MODELING OF FUEL CELL ENERGY SYSTEM FOR USE IN AUV

Jerzy Garus
Polish Naval Academy, Poland

The endurance is one of the most important performances of the Unmanned Underwater Vehicles. Especially power determines the range and mission characteristics of the vehicle. A new sources of energy dedicated to underwater applications are developed. A simulation model of an energy system, based on fuel cells, designed to supply Autonomous Underwater Vehicles is presented in the paper. The model was implemented in MATLAB/Simulink environment after considerable simplifications. The developed simulator of the PEM Fuel Cell energy system can be a useful tool to analyze the main electrical quantities under changing working conditions.

Keywords: Underwater vehicle, PEM fuel cell, Mathematical modeling.

Introduction

The main benefits of usage of an Unmanned Underwater Vehicles (UUV) can be removing a human being from dangers of the undersea environment and reduction in cost of exploration of seas. The UUVs are divided into two main categories. The first one is the Remotely Operated Vehicle (ROV) connected to a host platform by a flexible tether to feed power and control signals. The second category is the Autonomous Underwater Vehicle (AUV) being an untethered and free-swimming marine craft with its own source of energy.

The power determines the range and mission characteristics of the AUV. The typical sources of power are batteries, but alternative energy sources are still searched and developed. One of the most promising sources are Fuel Cells (FCs) which convert a chemical energy of reactants into an electrical energy. The FC consists of two electrodes (anode and cathode) where the reaction takes place. Between the electrodes is an electrolyte material, which the ions flow through to keep the reactions continuous.

The FCs are classified by the type of the electrolyte material being used. One of them are Polymer Electrolyte Membrane (PEM) FCs which use two reactants, i.e., hydrogen and oxygen. They are considered to be most useful for marine automotive applications due to operating at low temperatures, less than 100 degrees Celsius, and having the startup time less than a minute.

In the paper a model of the PEM FC is developed and implemented in MATLAB/Simulink environment. The case study shows that the worked out simulator can be a useful tool to demonstrate the behaviour of the FC energy system in different operating conditions.
Fuel Cell Energy System

A typical energy system based on the FCs consists of numerous interconnected components, as presented comprehensively in many books, papers and surveys [1, 4, 6, 7, 8, 12, 14, 15]. The considered energy system (see Figure 1) is composed of the following components:

- oxygen and hydrogen closed cycle supply subsystems,
- thermal management subsystem,
- control and monitoring subsystem,
- power electronic converter for the power conditioning,

and there is applied a mathematical model developed for dynamic power simulation of PEM FCs available in the literature [3, 5, 9]. The assumptions for the model are as follows:

- gases are ideal,
- incompressible and laminar reactant gas flow,
- macroscopic model of mass and energy transport inside the anode and the cathode,
- the FC stack is isothermal.

A cell voltage $E$ under ideal chemical conditions and no load is calculated by so called the Nernst equation [2, 10]. By summing the cell reversing voltage $E$ for the number of stacks, it is possible to obtain the reversing voltage of the PEM FC. In load working conditions the real voltage can significantly differ from the ideal $E$. Equations which describe in details the behaviour of the PEM FC in dynamical operating conditions can be found in various works, e.g. [5, 6, 15].

![Figure 1. Main components of the PEM FC system.](image-url)
Simulation of Energy System

A goal of the simulator design has been to create a useful tool to evaluate the behaviour of the PEM FC with nominal power 5 kW in various working conditions. In the beginning, the regarded FC system was simplified according to predefined needs, as is presented in Figure 2. Then, an analytical, steady-state, isothermal mathematical model was built in the MATLAB/Simulink environment in a form of differential equations. The model predicts the fuel cell voltage as a function of the operating conditions – i.e. reactants stoichiometric flow rate, pressure and humidity as well as cell’s temperature.

Many simulations have been executed to find out a correct parameters of the mathematical model. Designed simulator was verified basis on characteristics of the real PEM FC achieved during investigations carried out in Nedstack Laboratories in Arnhem, the Netherlands. Main data used to validation are presented in Table 1. Basis on them, the mathematical model of the regarded PEM FC was tuned. The obtained results allow to state that the parameters of the model are selected correctly and finally behavior of the system is satisfied [11, 13].

Table 1. FC parameters.

<table>
<thead>
<tr>
<th>Quantity description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of cells used in the stack</td>
<td>40</td>
</tr>
<tr>
<td>cell’s temperature</td>
<td>65 C</td>
</tr>
<tr>
<td>cell’s active area</td>
<td>200 cm²</td>
</tr>
<tr>
<td>hydrogen partial pressure</td>
<td>1 atm</td>
</tr>
<tr>
<td>oxygen partial pressure</td>
<td>1 atm</td>
</tr>
<tr>
<td>maximum power</td>
<td>5000 W</td>
</tr>
<tr>
<td>maximum voltage</td>
<td>38 V</td>
</tr>
<tr>
<td>minimum voltage</td>
<td>20 V</td>
</tr>
<tr>
<td>maximum current</td>
<td>250 A</td>
</tr>
</tbody>
</table>
Then a user graphic interface has been established (see Figure 3). It allows to observe and analyze main system variables under changing working conditions for given values of gas temperature and pressure. Moreover, the simulator allows to measure and display the following characteristics: voltage, power and efficiency as functions of current density.

![Figure 3. Graphic user interface for the data acquisition.](image)

Two of them are depicted in Figure 4 and Figure 5. The first one shows the current-voltage characteristic and the second the current-power characteristic. Both are obtained under the same operating conditions: the pressure is 1.0 atm, the cell temperature 65°C and the relative humidity 100%. As it is seen there is excellent agreement between modeled and experimental data. The average prediction error is below 5%.

Operating parameters are set during the operation of the FC’s simulator to give the desired output. The most important ones are pressure, temperature, and relative humidity. The effects of them on FC performance are presented in Figure 6, 7 and 8.
Figure 4. Modeled and measured current-voltage characteristics.

Figure 5. Modeled and measured current-power characteristics.

Figure 6 shows that pressure is this operating parameter which has a large impact on the FC’s performance. In this study, the temperature is kept at 65°C, the relative humidity 100%, while the pressure is varied from 1.0 atm to 1.7 atm. As noticed the higher pressure is beneficial to FC’s performance.
As seen in Figure 7, increasing of temperature has negative influence on FC’s performance. In regarded case, the pressure is 1.0 atm, the relative humidity 100 %, while the temperature is varied from 30 C to 90 C.

Also the relative humidity effects FC performance, as presented in Figure 8. The best results are obtained for humidity close to 100 %. In this study, the pressure is 1.0 atm, the temperature 65 C, while the relative humidity decreases from 100 % to 60 %.

Figure 6. Effect of pressure p on FC performance.

Figure 7. Effect of temperature T on FC performance.
Conclusions

Fuel cell modeling has received a lot of attention in the past two decades and a large number of models have appeared in the literature. Most of them are extremely useful for specialists in area of FC energy system design, but due to complexity are of less interest for others.

A goal of the worked out simulator has been to create the useful tool allowing to analyze the behavior both the whole FC energy system and its chosen components.

The developed MATLAB/Simulink model has the ability to emulate satisfactorily the behavior of 5 kW PEM FC by variation of certain parameters, mainly pressure, temperature, and relative humidity.

It is dedicated to specialists in marine technology and can be used for the analysis of underwater power systems in current and future applications.

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References