14^{th} INTERNATIONAL SYMPOSIUM on
POWER ELECTRONICS - Ee 2007
XIV Međunarodni simpozijum Energetska elektronika – Ee 2007
NOVI SAD, REPUBLIC OF SERBIA, November 7^{th} - 9^{th}, 2007

PARAMETRIC PSPICE MODEL OF A PEM FUEL CELL*

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Abstract: *This paper presents a generalized circuit model for a PEM fuel cell that can be used for design and analysis of fuel cell power systems. The PSpice-based model uses bipolar junction transistors and resistors available in the PSpice library. The model includes the phenomena like activation polarization, ohmic polarization and concentration polarization (mass transport effect) present in a PEM fuel cell. Using the parametric modeling the model of a basic fuel cell can be extended to a fuel cell stack. The static and dynamic characteristics obtained through simulation are compared with some experimental results, given in the literature, obtained on a commercial PEM fuel cell module.*

Key Words: **Fuel Cell/Modeling/Simulation/PSpice**

1. INTRODUCTION

Today, fuel cells of various types have emerged as a promising alternative sources of “clean energy” for applications ranging from automotive industry to residential and commercial installations. This has created a need for a class of specialized power converters geared to interface between the fuel cell device and the end-user appliance, often as a battery charger. Specifications for power conversion equipment depend on the fuel cell's physical properties and manufacturing economics.

The cells' output voltage is dependent on the load. So, there is a need to model the fuel cell for optimizing its performance and also for developing fuel cell power converters for various applications.

The proton exchange membrane fuel cell (PEMFC) has been considered as a promising kind of fuel cell during the last 15 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.

A fuel cell stack is composed of several fuel cells connected in series separated by bipolar plates and provides fairly large power at higher voltage and current levels.

Up to now different type of models of PEM fuel cell were proposed.

Almost all models proposed for PEMFC consist of mathematical equations and are not of much use in power converter/system simulation and analysis [1]–[4]. Some other PEMFC models 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.

Among the various proposed models the electronic circuit model for a *PEM* fuel cell proposed in [7] is very suitable for this purpose.

Unfortunately, this model suffers from the need to define its parameters for every individual case where fuel cell stacks are used.

The aim of this paper is to extend the model proposed in [7] to a generalized one for a *PEM* fuel cell that can be used for design and analysis of fuel cell power systems with different voltage and current capabilities.

2. I/V 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 *I–V* characteristic of a typical single cell operating at room temperature and normal air pressure [8]. 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 [8]. The losses, which are also called polarization, originate primarily from three sources: (a) activation polarization [9], (b) ohmic polarization, and (c) concentration (mass transport) polarization [9], [10]. 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

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* This work is supported by the Ministry of Education and science of Republic of Macedonia (Project No: 13-936/3-05)

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 1.2V at 25°C and atmospheric pressure for a single fuel cell [8]. A higher output voltage is obtained by connecting several cells in series. The area of the cell decides the output current.

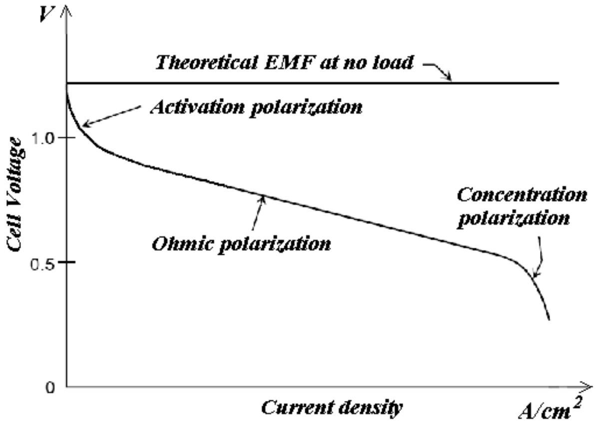


Fig. 1. *I–V characteristic of a single PEM fuel cell*

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]:

$$V_A = A\ln\left(\frac{I}{I_o}\right) \tag{1}$$

where A is the constant, V_A the over-voltage, I the current density, and I_o is the current density at which the voltage begins to drop.

The ohmic region can be described by:

$$V_R = RI \tag{2}$$

where I is the current density through the cell and R is the total ohmic resistance due to the resistance of the polymer electrolyte membrane to the ions and the resistance of imperfect electrodes [8].

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. 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 concentration polarization region can be described by [9], [10]:

$$V_C = mI_m e^{nI_m} \tag{3}$$

where m and n are mass transfer parameters, and I_m is the point where the I–V characteristic starts to deviate from being linear (start of mass transport action).

So, the overall dependence between the voltage and the current density of a fuel cell can be expressed as:

$$V_o = E - V_A - V_R - V_C \tag{4}$$

where E is the ideal emf of the fuel cell at no load. It should be noted that the parameters used in Eqs. (1) - (4) are dependent on the pressure and temperature in the cell.

The fuel cell can be catastrophically damaged if overloaded. Thus, when designing the fuel cell system the current rating of the cell itself must be taken into account. One way to anticipate the fuel cell current limits is through computer simulation of the fuel cell system using the appropriate simulation model of the cell itself.

3. CIRCUIT MODEL OF PEM FUEL CELL

In [7] a PSpice model for commercial fuel cell has been proposed (Fig. 2). The complete model is developed by modeling the three different operating regions using elements from the PSpice simulation library.

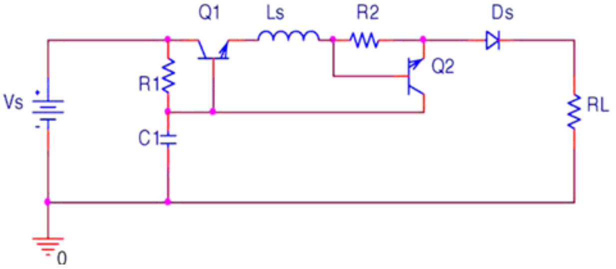


Fig. 2 *PSpice circuit model for a PEM fuel cell module*

In the model proposed, a diode is used to model the activation polarization of the fuel cell. Actually, the similarity can be seen by comparing Eq. (1) and the diode equation:

$$V_D = nV_T\ln\left(\frac{I_D}{I_s}\right) \tag{5}$$

where V_D is the voltage across the diode and I_D is the current through the diode, n the empirical constant having values between 1 and 2, I_S the reverse saturation current, and V_T so called "volt-equivalent of temperature".

So, it is reasonable to use a diode to model the activation polarization region in a fuel cell. In the simulation package PSpice, the diode model can be adjusted to match the I–V characteristics of a fuel cell stack by choosing suitable values for the following parameters: I_S (saturation current), R_S (parasitic resistance) and N (emission coefficient) [11]. Among the several parameters, N affects the shape of the characteristic most and it has to be chosen to match the I–V characteristics of the diode and the fuel cell stack. In [7] the diode characteristics matches that of the chosen fuel cell for N=80 and I_S = 0.02 A. As these values have no real values the proposed model is useful only for simulation purposes but not for realization of fuel cell simulator.

The ohmic polarization can be modeled using a resistor. Instead of using a separate resistor, the "parasitic resistance (R_s)" in the diode is used for this purpose.

To model the concentration, or mass transport overvoltage, 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. (3). The transistors Q_1 and Q_2 are assumed to be identical with current gain β and base-emitter voltage V_{BE}. Using the basic relations for the voltage to current dependences in a bipolar transistor, assuming that the BJTs have identical parameters and that $\beta >> 1$, $R_2 << R_1$ and $V_{C1,E2} >> V_{BE}$ [7], the following equation can be written:

$$V_{C_1E_2} = R_1 I_{CS} e^{R_2 I_O / V_T} \tag{6}$$

This equation is very similar to (3).

From the above analysis it becomes clear that by appropriate determination of the circuit parameters, the circuit model shown in Fig. 2 can be used for simulation of the *I–V* characteristics of a specified fuel cell stack. If the characteristic of a specified fuel cell is known or can be measured than the model parameters can be calculated using the method described in [7].

It is shown in [7] that the dynamic response of a fuel cell can be modeled using a capacitor (C_1) and an inductor (L_s) as shown in Fig. 2.

4. PARAMETRIC MODEL OF A PEM FUEL CELL STACK

The described model of PEMFC presented in [7] can give us a good basis for simulation of static and dynamic characteristics of specified fuel cell or fuel cell stack. The investigation of the adaptability of this model has shown two main problems with its application:

1. As the model parameters are determined for every single module, the parameter extraction should be repeated every time when we change the area of the cell or the number of cells in a cell stack;
2. Considering the fact that the transistor parameters are constant (according to the authors of [7] only the transistor area should be changed depending on the current capability of the cell) this model is non applicable for fuel cells where the ideal emf is less than 10 V. (Even more, this model is unacceptable for modeling the single fuel cell where the ideal emf is around 1.2 V.)

These two specified problems can be overcome if some of the model parameters are made dependent on the cell area (fuel cell current capability) and cell ideal emf (number of single cells connected in series in the stack).

To overcome the problem of the voltage drop between the base and the emitter of the BJTs we should introduce the emitter emission coefficient N_f and make that it changes with the cell area and cell ideal emf. The current capability of the cell can be modeled using the parameter proportional with the actual cell area. This parameter should be incorporated in the diode model and in the BJTs models as well.

To match the changes in the concentration polarization region it is, also, necessary to make corresponding adaptations for the resistors R_1 and R_2.

We should note also that, because we change the diode area to match the diode characteristics to the cell current capabilities, we also have to change, in an appropriate way, the diode reverse saturation current.

All these changes in the fuel cell PSpice model characteristics were enabled when the command **.PARAM** was included in the PSpice program package, as well as with the possibility that some model parameters can be defined with mathematical expressions.

We have made modifications of the PSpice fuel cell model presented in [7] by introducing 2 parameters: the *first* – proportional to the number of individual cells connected in series, (or in other words, proportional to the ideal *emf* of the stack to ideal *emf* of a single fuel cell ratio), and the *second* – proportional to the area of the fuel cell (the initial area has been taken to be 1cm^2).

Thus, once the model parameters are extracted for a single fuel cell, as explained in [7], they can be extended to any fuel cell stack module, of the same type, by using parametric modeling incorporated in PSpice simulation package in the following manner:

a) For the diode –

$$n = n_o \cdot m \tag{7}$$

$$A_D = A_{D_o} \cdot k / m \tag{8}$$

$$I_S = I_{So} \cdot m \tag{9}$$

where n is the diode emission coefficient, A_D is the diode area and I_S is the diode reverse saturation current;

b) For the transistors –

$$A_Q = A_{Q_o} \cdot k \tag{10}$$

$$n_F = n_{Fo} \cdot m \tag{11}$$

where A_Q is the transistor area and n_F emitter emission coefficient;

c) For the resistors –

$$R_1 = R_{1o} \cdot m / k \tag{12}$$

$$R_2 = R_{2o} \cdot m / k \tag{13}$$

d) For the ideal ***emf*** of the fuel cell stack –

$$E = E_o \cdot m \tag{14}$$

e) For the capacitor –

$$C = C_o \cdot k \cdot \mathrm{m}; \tag{15}$$

f) For the inductor –

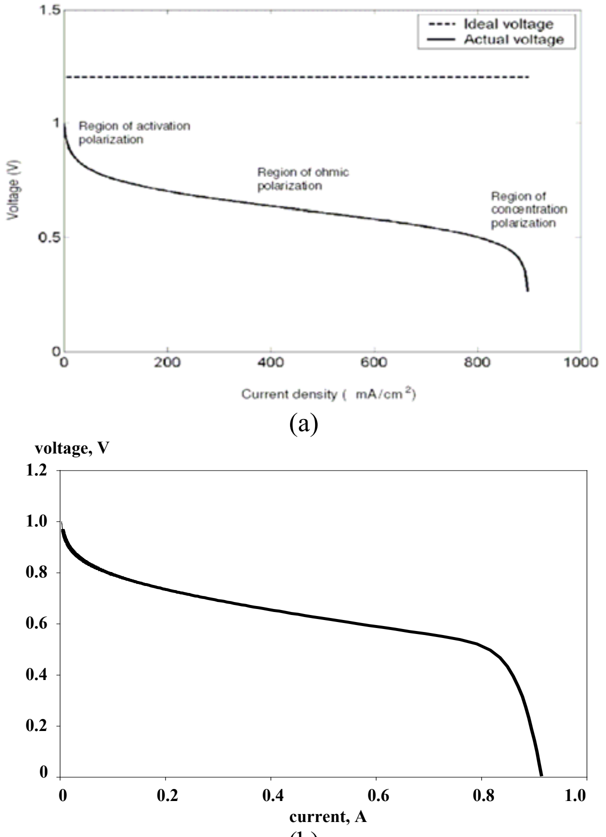
$$L = L_o \cdot m / (k \cdot k^{1/4}) \tag{16}$$

In these equations m is the parameter dependent on the number of fuel cells connected in series (voltage capabilities of the cell), k is proportional to the cell area (current capabilities), and the subscript "o" indicates the initial parameters obtained for the single fuel cell at specified temperature and pressure.

5. SIMULATION RESULTS

To validate the proposed model, extensive simulations were performed.

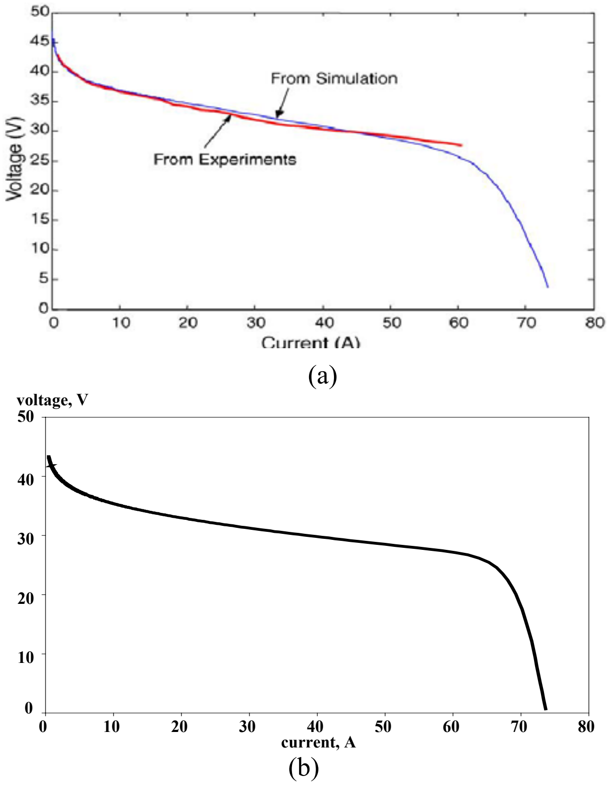
First we have extracted the parameters for a single PEM fuel cell according to the method described in [7] and the characteristics given in [9]. The simulation results are given in Fig. 3-b, while the corresponding measured characteristics in Fig. 3-a.



(a)

(b)

Fig. 3 - *a) characteristics of a real single PEMFC according* [9]; *b) simulation results using the extended model with k*=1, *m*=1



(a)

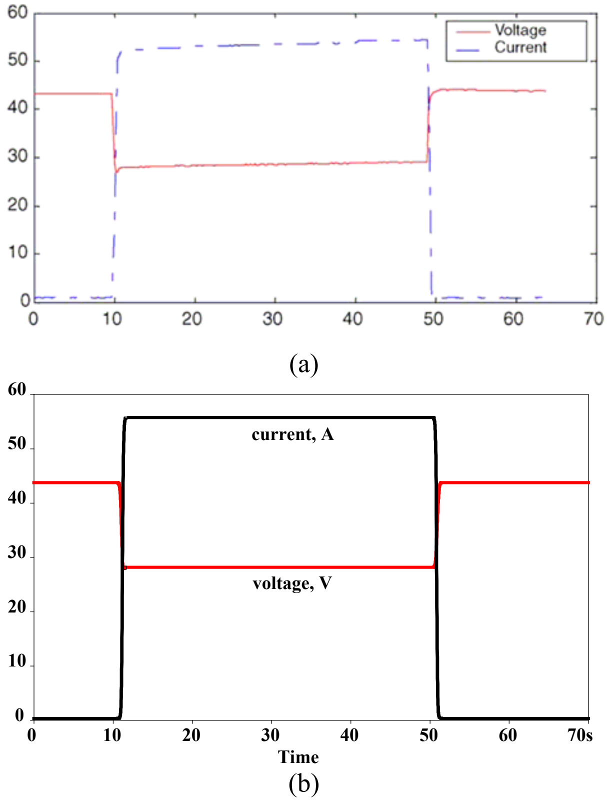
(b)

Fig 4 - *a) I-V characteristics of a PEM fuel cell from experiment and simulation* [7] [12], *b) I-V characteristics of a PEM fuel cell by simulationusing extended model with k*=80, *m*=45

The static and dynamic characteristics of different PEM fuel cell stacks obtained through simulation are compared with some experimental results, given in the references, measured on a comercial PEM fuel cell modules, [12]-[14]. Some of them are presented below.

In Fig. 4 we show comparative diagrams obtained experimentaly (given in [7] and [12]) and by simulation with the parametric model for a fuel cell stack 45 V, 60 A. All values of the used parameter can be seen in the PSpice listing given in the appendix.

For the dynamic response we have used the equations (15) and (16). In the lack of real elementary fuel cell, the initial values C_0 and L_0 were determined using trial and error method. The load was changed suddenly from 124 to 0.5 ohm. The experimental and simulation results are shown in Figs. 5 - *a* and *b*. It is seen that the undershoots in the two waveforms agree.



(a)

(b)

Fig. 5 - *Transient characteristics of a PEM fuel cel: a) experimental waveforms [7], b) simulated waveforms usig extended model with k=80, m=45 (L≅11.3mH, C≅7.2F)*

5. CONCLUSIONS

An extended (parametric) circuit model for the PEM fuel cell stack based on the model presented in [7] is developed. It allows us to develop a generalized model for a *PEM* fuel cell that can be used for design and analysis of fuel cell power systems with different voltage and current capabilities.

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 modules.

We should note that because some of the values, for the transistor and diode parameters, have no real values the proposed model is useful only for simulation purposes but not for realization of fuel cell simulator.

Although the model does not include the temperature and pressure dependences of the *I-V* characteristics of a PEM fuel cell these can be easily added in the model by behavioral modeling of the *emf* source and some of the circuit parameters according to the Nernst equation [8].

6. REFERENCES

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APPENDIX

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*Fuel Cell
.param k=80
.param m=45

V1 1 0 {1.12*m}
r1 1 2 {30*m/k}

c1 2 0 {0.002*k*m}

q1 1 2 3 npnq1 {4.5*k}
.model npnq1 npn(bf={2500} is={(1e-16)} nf={m/45})

l1 3 4 {60m*m/(k*sqrt(sqrt(k)))}

q2 2 4 5 npnq2 {4.5*k}
.model npnq2 npn(bf={2500} is={(1e-16)} nf={m/45})

r2 4 5 {.02*m/k}

d 5 6 d1 {8*k/m}
.model d1 d(n={2*m} is={.00005*m} rs={1.5*m/k})

*rl1 6 0 {110*2*m/k}
*rl2 6 7 {.45*2*m/k}
*sw 7 0 10 0 s1
*.model s1 vswitch(ron=.1m von=0  roff=1e6 voff=1v)

*vsw 10 0 pwl(0 1 10 1 12 0 50 0 52 1)
*rsw 10 0 10meg

rl 6 0 rmod 1
.model rmod res

*.tran .01 70 0 10m

.DC LIN res rmod(r) .01 500 .05
.OPTIONS ITL4=40
.OP

.lib nom.lib
.probe

.END
```