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Short communication

Electronic circuit model for proton exchange membrane fuel cells☆

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Abstract

The proton exchange membrane (PEM) fuel cell is being investigated as an alternate power source for various applications like transportation and emergency power supplies. The paper presents a novel circuit model for a PEM fuel cell that can be used to design and analyze fuel cell power systems. The PSPICE-based model uses bipolar junction transistors (BJTs) and *LC* elements available in the PSPICE library with some modification. The model includes the phenomena like activation polarization, ohmic polarization, and mass transport effect present in a PEM fuel cell. The static and dynamic characteristics obtained through simulation are compared with experimental results obtained on a commercial fuel cell module.

Keywords: Fuel cell; Polarization characteristics; Circuit model; PSPICE

1. Introduction

Fuel cells of various types are considered as alternatives to fossil energy mostly for reasons of pollution and efficiency. The proton exchange membrane fuel cell (PEMFC) has been considered as a promising kind of fuel cell during the last 10 years because of its low working temperature, compactness, and easy and safe operational modes. The proton exchange membrane (PEM) fuel cell is very simple and uses a polymer (membrane) as the solid electrolyte and a platinum catalyst. The hydrogen from a pressurized cylinder enters the anode of the fuel cell and the oxygen (from air) enters the cathode. Protons and electrons are separated from hydrogen on the anode side. In a basic PEM cell, the protons are transported to the cathode side through the polymer and the electrons are conducted through the load outside the electrode [1]. A fuel cell stack is composed of several fuel cells connected in series separated by bipolar plates [2] and provides fairly large power at higher voltage and current levels.

There is a need to model the PEMFC for optimizing its performance and also for developing fuel cell power converters for various applications. Almost all the models proposed for the PEMFC consist of mathematical equations and are not of much use in power converter/system simulation and analysis [1–4]. Other models of PEMFC use Matlab–Simulink [5] and PSPICE [6], but they are still mathematical in nature. The models include several chemical phenomena present in the fuel cell and hence are complex. Some of the physical variables like pressure and hydrogen input are constrained in a commercial fuel cell module and this makes the fuel cell operation simpler. This also allows the use of a simpler electric circuit model useful to a power electronics designer.

This paper presents a novel circuit model for a PEMFC, which is simple and at the same time includes all the important characteristics of a fuel cell stack. The model uses the nonlinearity of a junction diode and the current control feature of bipolar junction transistors (BJTs). In the proposed model, a diode is used to model both the activation losses and the ohmic losses in a PEMFC, while two BJTs are used to model the mass transport losses [7,8]. The equations governing the

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different polarization effects in a fuel cell are related to the equations of the electrical circuit elements making up the model. The model is justified through experiments performed on a commercial PEMFC stack for both static and dynamic responses.

2. Polarization characteristics of a PEM fuel cell

Proton exchange membrane fuel cells combine hydrogen and oxygen over a platinum catalyst to produce electrochemical energy with water as the byproduct. Fig. 1 shows the *V–I* characteristic of a typical single cell operating at room temperature and normal air pressure [9]. The variation of the individual cell voltage is found from the maximum cell voltage (or EMF) and the various voltage drops (losses). Multiple factors contribute to the irreversible losses (voltage drop) in an actual fuel cell that cause the cell voltage to be less than its ideal potential [9]. The losses, which are also called polarization, originate primarily from three sources: (a) activation polarization, (b) ohmic polarization, and (c) concentration (mass transport) polarization. Each of these is associated with a voltage drop and is dominant in a particular region of current density (low, medium, or high). Fig. 1 shows the different regions and the corresponding polarization effects.

The ideal voltage is the maximum voltage that each cell in the stack can produce at a given temperature with the partial pressure of the reactants and products known. For the PEMFC, where pure hydrogen and air are used, the ideal voltage can be calculated based on Gibbs free energy and it is equal to 1.2 V at 25 °C and atmospheric pressure for a single fuel cell [9]. A higher output voltage is obtained by connecting several cells in series. The area of the cell decides the output current.

2.1. Activation polarization

The activation polarization loss (dominant at low current density) is present when the rate of the electrochemical reaction at an electrode surface is controlled by sluggish electrode kinetics [9]. Activation losses increase as the current increases. The activation losses can be obtained by Tafel equation [8]:

$$V = A \ln\left(\frac{i}{i_o}\right) \tag{1}$$

where A is the constant, V the over-voltage, i the current density, and i_o is the current density at which the voltage begins to drop.

2.2. Ohmic polarization (loss)

The ohmic loss is due to the resistance of the polymer electrolyte membrane to the ions and the resistance of imperfect electrodes. The loss (voltage drop) in the fuel cell is approximately linear in this region.

2.3. Concentration polarization (mass transportation losses)

The concentration polarization relates to the change in the concentration of the reactants at the surface of the electrodes as the fuel (hydrogen) is used. The concentrations of the fuel and oxidant are reduced at the various points in the fuel cell gas channels and are less than the concentrations at the inlet portion of the stack. This loss becomes significant at higher currents when the fuel and oxidant are used at higher rates and the concentration in the gas channel is at a minimum.

In general, the mass transportation (transfer) losses are given by Eq. [7]

$$V = V_s' - m I_m e^{n I_m} \tag{2}$$

where $I_m = I - I_1$, and V_s' and I_1 are the coordinates of the point where the *V–I* characteristic starts to deviate from being linear (start of mass transport action), and m and n are mass transfer parameters. While I_1 is the limiting current at which the fuel is used up at a rate equal to its maximum supply rate, other constants depend on the fuel cell and its operating condition.

3. Circuit model of PEM fuel cell

Fig. 2 shows the proposed circuit model of a commercial PEMFC module. The complete model is developed by modeling the different operating regions using elements from

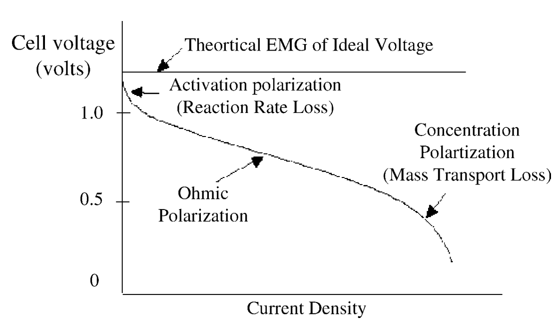

Fig. 1. *V–I* characteristic of a single PEM fuel cell.

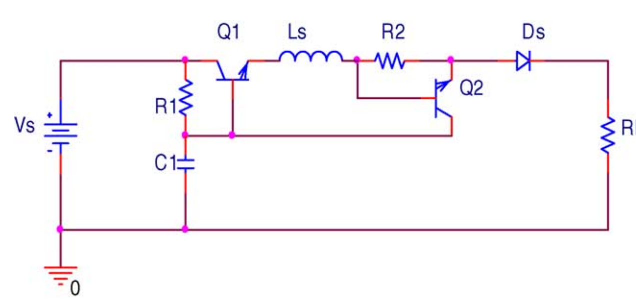

Fig. 2. Proposed circuit model of PEM fuel cell module.