but difficult to implement in a stack environment. Both simulation and test on PEMFC have revealed that the current-voltage (V-I) performance of PEMFC stack is affected obviously with respect to the increase of current density, and this causes the operating voltage to decrease sharply. When the current density goes up, the membrane resistance itself remains the same, but the overall equivalent resistance of the stack increases quickly because the water balance in the stack is altered and the moist condition of the membrane may become inappropriate [3].

The performance of a PEMFC at a given set of operating conditions is shown by a polarization curve as in Fig. 1. The V-I curve is a graph of the cell voltage against current density. Fig. 1 illustrates the ideal and actual voltages of a PEMFC. It shows that there are different losses at different current densities. These losses, which are called the irreversible losses, are associated with the internal structures of the fuel cells, the external operating conditions, and control strategies. Four primary irreversible losses that result in the degradation of fuel cell performance are activation polarization loss, Ohmic loss, concentration polarization loss and leakage loss [4, 5].

Fig. 1. Ideal and actual performance curves of a PEMFC

In order to realize appropriate water management and balance for improving the PEMFC performance, the following techniques can be used: (1) Optimization design of the
membrane electrode assembly and the structure of fuel cell; (2) Appropriate approach of water removal; and (3) Appropriate approach of reaction gas humidification. Moreover, in order to improve the reliability and the overall performance of PEMFC systems, a number of design and control strategies have been proposed and some examples can be found in [6]. Many researchers have devoted themselves to the steady-state model of PEMFC, describing the relationship between physical variables through the Nernst equation, the gas diffusion equation, the conservation equations of mass, momentum, energy, species, charge, voltage drop equation, and other governing equations. Most recently, an increasing number of researches have focused on dynamic models for describing the transient response of PEMFC system response with minimal errors [7].

This paper, based on analyzing the performance and basic model of the PEMFC in details in Section II, conducts research work in intelligent comprehensive control of the operational parameters of the PEMFC stack in Section III, such as the temperature and pressure, mass flows of the hydrogen and air, the exhaust emission quantity of reactant gas, and the humidity of the hydrogen and air/oxygen. Experimental results in Section V show that with the proposal control on the stack parameters and water management, the performance of PEMFC is improved.

II. PERFORMANCE ANALYSIS OF PEMFC

The analysis model of PEMFC performance, previously applied in [8], is further developed in this paper. In the proposal model, the PEMFC stack terminal voltage, $V_{\text{stack}}$ is determined by subtracting the various voltage losses from the reversible voltage as the following:

$$V_{\text{stack}} = V_{\text{reversible}} - V_{\text{act LOSS}} - V_{\text{ohm LOSS}} - V_{\text{con LOSS}} - V_{\text{leak LOSS}}$$

where $V_{\text{reversible}}$, $V_{\text{act LOSS}}$, $V_{\text{ohm LOSS}}$, $V_{\text{con LOSS}}$, and $V_{\text{leak LOSS}}$ are the maximum theoretical ideal voltage or reversible voltage, activation polarization loss, Ohmic loss, concentration polarization loss and leakage loss of the PEMFC, respectively.

These voltage losses result in an operating voltage to be less than the reversible voltage, as shown in the typical polarization curve in Fig. 1.

A. Theoretical Reversible Voltage

The theoretical voltage of a fuel cell is expressed as [5]:

$$V_{\text{CELLreversible}} = -\frac{\Delta G}{nF}$$

where $\Delta G$ is the change in Gibbs free energy at the standard temperature and pressure (STP) of 237.34 kJ/mol$^{-1}$, $n$ is the number of electrons per molecule of H$_2$ (2 electrons per molecule), and $F$ is the Faraday’s constant (96485 C/mol).

Because $\Delta G$, $n$, and $F$ are all known at 25 °C, the theoretical fuel cell voltage can also be calculated as 1.23 V.

The theoretical fuel cell voltage changes with the temperature and pressure. The reversible voltage at varying temperature and pressure can be expressed as [9]:

$$V_{\text{reversible}} = N_{\text{CELL}} V_{\text{CELLreversible}} + \frac{RT}{2F} \ln \left( \frac{P_{H_2}^*}{P_{O_2}^*} \right)^{\frac{1}{2}} - \frac{N_{\text{CELL}} \Delta S_{298.15 K}}{2F} (T - 298.15)$$

where $N_{\text{CELL}}$, $V_{\text{CELLreversible}}$, $R$, $T$, $F$, $P_{O_2}$, $\Delta S_{298.15 K}$ are the number of cells in a PEMFC stack, the reversible voltage at STP (V), the universal gas constant (J/mol·K), the temperature of PEMFC stack (K), Faraday’s constant (C/mol), the standard pressure (kPa), the change in the molar entropy at STP (J/mol·K), and the partial pressure of species $m$ (H$_2$, O$_2$/air, and liquid water), respectively.

With the pressure in atmosphere and using the standard values for the constants in the above equation, the reversible voltage is reduced to

$$V_{\text{reversible}} = 1.23 N_{\text{cell}} + \left(4.308 \times 10^{-5}\right) T \ln \left( \frac{P_{H_2}^*}{P_{O_2}^*} \right)^{\frac{1}{2}} - N_{\text{cell}} \left(8.453 \times 10^{-4}\right) (T - 298.15)$$

B. Activation Polarization Loss

The activation polarization, i.e. the activation voltage loss $V_{\text{act LOSS}}$ is due to voltage loss in activating the chemical reactions to take place at the PEMFC electrodes. This voltage loss is important at low currents and can be expressed as

$$V_{\text{act LOSS}} = \frac{RT}{naF} \ln \left( \frac{i}{i_0} \right) = A \ln \left( \frac{i}{i_0} \right)$$

where $a$ is the transfer coefficient, $A$ the Tafel slope which is measured in volts, $i$ the PEMFC stack current density in mA/cm$^2$, and $i_0$ the exchange current density in mA/cm$^2$, which is expressed as [10]

$$i_0 = i_0^{\text{ref}} a_c L_c \left( \frac{P_r}{P_r^{\text{ref}}} \right)^\gamma \exp \left[ -E_a \left( \frac{T}{RT} - 1 - \frac{T}{T_{\text{ref}}} \right) \right]$$

where $i_0^{\text{ref}}$ is the reference exchange current density in A/cm$^2$, $a_c$ the catalyst specific area in cm$^2$/mg, $L_c$ the catalyst loading, $P_r$ the reactant partial pressure in kPa, $P_r^{\text{ref}}$ the reference pressure in kPa, $\gamma$ the pressure coefficient (0.5 to 1.0), $E_a$ the activation energy (66 kJ/mol), $T$ the temperature in K, and $T_{\text{ref}}$ the reference temperature (298.15K).
C. Ohmic Loss

The Ohmic loss $V_{ohmLOSS}$ is caused by the electrolyte resistance $R_{CELLelectronic}$ against the flow of ions through it, and the resistance $R_{CELLmembrane}$ of the electrode material against the flow of electrons. The Ohmic loss is linearly proportional to the stack current and can be given by Ohm's law as

$$V_{CELLOhmLOSS} = i(R_{CELLelectronic} + R_{CELLmembrane})$$

The Ohmic loss of PEMFC is related to the current density, temperature and water content in the membrane. The water content in the membrane is related to the humidity, pressure and stoichiometry of the inlet gases. The relative humidity of hydrogen is of particular importance to water content. In this section it is assumed that the water content has been kept at a reasonable level.

D. Concentration Polarization Loss

The concentration loss $V_{concLOSS}$ is related to the consumption of reactants by the PEMFC. As the reactants are used by the PEMFC, their concentration changes at the surface of the cell electrodes will cause a sharp distinguished drop in cell voltage at limiting current density. Concentration loss is related to the fuel cell current by the following equation

$$V_{concLOSS} = \frac{RT}{nF} \ln \left( \frac{i_L}{i_L - i} \right) = B \ln \left( \frac{i_L}{i_L - i} \right)$$

where $B$ is a concentration loss constant given, and $i_L$ is the limiting current density at which the cell voltage will fall rapidly. $i_L$ is measured in A/cm² and is expressed as $[4, 10]$.

$$i_L = \frac{nFD_{eff} C_B}{\delta}$$

where $D_{eff}$ is the effective reactant diffusivity within the catalyst layer in cm²/s, $C_B$ the bulk concentration of reactant in mol/cm³, and $\delta$ the electrode thickness of the diffusion layer in cm.

E. Leakage Loss and Internal Current

The leakage loss $V_{leakLOSS}$, also called the internal current loss, is associated with the parasitic loss due to current leakage, gas crossover, and unwanted side reaction. In almost all fuel cell systems, some current is lost due to the parasitic processes $[4]$. Reasons for this include the waste of fuel that passes directly through the electrolyte producing no electrons and electron conduction through the electrolyte and not passing through the electrodes. This will have an increasing effect on the current withdrawn from the cell by a value of internal current.

Mathematically,

$$i_{gross} = i + i_n$$

where $i_{gross}$ is the gross current produced at the fuel cell electrodes, and $i_n$ the internal current or parasitic current that is wasted, and $i$ the actual fuel cell operating current, which can be measured and used.

By combining (1), (4), (5), (8), (9) and (11) and introducing the leakage loss, the internal current and fuel crossover equivalent current density, the mathematical polarization curve model of the PEMFC can be obtained:

$$V_{stack} = V_{reversible} - N_{CELL} \frac{RT}{nF} \ln \left( \frac{i+i_L}{i_{o}} \right) + R_{ohmic} \frac{RT}{nF} \ln \left( \frac{i_n}{i_L - (i+i_L)} \right)$$

The most noticeable effect of the leakage current is to reduce the fuel cell’s open-circuit voltage below its theoretical reversible voltage. At high current density, the limiting current density will also be reduced by the leakage current. However, at low and mid-range current density, the leakage current effects are the same as the other ranges. Fig. 2 shows the effect of the leakage current loss on a 300 W 60-cell PEMFC.

Fig. 2. Effect of the leakage current loss on the PEMFC performance

III. METHODS OF IMPROVING PEMFC PERFORMANCE

A lot of work has been conducted on the PEMFC water management by various researchers and some methods have been put forward to control the key PEMFC parameters for improving the PEMFC water management and performance $[3]$.

A. Internal Structure Optimization

As a large amount of water is generated during the operational process, it is important to realize an effective water management. The research of Mosdale $[12]$ indicated that changing the plate structure by using a porous carbon electrode to substitute for the traditional plate with the flow field could prevent the membrane from dehydration. Dhar $[13]$ prevented...
the water loss by optimizing the membrane electrode assembly structure. Wood et al. [14] improved the water balance in PEMFC by designing a new kind of gas flow channel.

B. Draining Methods

The PEMFC has two ways of draining: one is the liquid draining method and the other is the gaseous draining method [15, 16]. The liquid draining method mainly enhances the waterproof performance of the fuel cell’s cathode, thus it makes the water in the side of the anode directly discharge with the liquid state through the liquid flow channel of the cathode. Using the liquid draining, the stack will more or less lose part of the reaction area, lowering the polarization performance of the cathode. Considering that the polarization of PEMFC mainly happens on the cathode, it is not the best way to adopt the direct liquid draining.

The gaseous draining is to improve the fuel cell structure to form a certain water concentration gradient from the cathode to the anode. Thus the water generated in the cathode may return to the anode and discharge along with the anode exhaust emission in the state of gas. Because this method drains water through the anode, it has little influence on the cathode polarization and hence the fuel cell performance is better.

C. Humidification of Reactant Gas

In order to prevent the effect of water loss of the proton exchange membrane on the performance of PEMFC, the hydrogen and the air entering the stack should be humidified previously. At present, there are four methods of humidifying: increasing temperature, injecting steam, circulating humidity, and direct liquid water injecting humidity. These methods can be found from relevant publications.

D. Intelligent Comprehensive Control of PEMFC Parameters

Regarding the comprehensive control, there exist little publications. According to the operating parameters of PEMFC stack, such as the pressure, humidity and input and output mass flow of the hydrogen and the air, operating temperature, and current density, this paper presents an intelligent comprehensive control strategy to improve the PEMFC performance. The control strategy includes the operating temperature control, the current density monitoring and control, humidification control, control of the pressure and the exhaust emission quantity of reactant gas, fuzzy logic control for mass flows of the hydrogen and air.

1) Intelligent Control of Operating Temperature

The PEMFC belongs to the low temperature stack (<100°C) in the fuel cell family, but its operating temperature is still higher than the ambient temperature and should be maintained within an appropriate range. The operating temperature is selected according to the characteristics of the PEMFC offered by the manufactures. In this paper, the best operating temperature employing the PEMFC is at 60–65°C according to the operating temperature demands, otherwise the performance of the PEMFC will deteriorate.

The work in this paper uses two kinds of cooling method: air cooling and water cooling. Under the low current and power (<200W), it is possible to use the air cooling to obtain a satisfactory result. However, when operating in high current and power, the stack should adopt the water cooling. The heat management system of PEMFC will be controlled.

The intelligent control rules are:

- If the current is in the range of 5–10 A and the temperature is less than 60 °C, air cooling is applied;
- If the current is in the range 10–30 A and the temperature is less than 65 °C, both air cooling and water cooling are applied;
- If the current is over 30 A or the temperature is over 65 °C, the PEMFC stack is shut down.

2) Monitoring and Control of Power Density

A double closed-loop (current and voltage) control system has been developed for the PEMFC. According to the real-time current and power, which is about 200 W, the intelligent comprehensive controller passes distilled water through the cooling loop of the stack. Up to about 150~200 W of the power, the stack can be cooled using the cooling fans provided with the stack.

3) Intelligent Humidification Control

In the PEMFC system, an advanced intelligent humidification control system E-7000 (BRONKHORST HIGH-TECH®) is applied. The E-7000 has two separate modules as shown in Fig. 3. There are two controllers: one is a temperature control for the controlled evaporator mixer (CEM) system in order to power the heater; the other is a modular digital readout and control system with the mass flow sensors and controllers, which is used to control the liquid water mass flow and the mixing of the hydrogen with the water evaporator. The hydrogen relative humidity is controlled within 75~95%, and the air relative humidity is within 65~95%.

4) Constant Control of Pressure and Exhaust Emission Quantity of Reactant Gas

An increase in PEMFC operating pressure results in higher cell voltage according to the Nernst equation and the increase in exchange current density due to increased concentration of reactant gases in the PEMFC electrodes. There are two methods for exhaust emission. One is the continuous exhaust emission, namely adding a resistance limiting device in the stack to guarantee that the reactant gas pressure is at a predetermined value, and has a stable value of air displacement, which closely corresponds to the purity of the reactant gas and the resistance between cells. By using the continuous exhaust emission
method, the reactant gas pressure in the stack is stable, but the rate of utilizable reactant gas is low. The other method for exhaust emission is the pulse method, namely adding a normally closed solenoid valve for the exhaust emission. Thus the exhaust emission quantity can be controlled by the opening frequency and opening time of the valve. Generally the discharging time is fixed. In order to enhance the rate of utilizable reactant gas, the opening frequency and opening time of the valve can be adjusted according to the working current of the stack. The advantage of the pulse exhaust emission method is that the rate of utilizable reactant gas is high, and it can alleviate the undulation of the working pressure of the reactant gas, which is caused by the uneven resistance among various cells in the stack. The undulation could damage the membrane electrode assembly.

According to the demands of the PEMFC, this paper adopts the steady pressure equipment and the pulse exhaust emission method to control the reactant gas pressure. The system can also control the hydrogen pressure at about 34.5 kPa. An air compressor is used to feed air. After the gas pressure reaches the predetermined value, the air quantity in the air compressor should be controlled according to the rate of utilizable air and the working current of the stack decided by the experiment. The air pressure value is adjusted to about 68.9 kPa.

5) Fuzzy Logic Control of Mass Flows of Hydrogen and Air

The fuzzy-PI controller input variable are the voltage error \( e(k) \), and the change of error \( c(k) \). The output variables of the controller are the optimal \( P \) and \( I \) gains of a subsequent PI controller device, one of them gives the proportional part \( K_p \) as a function of \( e(k) \) and \( c(k) \), and the other gives the increment \( \Delta T \), which is then integrated to provide the integral term \( T \) of the PI controller. There are seven fuzzy subsets: positive big (PB), positive medium (PM), positive small (PS), zero (ZE), negative small (NS), negative medium (NM), and negative big (NB), have been selected for the input and output variables \( e(k) \), \( c(k) \), \( K_p \) and \( T \). The fuzzy control rules are obtained from the behavior analysis of the PEMFC system. Because the rule-base represents the intelligence of the controller, the formulations must be carefully considered. Correct use of control laws according to the operating conditions can greatly improve the system stability. A fast response with a small overshoot for the PEMFC system can be achieved with proper handling of the proportional and integral part. It is the cause that the fuzzy-PI controller is more advantageous than a standard PI controller [17].

The selected control rules or laws are described as follows:

When the output voltage is far from the set point \( (e(k) \) is PB or NB), the corrective action must be strong; this means that \( K_p \) should be NB (or PB) while \( T \) should be zero (ZE), in order to prevent the continuous increase (or decrease) of integral term that would cause overshoots. In this case, the change of error plays little part.

The basic control rules are:
- If \( e(k) \) is PB, then \( K_p \) is PB and \( T \) is ZE;
- If \( e(k) \) is NB, then \( K_p \) is NB and \( T \) is ZE.

When the output voltage is close to the set point, the change of error must be properly taken into account in order to ensure stability and speed of response. The goal of the fuzzy controller is to achieve a satisfactory dynamic performance with small sensitivity to parameter variations.

The control rules are:
- If both \( e(k) \) and \( c(k) \) are ZE, then \( K_p \) and \( T \) are ZE;
- If both \( e(k) \) and \( c(k) \) are negative, \( K_p \) and \( T \) are negative;
- If both \( e(k) \) and \( c(k) \) are positive, \( K_p \) and \( T \) are positives.

The detail design procedures can be found in [9].

IV. TEST CONTROL SYSTEM

The PEMFC test system is comprised of PEMFC hardware module and control software. The hardware module consists of a PEMFC stack, water cooling and air cooling system, hydrogen humidification filtering and water management system, the sensors for temperature, pressure, humidifying, voltage and current, the actuators for all kinds of valves, mass flow controllers, and the electronic control units. There are three gases used to operate this system: hydrogen and oxygen. The control software could be used to control the whole process. The block diagram is shown in Fig. 4.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The proposed intelligent comprehensive control strategies have been implemented in the PEMFC test system. Based on the intelligent comprehensive control, the output voltage and current values of the stack are controlled according to the operating parameters of the PEMFC stack. The intelligent comprehensive control performance curve and the conventional PI control performance of PEMFC stack are given in Fig. 5.

In general, higher operating temperature is desirable due to decreased mass transport limitations and increased electrochemical reaction rates; at the same time, high temperatures may lead to increased mass transport losses due to the increases in water vapor. Therefore, in this experiment, the stack temperature is controlled within 60~65 °C, in order to keep the water balance and reduce the effect of the internal resistance or Ohmic losses.

This paper adopts the steady pressure equipment and the pulse


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exhaust emission method to control the reactant gas pressure, while the maximum hydrogen pressure is 34.5 kPa and the maximum air pressure is 68.9 kPa. For given conditions, the stack voltage gain at elevated pressure applies to any current density, which results in an elevated polarization curve at elevated pressures. In addition, the elevated pressure may have an effect on the exchange current density and the limiting current density by improving mass transfer of the gaseous species. According to (6), we could analyze the effect on the exchange current density. As we have previously discussed, the limiting current density (10) shows that the limiting current density depends on the coefficient $D_{\text{eff}}$, $C_B$ and $\delta$ where $D_{\text{eff}}$ and $\delta$ are mostly determined by the electrode. Furthermore, the limiting current density only has an effect at very high current densities approaching the limiting current density. At low current densities there is almost no effect. Therefore, at high current densities, there is an elevated polarization curve.

Therefore, the experimental results reveal that when the intelligent comprehensive control method is introduced, the output voltage and current characteristics could be elevated. In other words, the V-I characteristics of PEMFC stack becomes the elevated performance.

Fig. 5. Experimental results of the performance of PEMFC stack

VI. CONCLUSION

In this paper, based on the performance and basic model analysis of the PEMFC stack and its existing control methods, an intelligent comprehensive parameters control method is developed for improving the PEMFC performance at different operational conditions. A fuzzy logic controller has been designed to basically control the input and output mass flow rates of hydrogen and air. The proposed intelligent comprehensive control includes the intelligent temperature control, the current and power density monitoring and control, intelligent humidifying control, pressure control, and fuzzy logic control for the mass flows of hydrogen and air. The experimental results have proved that the proposed intelligent comprehensive control can work better comparing with the conventional and normal PI controller. A major advantage of the intelligent comprehensive control over the existing conventional PI control is its capability to further improve the V-I performance of PEMFC.

REFERENCES