Analysis of individual PEM fuel cell operating parameters for design of optimal measurement and control instrumentation

Davor Živko[1], Vedran Bilas[2]

[1]Koncar – Electrical Engineering Institute, Fallerovo setaliste 22, HR-10000 Zagreb, Croatia, Phone: +385 (99) 241 – 4669, Fax: +385 (1) 3666 – 377, davor.zivko@koncar-institut.hr
[2]Faculty of Electrical Engineering and Computing, University of Zagreb, Unska 3, HR-10000 Zagreb, Croatia, Phone: +385 (01) 6129 – 974, vedran.bilas@fer.hr

Abstract - Number of applications, power span and implementation areas for PEM (proton exchange membrane) fuel cells are increasing daily. All these applications require adequate measurement and control that will ensure optimal functionality of PEM fuel cell. Number of measuring quantities, especially in high – power systems, is numerous so pricing of measurement and control equipment is appreciable. In this paper we have implemented simple PEM fuel cell model and analyzed individual influences of fuel cell operating parameters, like temperature, partial pressures and membrane humidity. We have found out that influence of each operating parameter on fuel cell's power output is different. Therefore we can design measurement and control equipment with different complexity. With that we can ensure optimal control of fuel cell's output power and efficiency without use of costly equipment.

I. Introduction

PEM (*proton exchange membrane*) fuel cells are energy converters that convert chemical energy of oxygen and hydrogen into electrical energy. By – products of this conversion are water and heat. Many fuel cell models have been developed and reported in literature. Also we can find several researches regarding influences of certain operating parameters on fuel cell characteristics [1]. Some measuring and control systems for PEM fuel cells have been developed [2], [3] but they didn't focus on measuring sensors and impact of individual operating parameters on fuel cell output characteristics. In this paper we have implemented simple model of a PEM fuel cell [4], [5]. We have analyzed impact of individual fuel cell's operating parameters on cell's output power. Purpose of this analysis is to find which operating parameter would require better control to ensure optimal power output and higher efficiency of a fuel–cell system.
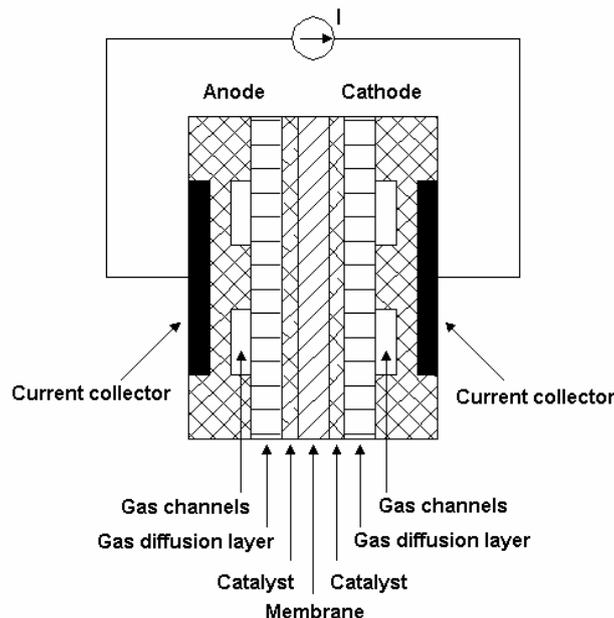
II. PEM fuel cell modeling

Figure 1. Schematic of a PEM fuel cell

PEM fuel cell consists of membrane, which is ionic conductor and through which hydrogen ions diffuse from anode to cathode. Beside membrane, fuel cell has two catalyst layers, made of platinum, gas diffusion layers, gas channels and current collectors. Schematic of a PEM fuel cell is shown in Figure 1. Hydrogen flows through gas channels on anode side of a fuel cell. It diffuse through diffusion layers to catalyst where it oxidize according to (1).

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

Hydrogen ions are conducted through membrane, which is insulator for electrons. Electrons pass through current collector and external electric circuit to cathode. On cathode side of a fuel cell, hydrogen ions, electrons and oxygen that flows through cathode gas channels, react according to (2).

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

Therefore overall chemical reaction occurring inside PEM fuel cell is

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \, . \tag{3}$$

Fuel cell's output voltage is determined by cell's reversible voltage that arises from potential difference produced by chemical reaction and several voltage losses that occur inside a cell. Fuel cell's reversible voltage is a function of temperature and partial pressures of reactants and product as is shown in equation (4).

$$E = E_0 + \frac{\Delta S}{nF}(T - T_{ref}) + \frac{RT}{nF}\ln(\frac{p_{H2}\sqrt{p_{O2}}}{p_{H2O}}) \tag{4}$$

E_0 represents fuel cell's reversible voltage at standard temperature and pressure. ΔS is change of cell's entropy and n is number of electrons transferred in chemical reaction. R is universal gas constant and F is Faraday constant. System's reference temperature, T_{ref}, is 298.15 K. T is cell's operating temperature and p_{O2}, p_{H2} and p_{H2O} represent, respectively, partial pressures of oxygen, hydrogen and water. Fuel cell's output voltage is significantly lower because of several loses that happen inside a cell. Activation losses occur because of rate of reactions happening on electrode surface. Expression for activation losses is (5).

$$V_{activation} = \frac{RT}{\alpha nF}\ln(\frac{i}{i_0}) \tag{5}$$

α is electron transfer coefficient, i represents cell's current density, whereas i_0 is exchange current density. Because of higher anode exchange current density, cathode activation losses are significantly higher so anode activation losses are negligible. Value of cathode exchange current density also depends on operating parameters what is shown in (6).

$$i_{0c} = n_c Fk_c \exp\left[\frac{-\beta n_c FE_0}{RT}\right] \tag{6}$$

β and k_c are, respectively, symmetry factor and factor related to reaction speed. Concentration losses arise because of limitations in reactant diffusion from electrode surface. Expression for fuel cell's concentration losses is given in (7).

$$V_{concentration} = \frac{RT}{nF}\ln(1 - \frac{i}{i_L}) \tag{7}$$

i_L represents limiting current density. This parameter describes maximum current density that can flow through electrode. We can find reported value of limiting current density for PEM fuel cell of 0.81 A/cm^2 [5]. Furthermore, we have ohmic losses in fuel cells from membrane ionic resistance r_{ion} and electrode electronic resistance r_{el} (8).

$$V_{ohm} = iR = i(r_{ion} + r_{el})$$ (8)

We can calculate ionic resistance using expression (9).

$$r_{ion} = t_m \frac{181.6\left[1 + 0.03i + 0.062(\frac{T}{303})^2 i^{2.5}\right]}{(\lambda - 0.634 - 3i)\exp\left[4.18(\frac{T-303}{T})\right]}$$ (9)

Parameter t_m is membrane thickness. Ionic resistance represents PEM fuel cell's membrane resistance to transit of hydrogen ions. This resistance strongly depends on membrane water content. Membrane water content is described by parameter λ which represents number of water molecules with respect to SO_3^- molecules in membrane [5]. Parameter λ can be related to membrane relative humidity Φ [6] with expression (10).

$$\lambda_m = 0.043 + 17.81\phi_m - 39.85\phi_m^2 + 36\phi_m^3$$ (10)

Fuel cell's electrode electronic resistance can be written as (11).

$$r_{el} = \frac{2l_d}{\sigma_d}$$ (11)

Parameter l_d is diffusion layer thickness and σ_d is diffusion layer electronic conductivity. In addition to current that flows through cell, there is an additional internal current that represents losses because of fuel crossover. This current further decreases fuel cell's output voltage. We can find that value of internal current is typically 2 mA/cm^2. This current must be added to fuel cell's current density in simulations. Considering all this losses we can write fuel cell's output voltage as shown in (12).

$$V_{cell} = E - V_{activation} - V_{concentration} - V_{ohm}$$ (12)

Fuel cell's output power density is given as

$$P_{cell} = V_{cell} \cdot i.$$ (13)

III. Results and discussions

Fuel cell's voltage as a function of cell's current density is shown in Figure 2. In Figure 3 cell's power density is shown as a function of current density. These simulations were performed in the Matlab using fuel cell's standard operating conditions, fuel cell's operating temperature 353.15 K, membrane humidity 100% and atmospheric reactants partial pressures. We can see from these figures that fuel cell's efficiency is low and that significant part of theoretical output voltage is lost because of different losses inside a cell. In this model fuel cell reaches maximum power in range between 0.6992 and 0.7128 A/cm^2. That represents 86.3 to 88% of the maximum loading. In that loading range fuel cell losses are around 60%. Therefore, only 40% of the theoretical power will be available. Because of this optimal management of fuel cell system is crucial.
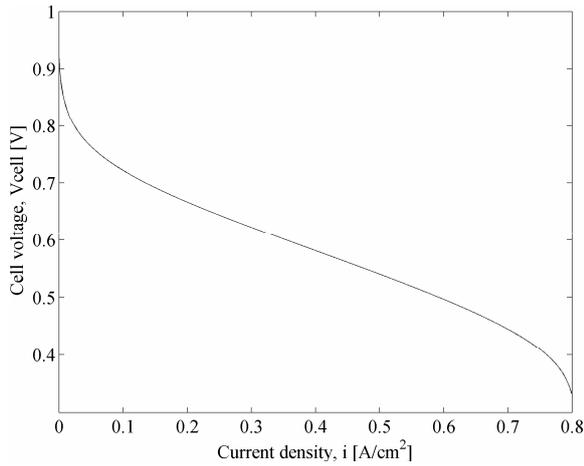
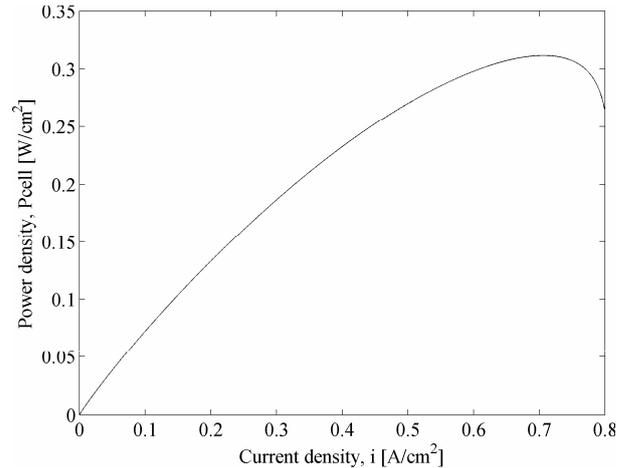Figure 2. Fuel cell voltage as a function of cell's current density

Figure 3. Fuel cell power density as a function of cell's current density

If we vary fuel cell's operating temperature we will have increase of cell voltage and power as it is shown in Figures 4 and 5.
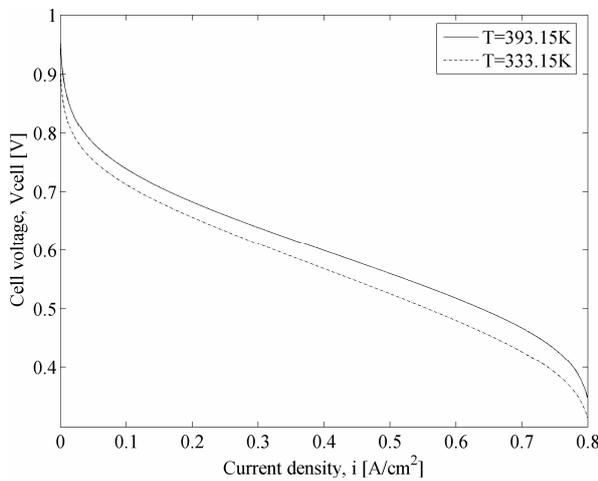

Figure 4. Fuel cell output voltage as a function of cell's current density for different temperatures
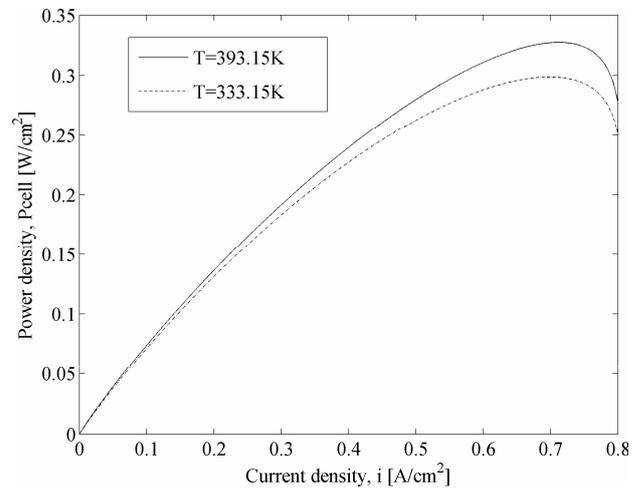

Figure 5. Fuel cell's power density as a function of cell's current density for different temperatures

We can notice that increase of fuel cell's operating temperature will cause increase of cell's output voltage and power. In temperature range of 60K we have maximum increase of cell's voltage for 0.0512V. That temperature change will cause increase in output power for 8.74% with maximum power slightly shifted towards higher loadings. In applications with high – power fuel cells these percentages would represent power variations in range of several kW. Therefore system's operating temperature must be strictly measured and controlled to avoid fluctuation in output power caused by temperature variations. Beside temperature, partial pressures of reactants and product must be monitored. Span of the pressure variations for simulation is taken from [7] and shown in Table 1.

	p_{H2} [Pa]	p_{O2} [Pa]	p_{H2O} [Pa]
Low pressure	$0.995 \cdot 10^5$	$0.606 \cdot 10^5$	$0.389 \cdot 10^5$
High pressure	$1.01 \cdot 10^5$	$1.01 \cdot 10^5$	$0.389 \cdot 10^5$

Table 1. Fuel cell's reactants and product partial pressure span

Fuel cell temperature and membrane humidity are set to standard operating conditions. Change in output power related with increase in partial pressures is shown in Figure 6. We can see that power increase because of reactant pressure increase is 1.29% and it is smaller than change caused by temperature variations. Therefore fuel cell system is less sensitive to pressure variations than to temperature variations. Finally we have performed

simulations of power output with different membrane humidity, as it is shown in Figure 7. Results show that decrease in membrane humidity for 1% will cause fuel cell's power drop for 0.67%.
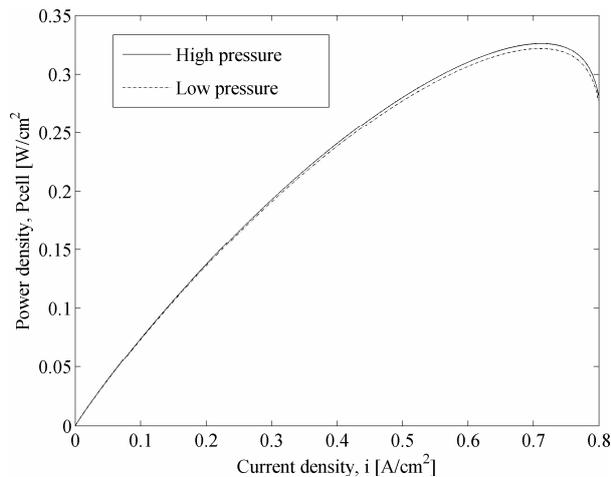

Figure 6. Fuel cell's power density as a function of cell's current density for different pressures
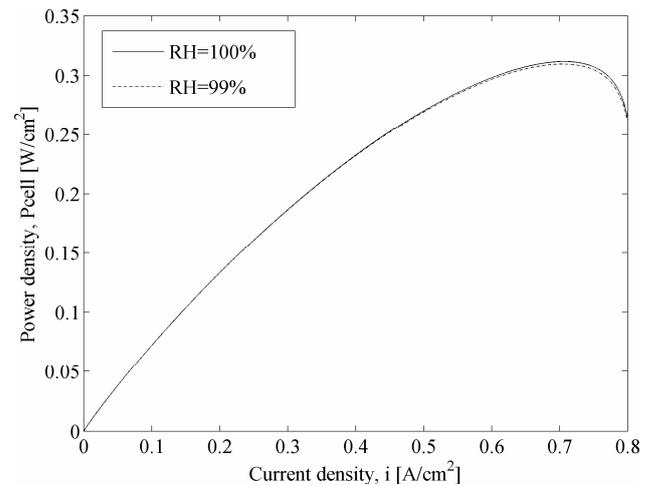
Figure 7. Fuel cell's power density as a function of cell's current density for different membrane humidity

If we decrease membrane relative humidity to 90%, fuel cell power output would decrease for 4.11% and if we simulate fuel cell power output with 80% membrane relative humidity, power output would decrease for 22.63%. From these simulations we can see that in designing measurement equipment we must pay special attention on temperature measurements while reactant pressures and membrane humidity are less significant regarding influences on fuel cell's output power. Fuel cell's membrane humidity requires special monitoring because of possible damages on fuel cell caused by improper membrane humidification, but small variation of membrane humidity would not cause significant changes in output power.

IV. Conclusion

Using simple PEM fuel-cell model and incorporating results of the recent studies, we have analyzed influence of individual fuel cell operating parameters (temperature, partial pressures and membrane humidity) to determine their correlation with fuel cell's output power.
We have found that temperature has significant influence on fuel cell's characteristics whereas influence of reactants partial pressures and membrane humidity is lower. Based on the findings, we can define design criteria for measurement and control equipment in fuel–cell systems with different complexity to ensure optimal operation.

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