PEM Fuel Cell System Evaluation Using Operational Data and Updated Matlab/Simulink Simulation Tools

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Abstract: The aim of this paper is the evaluation of the performance of a low pressure PEM (proton exchange membrane) fuel cell stack to step load changes, which are characteristic of standalone fuel cell system applications. The goal is a better understanding of the electrical behavior of the FC (fuel cell), as a result of the electrochemical processes, via the cell’s voltage characteristic during transient response. While changing the load, the performance of significant parameters affected such as temperature, pressure, purge status etc. are registered and evaluated. The analysis and experiment are based on a low pressure 1.2 kW PEM fuel cell stack (NEXAS power module). Then, the experiment is simulated using Matlab/Simulink tools, while PCU (power conditioning units) are added in order to control power flow for enhanced performance. Finally, both operational and simulation data are compared to each other showing that simple PCUs applications can improve system’s efficiency.

Key words: Distributed generation, dynamic-transient response, PEM fuel cell, standalone power systems, PCU (power conditioning units).

1. Introduction

Research and development of fuel cell systems for various applications has been dramatically increased in the past few years. PEMFC (proton exchange membrane fuel cell) system emerges as one of the most promising candidates for both stationary and automotive applications as a substitute of traditional systems such as internal combustion engines. PEM fuel cells are environmentally friendly since they use hydrogen as fuel. Moreover, knowing that there is only few fossil fuel supplies left, an alternative scenario could be one where fossil fuels would be used for providing hydrogen that can be fed directly into the fuel cells. Hydrogen can be obtained from hydrocarbons, biomass, nuclear energy, or from cleaner sources, such as water electrolysis [1].

PEM fuel cells consist of a solid polymer-electrolyte and operate at low temperature (50-100 °C). They do not pollute the environment, which is due to the fact that the only by-product is water. When the fuel (hydrogen) passes through the anode and the oxygen through the cathode, PEM fuel cell produces electrochemical power. Between the anode and the cathode, there is the previous mentioned electrolyte, which causes the exchange of electrical charge (ions). Due to the flow of ions through the electrolyte, an electrical current flows through an external circuit. A single cell produces approximately 1.23 V under normal operating conditions [2]. For higher requirements of power, several cells should be connected in series forming a stack. PEM fuel cells are considered to be an efficient energy source for supplying stationary—state power, but they are not suitable for fast load changes.

A typical PEM fuel cell stack is described by the following reactions [1-7]:

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Anode: \[ \text{H}_3 \rightarrow 2\text{H}^+ + 2e^- \] (1)
Cathode: \[ \text{O}_2 + 2\text{H}^+ + 2e^- \rightarrow \text{H}_2\text{O} \] (2)
Overall: \[ \text{H}_2 + \text{O}_2 \rightarrow \text{H}_2\text{O} \] (3)

The maximum amount of electrical energy generated in a fuel cell corresponds to Gibbs free energy, of the following reaction [2-8]:

\[ W_{el} = -\Delta G = \Delta H - T\Delta S \] (4)

The hydrogen-oxygen fuel cell reaction is written as follows using the Nernst equation [1-4]:

\[ E = \frac{-\Delta G}{2F} \] (5)

where the number 2 represents the electron pass round the external circuit for every mol of supplied hydrogen.

Assuming that all of the Gibbs free energy can be converted into electrical energy, the maximum possible (theoretical) efficiency is a ratio between the Gibbs free energy and hydrogen higher heating value: \( \eta = \frac{\Delta G}{\Delta H} = 83\% \) [2-8].

The theoretical (reversible) cell potential (Volts) is a function of operating temperature and pressure [1-4]:

\[ V_{open\ circuit} = E_{T,P} = E + \frac{RT}{2F} \ln \frac{PH_2P_0^{0.5}}{PH_2^0} \] (6)

In the following, the polarization curve of the fuel cell is represented in Fig. 1, as it came out from a simulation with Matlab based on the above equations [5] and NEXAS module technical data.

The polarization curve consists of three different regions: the active, the ohmic and the concentration. The output potential is given by the equation [1-8]:

\[ V_{output} = V_{open\ circuit} - (V_{act} + V_{ohmic} + V_{con}) \] (7)

where, \( V_{ohmic} = iR_{fc} \).

\( R_{fc} \) is the total ohmic resistance of the membrane during the flow of ions and the resistance of electrodes during the flow of electrons:

\[ V_{act} = A\log\left(\frac{j}{j_0}\right), \quad A = RT/2bf \] (8)

where \( j \) is the current density and \( j_0 \) is the exchange current density [7-10]. The constant \( b \) is called the charge transfer coefficient and is the proportion of the electrical energy applied that is harnessed in changing the rate of an electrochemical reaction [8-10].

\[ V_{con} = -\frac{RT}{2F} \cdot \ln(1 - j/j_1) \] (9)

where \( j_1 \) is the current density when pressure falls linearly down to 0 [1-8].

It is obvious that with a low current level, the ohmic voltage drop becomes less significant and the output voltage increases due to activity of slowness of chemical reactions. This region is called active polarization. At very high current density, the voltage falls down significantly because of the reduction of gas exchange efficiency due to over flooding of water in catalyst. This region is called concentration polarization. Lastly between the active region and concentrations region, there is a linear slope due to internal resistance of the fuel cell. This region is called ohmic region [6].

2. Fuel Cell Efficiency

After conducting series of measurements using different ohmic loads and based on LHV (lower heating value) for fuel cells efficiency \( (\eta = Vc_{el}/1.2) \) [1-8], they resulted in Figs. 2 and 3.

Fig. 2 shows that the efficiency of the fuel cell is reversely proportional to the current and the output power. At the rated value of the current (46 A) or at 1,200 W output power, the efficiency is about 50%.

As it is shown in Fig. 3, the relationship between the temperature and the efficiency is proportional. An increase in temperature results in an increase in
Fig. 2  (a) Fuel cell efficiency vs. current and (b) fuel cell efficiency vs. output power.

Fig. 3  Fuel cell efficiency vs. temperature.

Efficiency

Efficiency

Efficiency

Efficiency

Fig. 3  Fuel cell efficiency vs. temperature.

efficiency. This increase happens until 65 °C. For higher temperatures, nafion membrane is getting damaged, so the efficiency decreases [11]. Fig. 3 represents the efficiency near rated load.

3. Validation of 1.2 kW NEXAS Power Model

In order to validate the data sheets of 1.2 kW NEXAS power module, the theoretical data [11] are being compared with those that came out from the experimental procedure. Figs. 4 and 5 show these results for $T \approx 303$ K.

As it has been mentioned before for low values of current, the output voltage increases while, as the load decreases the current increases and the output voltage decreases as well.

The output power is proportional to the output current. At the rated value of the current (46.15 A), the highest value of the output power (1,200 W) is achieved.

In Figs. 4 and 5, it is obvious that experimental data and data sheet seem to almost match.

According to Fig. 6, as the temperature increases, the polarization curve falls down especially in the ohmic region. As mentioned before, the voltage drop in this region is proportional to the total ohmic resistance of fuel cell and this resistance increases as the temperature increases $R = R_0 \left[\alpha (T - T_0) + 1 \right]$, where $T$ is the operating temperature, $T_0$ is a reference temperature (usually room temperature), $R_0$ is the resistance at $T_0$, and $\alpha$ is the percentage change in resistivity per unit temperature).

In Fig. 7, the relationship between voltage and temperature for different load is illustrated. As the load increases, the cell voltage increases for the same temperature. Fig. 8 represents the typical behavior of 1.2 kW NEXAS power module as it came out from the oscilloscope (5 V/div, 100 ms/div), while a load (resistance, $R = 1$ Ohm) is being connected or disconnected. The dynamic response of a PEM fuel cell, when an ohmic load is being connected or disconnected, is affected by proton conduction in the membrane and water production from the overall reaction of fuel cell. The transient phenomenon during step changes affects the performance of the fuel cells and alters the stabilization time of the voltage [4].

4. Matlab/Simulink Simulation

4.1 System Model

A valid model for fuel cell and a DC/DC converter are connected in series and being simulated with simulink tools based on the NEXAS 1.2 kW operational data. The circuit of this model is illustrated in Fig. 9.

The design of the PEM fuel cell is based on the parameters that have been used during the experimental procedure in order to compare the equivalent results. The voltage at open circuit has been set at 42 V and the nominal values of the voltage and
current have been set at 26 V and 46 A. The number of cells is 47 and the operation temperature is about 303 K [11]. A step ohmic load change is applied to the system by using ideal switches which alter the value of the load every 3 s (6, 7, 8, 9, 10, 11 ohms).

4.2 Boost Converter

Due to the fact that the output voltage of the fuel cell is unregulated, this voltage can not be directly interfaced to the load. Therefore, DC/DC boost converters are used in order for the desired voltage to be achieved. The main advantage of a boost DC/DC converter is the high efficiency. In addition, the boost’s components should be selected carefully, so as to reduce the ripple generation for a given switching frequency [12, 13]. At CCM (continuous conduction mode), the equations that describe the operation of the converter are the followings [12, 13]:

\[
d = \frac{t_{on}}{T_s} \quad d: \text{the duty cycle}
\]

\[
V_{F.C.} t_{on} + (V_{F.C.} - V_{DC/DC}) t_{off} = 0
\]

\[
\frac{V_{DC/DC}}{V_{F.C.}} = \frac{T_s}{t_{off}} = \frac{1}{1 - d}
\] (10)
Without losses:

\[ V_{F.C.} = V_{DC} / DC \]
\[ I_{DC} = I_{F.C.} \]
\[ I_{DC} / DC = 1 - d \]

(11)

A feedback is being used in order to adjust the pulse width of semiconductor element to a proper value and as a result to continuously change the duty cycle of the converter, so as to set the output voltage to 80 V. The existence of feedback is necessary because as it can be seen below from the output figures of fuel cell, the voltage does not have certain constant value. On the contrary, its value changes according to the nature and the value of the load. Thus, without a control of duty cycle, the output voltage of boost would follow the output voltage of fuel cell having the same fluctuations, amplifying the boost’s output voltage width at a percentage.

The output voltage is sensed using a voltage divider (Fig. 10), and is compared with an accurate DC reference voltage \( V_{\text{ref}} \). The resulting error signal is passed through an op-amp compensation network. The analog voltage \( V_c(t) \) is next fed into a pulse-width modulator. The modulator produces a switched voltage waveform that controls the semiconductor elements.

The results of the simulation are represented below with \( R = 5.81 \) ohms as a load. Fig. 11 represents the output fuel cell voltage. It stabilizes at about 0.265 s at the value of 29.3 V.

Fig. 12 shows the DC bus voltage. The steady value (80 V) is achieved at 0.415 s.

Fig. 13 presents the DC bus current. It is given by the equation \( I = V / R \). (The used resistance as an output load is 5.81 ohms).

Fig. 14 demonstrates the effects of the DC bus voltage during a fuel input change (from 50 lpm to 85 lpm) at 10 s. While the output voltage of fuel cell alters with the previous change, the DC bus voltage maintains constant at 80 V due to the DC/DC boost converter.

Fig. 15 represents the fuel cell voltage as well as DC bus voltage reaction during step changes of the load every 3 s (6, 7, 8, 9, 10, 11 ohms). While the output voltage of fuel cell alters with the previous change in order to satisfy the requirement of energy for each value of load, the DC bus voltage maintains constant at 80 V due to the DC/DC boost converter (a small oscillation appears at every load change).

Fig. 16 shows the current response before and after the DC/DC converter. While input voltage increases,
input current and power decrease. In order to have $P_{in} = P_{out}$ on the converter, since the DC bus voltage is steady to 80 V, the DC bus current falls.

5. Conclusions

This paper analyzes the operation of 1.2 kW nexas power module. At first, efficiency diagrams were exported and characteristic curves ($V-I, P-I$) were verified by the experiment using a resistance load. The dependence between voltage and temperature was analyzed for different load values to make clear that as temperature grows up, the characteristic curve ($V-I$) falls down. Also, they were exported efficiency diagrams, near rated load, that present the increase of the efficiency until 65 $^\circ$C. In the oscilloscope, the authors have seen the slow response of the fuel cell voltage when an ohmic load is connected and disconnected. In conclusion, the experimental results confirmed the relative slow response of this device, making the use of PCU (power conditioning unit) and backup power source, such as a battery or supercapacitor, essential in order to operate with high dynamics.

Finally, aiming at the formation of stable output voltage, a simple fuel cell—DC/DC converter system was simulated in Matlab/Simulink. The simulation results were compared with those which came from the measurement, showing the effectiveness of the proposed method and the necessity of a DC/DC converter in such type of systems.

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References


