

A simple PEM Fuel Cell Emulator using Electrical Circuit Model

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Abstract—This paper presents the development of a simple emulator for proton exchange membrane (PEM) fuel cell. This emulator is built based on the dynamic model of PEM fuel cells using electrical circuits. The electrical circuit model has been modeled in Matlab Simulink environments. The double-layer charging effect characteristic inside the fuel cell is included in the models. The steady-state and transient response of the model is investigated. Emulator performance is validated using experimental data from a 500-W commercial PEM fuel-cell stack. The emulator could be used in PEM fuel-cell control related studies.

Keywords—component; Fuel Cell Emulator; PEM Fuel Cell; Electrical Circuit Model.

I. INTRODUCTION

Recently, the use of fuel cells in many applications have been received more attention. Fuel cell is a device that converts the chemical energy of a fuel directly to electrical energy. Fuel cell has higher energy storage capability and is a clean energy source [1-4]. Compared with any other energy production technology, the fuel cells have a wider range of applications. Their potential application ranges from systems of a few watts to megawatts.

Currently, there are three general areas of application for fuel cell technology: transportation, portable power supply and distributed power generation. For each application, it is generally found that one type of fuel cell is better suited than the others to satisfy the requirements of the application. The DMFCs are attractive for several applications in view of their lower weight and volume. The DMFCs are increasingly being developed to replace or support batteries, mainly for the high energy density of methanol. The DMFCs are promising candidates as portable power sources because they do not require any fuel processing and operate at low temperatures (30–60°C) [5–7]. The SOFC is a front-runner in distributed power applications at the industrial level because of its high power density and high grade waste heat that may be used in cogeneration applications [8–11].

Proton Exchange Membrane (PEM) fuel cells show great promise for use in distributed generation an electric vehicle applications. Compared with other distributed generation technologies, such as wind and photovoltaic (PV) generation,

PEM fuel cells have the advantage that they can be placed anywhere within the distribution system, without geographic limitations, to achieve the best performance. In electric vehicles application, the increased desire for vehicles with less emission has made PEM fuel cells attractive for vehicular applications since they essentially no pollutants emission and have high-power density and quick start.

PEM fuel cells are good energy sources to provide reliable power at steady state, but they have a slow response [12,13]. This is mainly due to their slow internal electrochemical and thermodynamic responses. In order to optimize the fuel cell performance and also to develop fuel cell power converters for various applications, the transient properties of fuel cells need to be studied and analyzed. Therefore, an appropriate model of a fuel cell is needed.

Some work has been reported in the literature on steady-state fuel-cell modeling [14–16], as well as transient behavior dynamic modeling [17–23]. These studies are mostly based on empirical equations and/or the electrochemical reactions inside the fuel cell. Study of the electrochemical properties of fuel cells and dynamic modeling of fuel cells using equivalent electrical circuit including a capacitor due to the double-layer charging effect inside fuel cells are reported in [24,25].

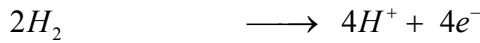
In this paper, a simple emulator for PEM fuel cell is developed based on their electrical circuit model. A comprehensive simulation analysis was conducted to verify the performance of the emulator. The steady-state and transient response of the model is investigated. Finally, the emulator performance is validated using experimental data from a 500W commercial PEM fuel-cell stack.

II. FUEL CELL OPERATION PRINCIPLE

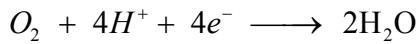
The fuel cells produce electricity from a simple electrochemical reaction, in which an oxidizer and a fuel react to form a product, which is water for the typical fuel cell. The fuel is typically hydrogen, and the oxidizer is usually the oxygen from air. The oxygen (air) continuously passes over the cathode and the hydrogen passes over the anode to generate electricity, by-product heat and water. The fuel cell itself has no moving parts, making it a quiet and reliable source of power. A schematic diagram of PEM fuel cell [24] is shown as in Fig. 1.

The electrolyte separating the anode and cathode is an ion-conducting material. At the anode, hydrogen is split into electrons and hydrogen ions (protons). The hydrogen ions pass through the electrolyte while the electrons flowing through an external electrical circuit. The hydrogen ions combine with the oxygen at the cathode and are recombined with the electrons to form water. The reactions are shown below.

Anode Reaction:



Cathode Reaction:



Overall Cell Reaction:



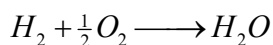
Theoretically, the reaction of H_2 and O_2 will produce a voltage of 1.23 V, but in practice, the real voltage generated from a unit elementary cell of fuel cell is less than this. At the rated current, an elementary cell produces a voltage from 0.6 V to 0.7 V. Voltage decreases as current increases, due to several factors such as: activation loss, ohmic loss (voltage drop due to resistance of the cell components and interconnects), mass transport loss (depletion of reactants at catalyst sites under high loads, causing rapid loss of voltage). To deliver the desired amount of energy, the fuel cells can be combined in series and/or parallel circuits, where series yields higher voltage, and parallel allows a higher current to be supplied. Such a design is called a fuel cell stack.

The potential power generated by a fuel cell stack depends on the number and size of elementary fuel cells that comprise the stack. In operation, the fuel cell stack requires fuel, oxidant, and coolant. The composition, pressure, and flow rate of each of these streams must be regulated. In addition, the gases must be humidified and the coolant temperature must be controlled. To achieve this, the fuel cell stack must be enclosed by a fuel system, fuel delivery system, air system, stack cooling system, and humidification system. When the fuel cells operate, the generated output power must be conditioned and absorbed by a load. The suitable alarms must shut down the process if unsafe operating conditions occur, and cell voltage monitoring systems have to monitor fuel cell stack performance. These functions are performed by electrical control systems

III. PEM FUEL CELL DYNAMIC MODEL

A. Fuel Cell Output Voltage

The overall reaction between hydrogen H_2 and oxygen O_2 in the PEM fuel cell can be simply written as



This reaction is a redox reaction that produces the electrical voltage in the cell. The developed voltage over a single cell is ideally described by the Nernst equation.

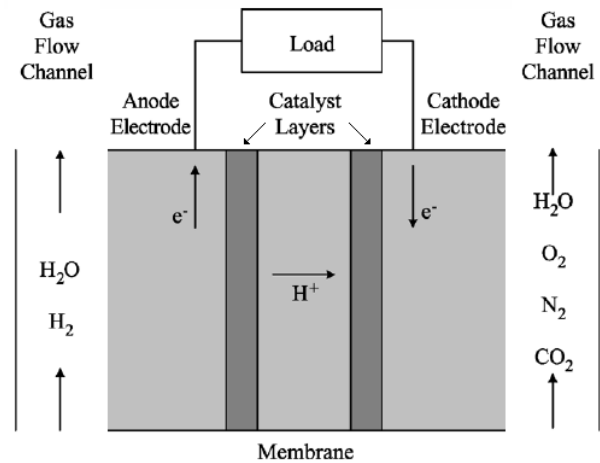


Figure 1. Schematic diagram of PEM fuel cell

$$E_{cell} = E_0 + \frac{RT}{2F} \ln \frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}} \quad (1)$$

Here, E_0 is the standard potential of the hydrogen/oxygen reaction (about 1.23V), R is the universal gas constant, F is Faraday's constant, T is the absolute temperature, and P_{H_2} is the partial pressure of hydrogen available at the anode, P_{H_2O} and P_{O_2} are partial pressures of water and oxygen at the cathode. The calculated E_{cell} is actually the open circuit voltage of cell. However, under normal operating condition, the cell output voltage is less than E_{cell} . Activation loss, concentration overvoltage and ohmic resistance losses cause a drop in the cell output voltage.

More extensive research in [14–25] states that the output voltage of the fuel-cell stacks can be obtained as

$$V_{FC} = N_{cell} E_{cell} = E - V_{act} - V_{conc} - V_{ohmic} \quad (2)$$

In this equation, V_{FC} is the fuel cell output voltage, E is the open circuit voltage, whereas V_{act} , V_{conc} , and V_{ohmic} are the activation, concentration, and the ohmic fuel cell overvoltage respectively. Relationship between the voltage and the current in the cell can be modeled [22,23] as

$$V_{FC} = E - AT \ln \left(\frac{I_{FC}}{I_o} \right) - BT \ln \left(\frac{I_L - I_{FC}}{I_L} \right) - I_{FC} R_{int} \quad (3)$$

in which V_{FC} is the output voltage of the fuel cell, E is the open circuit voltage, I_{FC} is the fuel cell output current, I_o is the exchange current, I_L is the limiting current, R_{int} is the internal

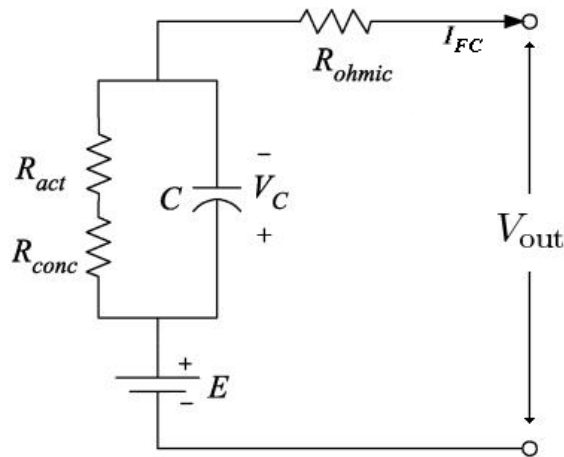


Figure 2. Equivalent electrical circuit of PEM fuel cell

resistance, A is the activation coefficient and B is the concentration coefficient. Furthermore, E , A , and B are dependent on the operating temperature of the fuel cell, whereas the internal resistance R_{int} in the fuel cell depends on the membrane characteristic.

B. Double Layer Charging Effect

From the view point of double layer capacitors, the electrons in a fuel cell will flow from the anode through the external load and gather at the surface of the cathode, to which the protons of hydrogen will be attracted at the same time. Thus, two charged layers of opposite polarity are formed across the boundary between the porous cathode and the membrane [24,25]. The layers, known as electrochemical double layer, can store electrical energy and behave like a super capacitor. The equivalent electrical circuit for the charge double layer effect on the cell voltage is shown in Figure 2 [24,25].

In this figure, C is the equivalent capacitance depending on the charge of the double layer, R_{act} , R_{conc} , and R_{ohmic} are equivalent resistors to the activation, concentration, and ohmic overvoltage respectively. V_C is the overvoltage due to the common effects of the double capacitive layer.

IV. FUEL CELL EMULATOR DESIGN AND IMPLEMENTATION

In this work, the fuel cell emulator is developed by using their electric circuit model from Figure 2. The open circuit voltage (E) of fuel cell is generated using a programmable dc power supply. The activation resistance (R_{act}) and concentration resistance (R_{conc}) are represented by two of 0.33Ω resistor. The capacitor C is modeled using two of $0.1F$ electrolyte capacitor in parallel connection. The ohmic resistance (R_{ohmic}) is assumed to be equal to the internal resistance of the programmable power supply, so it does not need a real resistor in its implementation. The photograph of fuel cell emulator is shown in Figure 3.

V. SIMULATION AND EXPERIMENTAL RESULTS

The fuel cell emulator circuit has been modeled using Matlab Simulink. A comprehensive simulation was conducted



Figure 3. Photograph of PEM fuel cell emulator

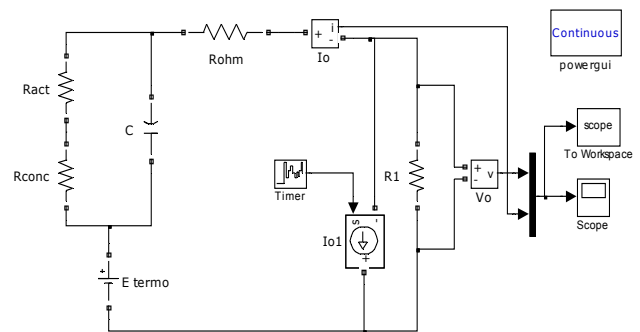


Figure 4. PEM fuel cell emulator simulation model

to verify the performance of the fuel cell emulator. Figure 4 illustrated the Simulink model of the PEM fuel cell emulator scheme.

A representative dynamic PEM fuel cell model has been presented in reference [23]. In order to verify the performance of the proposed fuel cell emulator, the same treatment according to the presented results in reference [23] is conducted. The PEM fuel cell performance results that have

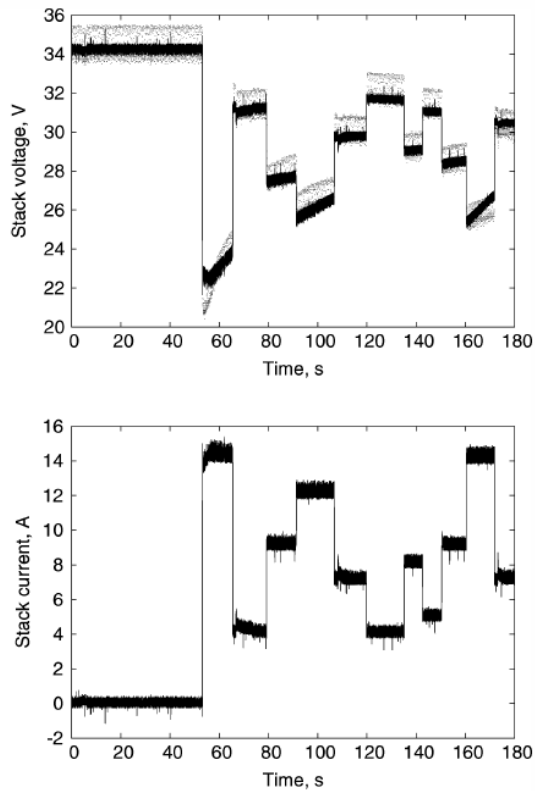


Figure 5. PEM fuel cell performance results, presented in [23]

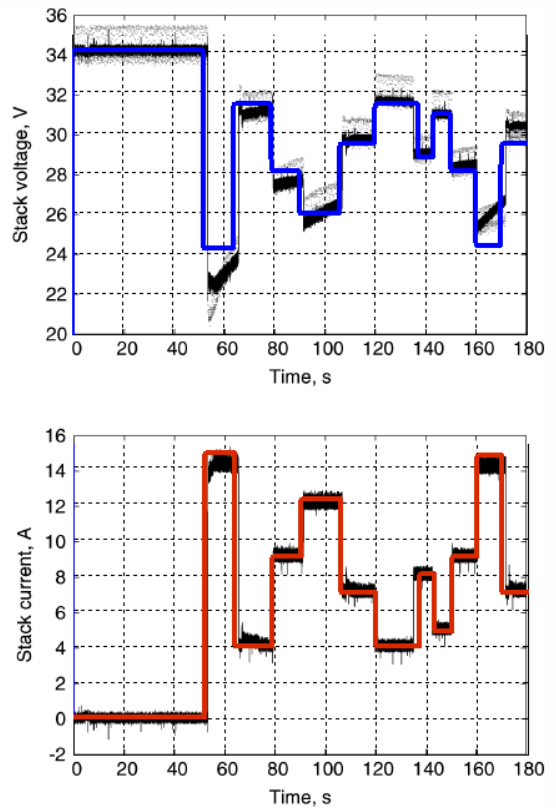


Figure 7. PEM fuel cell performance comparison

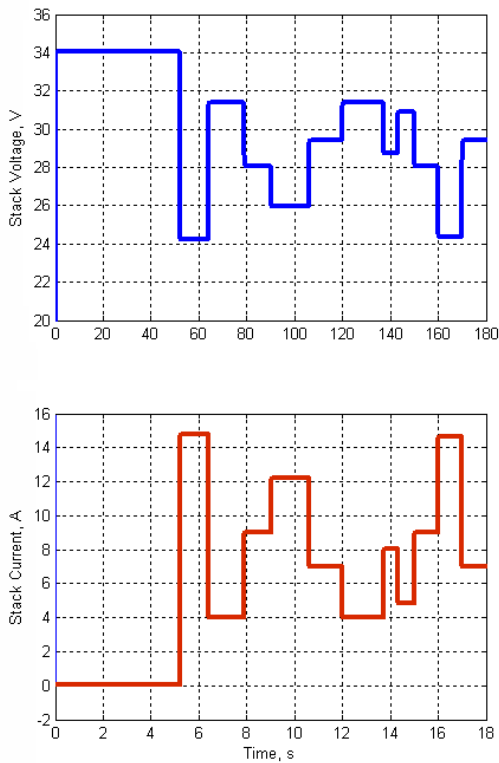


Figure 6. The proposed PEM fuel cell emulator performance results

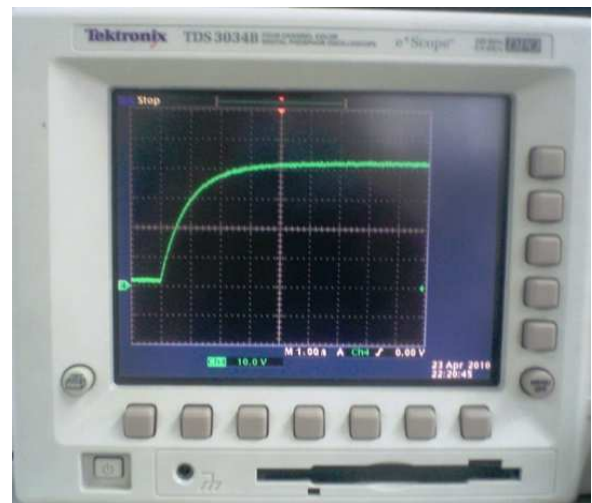


Figure 8. Photograph of PEM fuel cell emulator starting response

been presented in reference [23] are shown in Figure 5, whereas the performance results of the proposed PEM fuel cell emulator are shown in Figure 6.

Figure 7 show the comparison of both of PEM fuel cell performance. The comparison shows that the performance of the proposed fuel cell emulator is not so bad. The comparison results show that the models can predict the electrical response

of the PEM fuel-cell stack under steady-state as well as transient conditions. The models can also show the potential to be useful in external controller design applications for PEM fuel cells.

CONCLUSION

A simple PEM fuel cell emulator was proposed and developed. The performance of the fuel cell emulator under various load current has been investigated. Simulation results show that the emulator can predict the electrical response of the PEM fuel cell stack under steady state as well as transient conditions.

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