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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]:

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

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]

$$V = V_s' - m I_m e^{n I_m} \quad (2)$$

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

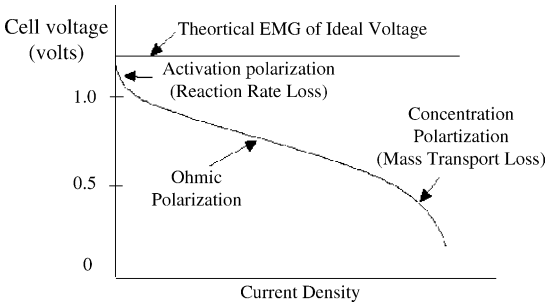

Fig. 1. *V–I* characteristic of a single PEM fuel cell.

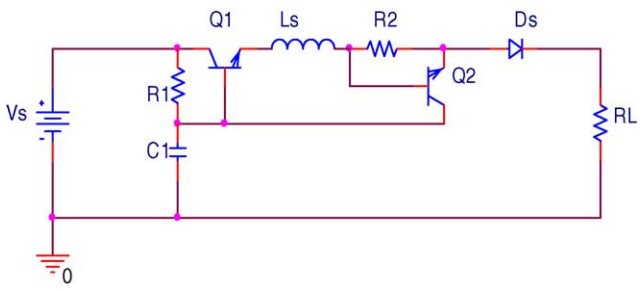

Fig. 2. Proposed circuit model of PEM fuel cell module.

the PSPICE simulation library. Both static and dynamic responses are considered in the model.

3.1. Static model

3.1.1. Activation polarization

In the model proposed, a diode is used to model the activation polarization of the fuel cell. It is well known that, in a semiconductor diode, the depletion region provides a potential barrier to inhibit the migration of carriers across the junction, which is similar to the "sluggish electrode kinetics" in the fuel cell. Actually, the similarity can be seen by comparing Eq. (1) and the diode equation:

$$V_D = nV_T \ln\left(\frac{I_D}{I_s}\right), \quad V_T = \frac{kT}{q} \tag{3}$$

where V_D is the voltage across the diode and I_D is the current through the diode, n the empirical constant between 1 and 2, I_s the reverse saturation current, k the Boltzmann's constant, T the absolute temperature, and q is the electronic charge. Thus, it is reasonable to use a diode to model the activation polarization in a fuel cell. In the simulation package PSPICE, the diode model can be adjusted to match the *V–I* characteristics of a fuel cell stack by choosing suitable values for the following parameters: I_s (saturation current), R_s (parasitic resistance), N (emission coefficient), I_{KF} (high-injection "knee" current), I_{SR} (recombination current parameter), and I_{BV} (reverse breakdown "knee" current) [11]. Among the several parameters, N affects the shape of the characteristic most and it has to be chosen to match the *V–I* characteristics of the diode and the fuel cell stack. Fig. 3 shows the *V–I* characteristics for different values of N along with the experimental characteristic. It is seen that the characteristic with $N = 80$ matches the experimental characteristic closely. I_s was selected as 0.02 A.

3.1.2. Ohmic polarization

A resistor is used to model the ohmic polarization. Instead of using a separate resistor, the "parasitic resistance (R_s)" in the diode is used in the model.

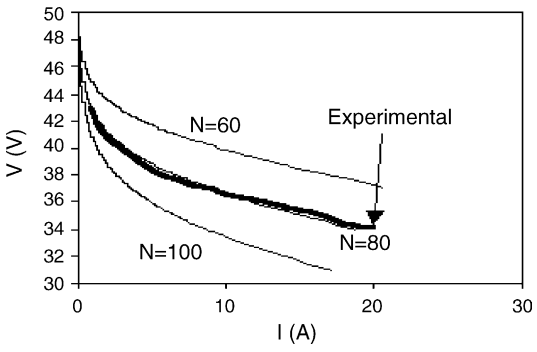

Fig. 3. Experimental *V–I* characteristic and simulated characteristics for different N for activation and ohmic regions.

3.1.3. Concentration polarization

To model the concentration or mass transport over-voltage, a "current limiting circuit" is used. In Fig. 2, the current limiting circuit is composed of two BJTs Q_1 and Q_2 and the current sensing resistor R_2. When, the current through R_2 exceeds a set limit, Q_2 starts conducting and reduces the base voltage of Q_1. As a result, the emitter voltage of Q_1 (output voltage) will decrease at an exponential rate similar to Eq. (2). The variation of output voltage as a function of load current is obtained using the steady equivalent circuit shown in Fig. 4. The transistors Q_1 and Q_2 are assumed to be identical with current gain β and base-emitter voltage V_{BE}. The following equations can be written:

$$I_{B1} = \frac{I_o - I_{C2}}{1+\beta} \tag{4}$$

$$I_{C2} \approx I_{CS} e^{I_o R_2 / V_T} \tag{5}$$

$$V_o = V_s - R_1 (I_{B1} + I_{C2}) - V_{BE1} - (I_o - I_{C2} - I_{B2}) R_2 \tag{6}$$

Substituting (4) and (5) in (6) and simplifying, we get

$$V_o = V_s - I_o \left(R_2 + \frac{R_1}{1+\beta}\right) - V_{BE} - \left[R_1 \left(1 - \frac{1}{\beta}\right) + R_2 \left(\frac{1+\beta}{\beta}\right)\right] I_{CS} e^{I_o R_2 / V_T} \tag{7}$$

Assuming β to be large (7) can be approximated as

$$V_o = V_s - R_2 I_o - V_{BE} - R_1 I_{CS} e^{R_2 I_o / V_T} \tag{8}$$

Eq. (8) is of the same type as that of the mass transportation phenomenon described by (2).

In the PSPICE model of the BJT, the area of the device can be increased (by 300 times) to match the large current of the fuel cell stack. The other parameters of the BJT in PSPICE library do not have much effect on the *V–I* characteristic of the fuel cell.

In the simulation, R_1 and R_2 decide the shape of the static characteristic in the concentration polarization region of the fuel cell. In particular, R_2 decides the current I_1, which corresponds to the starting point on the concentration polarization

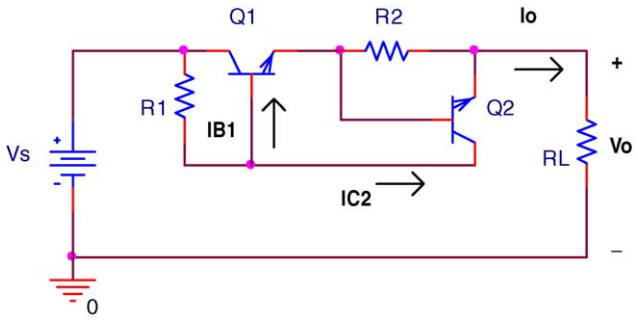

Fig. 4. Steady-state equivalent circuit of fuel cell module.

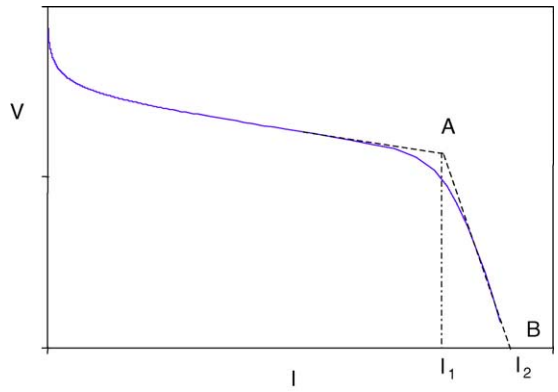

Fig. 5. Calculation of R_1 and R_2 from illustrative V–I characteristic.

region of the V–I curve (Fig. 5). The resistance R_1 decides the rate of change of voltage in the concentration polarization region for output currents beyond I_1. As shown in the illustrative characteristic of Fig. 5, the V–I curve is approximated by a set of straight lines to get points A (I_1) and B (I_2). The values of R_1 and R_2 are calculated as follows.

3.1.3.1. Calculation of R_1. In the static fuel cell model, R_2 is a series resistance, which actually decides the current limiting action. Hence, R_2 is generally very small. The resistance R_1 decides the regenerative action in the two transistor circuit. The values of the two resistors are obtained from the experimental data. For commercial PEM fuel cell modules, it is not possible to reach point B by conducting a load test. Over-current protection circuit shuts down operation slightly beyond A. However, the characteristic can be extrapolated to get point B and the current I_2. Based on simulation results, the following empirical equation relating I_2 and R_1 is found:

$$I_2 = a + \frac{b}{\sqrt{R_1}}. \tag{9}$$

The constants for the PEM module tested are obtained as: $a = 46.8$ and $b = 74$.

3.1.3.2. Calculation of R_2. For a given value of R_1 chosen from (9), the empirical relationship between I_1 and R_2 is obtained as:

$$I_1 = \frac{c}{R_2}. \tag{10}$$

For the module tested, the constant c is calculated as 0.65.

3.2. Dynamic model

3.2.1. The charge double layer

Due to diffusion effects and the reaction between the electrons (in the electrodes) and the ions (in the electrolyte), there is charge double layer around the cathode in a fuel cell. The layer of charge on or near the electrode interface behaves much like an electrical capacitor. The result is that if the current suddenly changes, the operating voltage takes some

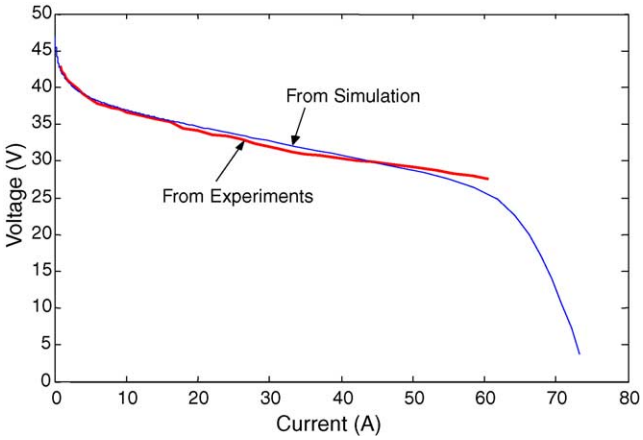

Fig. 6. Comparison of simulated and experimental characteristics.

time to arrive at its final equilibrium value [8]. Thus, it is quite reasonable to use a capacitor to model the capacitance effect resulting from the charge double layer. The capacitor C is connected to the voltage source V_s in the fuel cell.

3.2.2. Undershoot in stack voltage

The experimental response of the commercial fuel cell module to a step change in load shows a small undershoot. After a load step to full power, the air pump in the fuel cell takes about 0.5 s to reach a higher speed to provide a correspondingly higher airflow rate. In the mean time, the output current increases very quickly using up the air around the electrodes. It is the temporary shortage of the air that causes the undershoot of the output voltage. This behaves like a resonant circuit. A capacitor C and an inductor L_s in series with the emitter of Q_1 (as shown in Fig. 2) are used to model the undershoot in the stack output voltage. A small signal analysis of the transistor circuit of Fig. 2 can be done to obtain the transient performance. It can be seen that the value of undershoot and the width are decided by the values of L_s and C while the damping factor is decided by the value of L_s, and R_2' which is given by:

$$R_2' = R_2 \| r_\pi \tag{11}$$

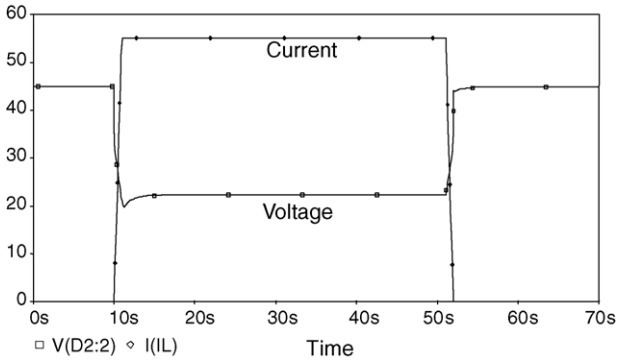

Fig. 7. Simulated waveforms of fuel cell ($C = 1$ F, $L_s = 10$ mH).

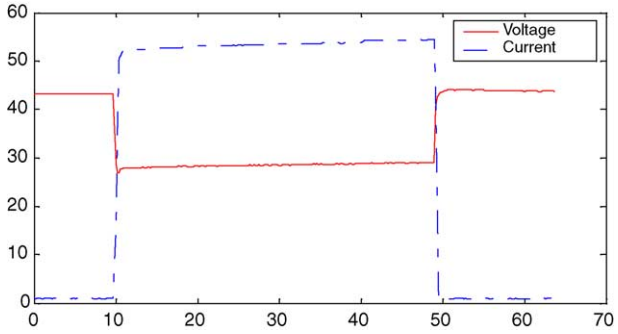

Fig. 8. Experimental waveforms of fuel cell.

where r_π is the base-emitter resistance of each BJT. The values of C and L_s are selected to match the transient response of the fuel cell. Since the air pump delay is about 0.5 s, the value of LC used is large.

4. Results

To validate the proposed model, several experiments were conducted on the commercial fuel cell module [10]. The module is a fully integrated system that produces unregulated dc power from a supply of hydrogen (fixed pressure of 72 psi) and air. It has a rated power of 1200 W. The output voltage varies from 43 V dc at system idle to about 26 V dc at rated current (46 A). The load current was varied from a small value to a maximum of 70 A (load resistance in the range 0.5–100 Ω). The values of I_1 and I_2 are 62 and 77 A, respectively. The corresponding values of R_1 and R_2 are 5 and 0.01 Ω. Fig. 6 shows the static characteristics obtained from simulation and experiment and the two agree. For the dynamic response, the load was changed suddenly from 108 to 0.55 Ω. The simulation and experimental results are shown in Figs. 7 and 8. It is seen that the undershoots in the two waveforms agree.

5. Conclusions

A novel circuit model for the PEM fuel cell stack is presented. The simple model, which can be used in the design of fuel cell power systems uses a diode and a pair of BJTs for describing the static conditions. A capacitor and an inductor are used to represent the dynamic conditions, which occur in switching power systems. All the elements used in the model are from the PSPICE library and slight changes are made in the parameter values. The model is validated by comparing the simulation and experimental results obtained on a commercial fuel cell module.

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