Electrical Modeling of 10kW PEMFC

Jinmok Lee, Ga-Woo Park, Jaeho Choi

Chungbuk National University, School of Electrical & Computer Engineering
410 Sungbong-ro, Cheongju, Chungbuk, 361-763, KOREA

Abstract

As arising the cost and decreasing of gasoline and fossil fuel, renewable energy sources such as photovoltaics, wind and fuel cell have been interested. Among of them, PEM fuel cells are good energy sources to provide reliable power at steady state regardless of weather, time of day and location as long as the fuel and air are supplied, but they cannot respond to electrical load transients as fast as desired. This is mainly due to their slow internal electrochemical and thermodynamic responses. Therefore, to use the fuel cells with high efficiency, this paper finds characteristic curve and understand operation of PEMFC based on three theoretical approaches such as activation, ohmic and concentration and make the model using MATLAB. That result was compared with real system to certify.

1. Introduction

As the rising the cost and decreasing of gasoline and fossil fuel, renewable energy sources such as photovoltaics, wind and fuel cell have been interested. These alternative sources make such an impact on environment because they are less or zero emission and operate more efficiently compared to the internal combustion engine like the conventional generators. Among of them, PEM fuel cells are good energy sources to provide reliable power at steady state regardless of weather, time of day and location as long as the fuel and air are supplied, but they cannot respond to electrical load transients as fast as desired. This is mainly due to their slow internal electrochemical and thermodynamic responses[1-3].

Additionally, there are five major types of fuel cells, differentiated from one anther by their electrolyte. Those types operate with different temperature, catalyst and cell components. Especially, PEMFC have advantages which are the light construction and the low temperature (typically 80℃) [4-6].

These qualities are also very convenient in domestic applications as decentralized energy generation system. Because fuel cells are efficient, low voltage, high current DC power generators which have a highly non-linear voltage-current characteristic. Therefore, a good understanding of the electrical behavior of fuel cells is necessary for designing power electronic applications using fuel cells as their main power source.

To find characteristic curve and understand operation, this paper presents the model based on three theoretical approaches such as activation, ohmic and concentration and make the model using MATLAB. That result was compared with real system to certify.

2. Model development

2.1 Chemical reaction

Each PEM fuel cell consists of two electrodes, an anode and a cathode, each of which coated on one side with a thin catalyst and separated by a proton exchange membrane, The hydrogen is flown to the anode while oxygen from air to the cathode, The protons go through the electrolyte while electrons pass the external circuit with a resistance to the cathode. The electrochemical reaction results in electricity and byproduct water vapor and heat. The basic chemical reactions at the electrodes of the PEM fuel cell are as (1~3)

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

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

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

Oxidation refers to a process where electrons are removed from a species. Electrons are liberated by the reaction in the anode side as shown as (1). Reduction refers to a process where electrons are added to a species. Electrons are consumed by the reaction in cathode side as shown as (2). Therefore, total cell reaction can represents by (3).

2.2 Model approach

The fuel cell produces DC electricity and water from the hydrogen and the oxygen by using the electrochemical reactions. In this paper we assumed that the gasses are an ideal uniformly distributed, the operating temperature, gas pressure are constant. The one-dimansional equation in the form of the cell output voltage can be expressed as shown as (4).

$$V_{cell} = E_{thermo} - \eta_{act} - \eta_{ohmic} - \eta_{con} \tag{4}$$

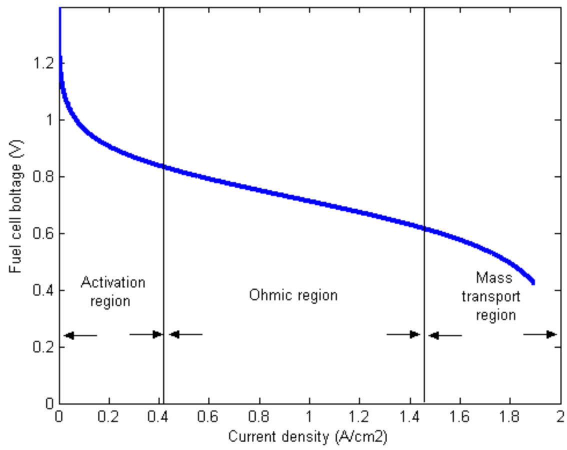

Fig. 1 I-V curve of fuel cell

Saying it again, the voltage output of a real fuel cell is less than thermodynamically predicted voltage output due to irreversible losses. There are three major types of fuel cell losses, which give a fuel cell I-V curve as shown in Fig. 1. This voltage (E_{thermo}) is the thermodynamic potential which depends on operating temperature and the partial pressure of fuel and oxidant. Additionally, three losses are associated with one of the basic fuel cell steps discussed in next. Three losses are activation (η_{act}), ohmic (η_{ohmic}) and concentration losses (η_{con}). The three major losses each contribute to the characteristic shape of the fuel cell I-V curve. The activation losses mostly affect the initial part of the curve and the ohmic losses are most apparent in the middle section of the curve, and the concentration losses are most significant in the tail of the I-V curve.

2.2.1 Activation losses

Activation losses are due to reaction kinetics. In fuel cells, thermodynamically favorable electron transfer processes are harnessed to extract electrical energy from chemical energy. When dealing with fuel cell reaction kinetics, the Butler-Volmer equation often proves unnecessarily complicated. The equation can be simplified with two useful approximations. These approximations apply when the activation overvoltage (η_{act}) in the Butler-Volmer equation is either very small or very large. Usually, the activation overvoltage is not small. Therefore, the equation simplifies to (5).

$$\eta_{act} = -\frac{RT}{\alpha nF}\ln j_0 + \frac{RT}{\alpha nF}\ln j \qquad (5)$$

Where

α : The transfer coefficient of charge

n : The number of electrons transferred in the electrochemical reaction

F : Faraday constant (96,485 c/mal)

R : Ideal gas constant (8.314 $J/mol \cdot k$)

T : Temperature

j_o : The current densities for the forward and reverse reactions

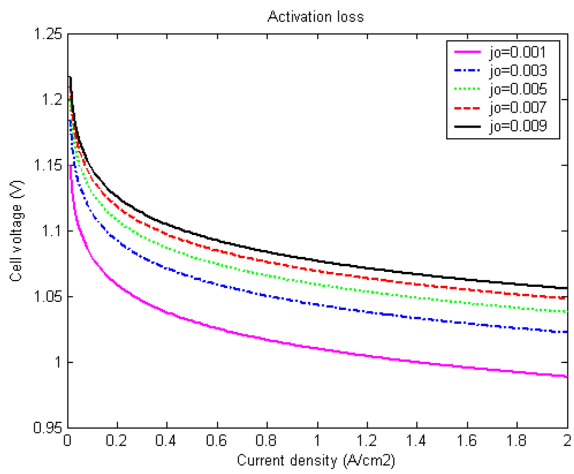

Fig. 2 Effect of activation voltage on I-V curve

From the (5), reaction kinetics typically inflicts an exponential loss on a fuel cell's I-V curve as determined by the Butler-Volmer equation. The magnitude of this loss is influence by the size of j_o. This curves calculated for various j_o values with $\alpha = 1$, $n = 2$ and $T = 353$K by MATLAB. As the current densities rise, the cell voltage increases.

2.2.2 Ohmic losses

The charge transport is not a frictionless process. It occurs at a cost. For fuel cells, the penalty for charge transport for charge transport is a loss in cell voltage. Because fuel cell conductors are not perfect, they have an intrinsic resistance to charge flow. Consider the uniform conductor. This conductor has a constant cross-sectional area A and length L. Applying this conductor geometry to the charge transport equation, it produces the related equation as shown as (6)

$$V = i(\frac{L}{A\sigma}) = iR \qquad (6)$$

Equation (6) can be rewrite where we identify the quantity $L/A\sigma$ as the resistance R of our conductor. This voltage loss arises due to our conductor's intrinsic resistance to charge transport, as embodied by $1/\sigma$. Because this voltage loss obey's Ohm's law, it is called as "ohmic" loss. Rewriting equation (6) to reflect nomenclature and explicitly including both the electronic (R_{elec}) and ionic (R_{ionic}) contributions to fuel cell resistance gives (7).

$$\eta_{ohmic} = iR_{ohmic} = i(R_{elec} + R_{ionic}) \qquad (7)$$

Because ionic charge transport tends to be more difficult than electronic charge transport, the ionic contribution to R_{ohmic} tends to dominate.

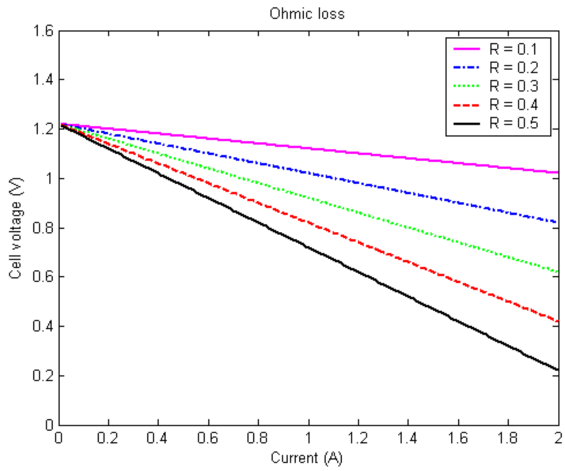

Fig. 3 Effect of ohmic losses on I-V curve

The magnitude of this losses are determined by the size of R_{ohmic}. Figure 3 was calculated for R_{ohmic} equal 0.1Ω, 0.2Ω, 0.3Ω, 0.4Ω and 0.5Ω, respectively. The slop of I-V curve increases as ohmic resistance increases.

2.2.3 Concentration losses

Activation losses are caused by sluggish electrode kinetics. There is a close similarity between electrochemical and chemical reactions in that both involve an activation energy that must be overcome by the reacting species. From the Nernst equation, concentration affects fuel cell performance can be derived as shown as (8). This is because the real reversible thermodynamic voltage of a fuel cell is determined by the reactant and product concentrations at the reaction sites, not at the fuel inlet.

$$\eta_{conc} = \left(\frac{RT}{nF}\right)\left(1 + \frac{1}{\alpha}\right)\ln\left(\frac{j_L}{j_L - j}\right) \qquad (8)$$

Where

j_L : The limiting current density

Figure 4 shows the effect of concentration loss on the I-V behavior of a fuel cell. The curves in this figure were generated for various values of $j_L = 1, 1.5$ and $2 A/cm^2$.

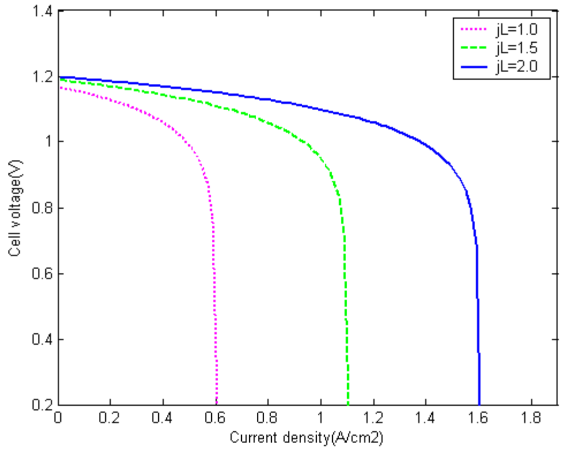

Fig. 4 Effect of concentration loss on I-V curve

3. Simulation result

From the basic expressions for each of the quantities in Eq. (4). The thermodynamically predicted voltage, activation, ohmic and concentration losses are studied in previous section. To verify the result, this simulation is compared with 10kW PEMFC.

The simulation result can be obtained from them as shown in Fig. 5. The parameters of PEMFC are used like as α : 0.9, n : 2, T : 70℃, j_o: 0.2µ, j_L : 1.44 and R_{ASR} : 0.112. The simulation result is fitted with the experimental result.

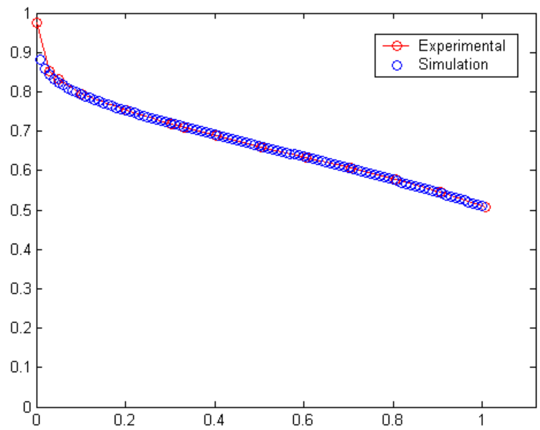

Fig. 5 I-V curves of experimental and simulation

3. Conclusion

This paper presents the I-V characteristic of PEMFC in MATLAB. Both the double-layer charging effect and the thermodynamic property of the fuel cell are taken into account in these models. The simulation result compared with 10kW PEMFC to verify.

This result will be base to study and simulation using active load.

Acknowledgment

This work was supported by New & Renewable Energy RD&D Program from national RD&D Organization for Hydrogen and Fuel Cell, Korea Energy Management Corporation, and MOCIE (Ministry of Commerce. Industry and Energy)

Reference

[1] C. Wang, M. H. Nehrir and S. R. Shaw, “Dynamic Models and Model Validation for PEM Fuel Cells using Electrical Circuits”, *Tans. on Energy Conversion*, Vol. 20, No. 2, 2005, June.

[2] J. C. Amphlett. R. M. Vaumert. R. F. Mamm, B. A. Peppley, and P. R. Roberge, “Performance modeling of the ballad Mark IV solid polymer electrolyte fuel cell, Ⅰ. Mechanistic model development”, *J. Electrochem. Soc.*, Vol. 142, No. 1, pp. 1-8, 1995 January.

[3] J. C. Amphlett. R. M. Vaumert. R. F. Mamm, B. A. Peppley, and P. R. Roberge, “Performance modeling of the ballad Mark IV solid polymer electrolyte fuel cell, Ⅱ. Mechanistic model development”, *J. Electrochem. Soc.*, Vol. 142, No. 1, pp. 1-8, 1995, Jan.

[4] C. E. Chamberlin, “Modeling of Proton Exchange Membrane fuel cell performance with an empirical equation”, *J. Electrochem. Soc.*, Vol. 142, No. 8, pp. 2670-2674, Agust, 1995.

[5] A. Rowe and X. Li, “Mthematical Modeling of Proton Exchange Membrane Fuel Cells”, *J. Power Sources,* Vol. 27, No. 11, pp. 1254-1264, 1997, November.

[6] D. Bevers ans M. Wohr, “Simulation of a polymer electrolyte fuel cell electrode”, *J. Appl. Electrochem.*, Vol. 27, No. 11, pp. 1254-1264, 1997, November.