Control of Fuel Cell's Reactant of Autonomic Underwater Vehicle's

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Abstract: - Paper presents a dynamic model of fuel cells designed to supply the autonomous underwater vehicle. This model was implemented in MATLAB / SIMULINK after considerable simplifications. In the model there was omitted modeling the measuring equipment, and some properties of gases were approximated. It was assumed that the designed model gives answer to the question of how to build a control systems of supply the fuel cell by reactants. For this reason, we attempt to develop control systems using fuzzy controller. The structures of fuzzy regulators were modeled on classical regulators of linear regulators P, PI, PD and PID. For designed controllers the simulation investigation were conducted.

Key-Words: - system modeling, simulation, underwater vehicles, fuel cell, fuzzy control

1 Introduction
Reduction of fossil fuel reserves, unstable prices of oil and rising air pollution are factors that force the development of alternate sources of energy. In response to these threats, there is observed a rapid growth of the hydrogen technology as a technology that convert chemical energy into electric one [6, 8]. A lot of conducted nowadays scientific researches concentrate their attention on the fuel cell technology. This solution guarantees reduction in air pollution and presents a wide range of usefulness simultaneously. This advantage is taken by a lot of producers and researchers making use of fuel cells for many varied applications, among other things for autonomic unmanned underwater vehicles.

As an autonomous underwater vehicle will be understood unmanned object completely submerged in water, having six degrees of freedom and with its own power source. This source is designed to ensure a continuous supply of energy to the parts and modules which are the equipment of underwater vehicle. Nowadays, as a power source in such type of vehicles are mostly used the sets of battery packs. However, such solutions do not allow to realize the mission of long time. For this reason, we are looking for new solutions which allow to extend the duration time of execute the mission. One of currently discussed solution might be using fuel cells to power both the vehicle's propulsions as well as devices that are on its equipment.

The fuel cell system considered for an autonomic unmanned underwater vehicles application is composed of the following components [1, 3, 11]:
- PEM fuel cell stack,
- oxygen and hydrogen closed cycle supply subsystems,
- thermal management subsystem,
- control and monitoring subsystem,
- power electronic converter for the power conditioning.

Fig.1 Fuel Cell System

The reactant supply subsystem is crucial to effectiveness of reaction. It is responsible for supply fuel cell by hydrogen and oxygen with rated
quantity and pressure. They have been also accountable for humidification of hydrogen and oxygen before entering a stack, what essentially improves efficiency and durability of a fuel cell [6]. Thus, the correct operation of a fuel cell depends on quality of a gas in supply process. To maintain the desired hydrogen and oxygen partial pressure and flow, there have been designed the control system with applications of fuzzy logic [5].

2 Control of Fuel Cell System

PEM fuel cells for a correct operation require a continuous supply of the reactants: hydrogen and oxygen. Any changes in the load resistance cause change of the chemical reaction rate which is taking place at the electrodes and what have an influence on the reactant mass demand. Moreover, a constant value of hydrogen and oxygen pressure inside the anode and the cathode are needed. These factors determine the need to control the hydrogen and oxygen supply at the constant pressure value. To provide all these functions, the fuel cell system must fulfill a number of requirements. To meet the all requirements mentioned above, the fuel cell system presented in Fig. 2 was elaborated.

In the PEM fuel cell system presented above, the regulating reactant gas flow valves are used as actuators of the control system [10]. From this point of view, the calculation of valve parameters have to be carried out. Undesirable effects appear while valves are redimensioned or undersized. Concerted effort has been made to find the best operating conditions. It was computed $k_v$ coefficient by using the tables and the formulas presented in [6]. The calculation of $k_v$ coefficient allows to use the relation between pressure fall and density of agent flow:

$$Q_N = \frac{k_v}{192.6} \sqrt{\frac{\Delta p \cdot p_2}{\rho_N \cdot T_i}}$$  \hspace{1cm} (1)

where:

- $Q_N$ – scaled volume of gas stream,
- $k_v$ – dimensional coefficient of valve,
- $\Delta p = p_1 - p_2$ – difference of absolute pressure across a valve,
- $\rho_N$ – gas density at nominal conditions,
- $T_i$ – gas inlet temperature.

Because the valves’ producers point at the linear dependence between the control voltage and the flow of agent and making an assumption that the electromagnetic constant is equal 30 – 40 [ms], we can describe dynamics of valve as a transfer function [4]:

$$G_{pv} = \frac{1}{0.04s + 1}. \hspace{1cm} (2)$$

The reactant gas pressure controller, which is placed directly behind the bottle of the compressed agent, determines a constant value of the gas pressure in the inlet manifold. It was implemented, as well as the reactant gas flow valves, as an inertial element of first order time-constant equal to 40 ms [4]. A command signal for control of valve is prepared in the flow’s fuzzy controller of hydrogen (oxygen).

The hydrogen recirculation pump is used to force the agent circulation in a closed cycle. The excess masses of hydrogen and oxygen in the inlet manifold are determined by the stoichiometry coefficient equals adequately 1.25 and 2. It means, that 20% of supplied hydrogen and 50% of oxygen don’t take part in the chemical reactions. Because the elaborated system was prepared for underwater applications, where store-rooms are very restricted, it seems necessity to reuse the supplied reactant by a renewed deliver to the circulation.

Dynamics of recirculation pump, for the purpose of mathematical modeling, there is shown in the state space model [4] as follow:

$$\begin{bmatrix} \frac{d\omega}{dt} \\ \frac{dW_{H_2}}{dt} \end{bmatrix} = \begin{bmatrix} -1.99 & [227] \\ [0.132] & [0] \end{bmatrix} \begin{bmatrix} \omega \\ i_{pom} \end{bmatrix}$$ \hspace{1cm} (3)

$$W_{H_2} = 0.132 \omega$$ \hspace{1cm} (4)

where:

- $\omega$ – angular velocity of rotor,
- $i_{pom}$ – control current,
- $W_{H_2}$ – mass flow rate of hydrogen.
The tanks of hydrogen and oxygen were modelled in the synthesized system as the constant equals 150. This constant implicates the maximum possible mass flow rate and it was experimentally determined.

Considering the pressure fall in the inlet manifold, there was used the experimental research shown in [4]. In that paper the author discussed the performance analysis of a fuel cell supply system in similar conditions as those presented in this paper. He proved that the behaviour of gases for changeable values of the pressure and the mass flow rate can be approximated by a first order model with the time-constant equal 4s. This assumption was applied in the elaborated system.

3 Automatic Control of Reactant Flow

The main goal of the automatic control of the reactant flow is to update the value of the reactant flow in response to the changes in the load resistance with the stoichiometry coefficient taken into consideration. Additionally, the automatic control is responsible for keeping constant pressure values inside the anode and cathode compartments which should be equal 1 bar. Considering the control system structure and type of used controller, it was assumed the series structure with fuzzy logic controllers. Motivation for this assumption was the expectation of the strong nonlinearity of the controlled system with the saturation of the final control elements and the large simplification assumed during control system synthesis. Applying a fuzzy controller seemed to be the best solution to overcome all these limitation because of its good performance characteristics for nonlinear systems over a wide range of a required value and for simplified mathematical models. All considered elements of both the hydrogen and oxygen supply subsystems were assumed to be identical. The only difference between this two models relies on taking into consideration different hydrogen and oxygen physical and chemical properties during analysis of the reactant flow valves.

In order to reduce system complexity, the following simplifications were applied [4, 9]:
- flow in gas channels are modelled for ideal gas,
- incompressible reactant gas flow,
- laminar reactant gas flow,
- macroscopic model of mass and energy transport inside the anode and the cathode,
- constant parameters of gas inside the manifold,
- isentropic reactant gases flow,
- ideal compressible wall of manifold.

In generally, taking into account that system will work on ships, the elaborated fuel cell control system led to formulate the following requirements:
- range of adjustment reactant gases flow- 0 – 150 Nl/min,
- overshooting – 10%,
- offset – 2%,
- settle time – 5s,
- difference of pressure drop between the anode and cathode less than 300 mbar,
- gas pressure in the inlet manifold equals 1 bar.

For the need of control the fuel cell work, the fuzzy controllers which task was to control the flow of oxygen and hydrogen as well as fulfil the requirements mentioned above were designed. Applying the theory of fuzzy sets makes possible to emulate PID controller performance with modification allowing utilize nonlinear control techniques [3, 5]. In this work, comparison analysis of the control system with fuzzy PD and PIPD controllers was carried out. Then parametric synthesis of proposed controllers was performed using a heuristic method to determine the controller setting. Example of fuzzy PIPD controller is shown in Fig. 3 [11].

![Fig. 3 Fuzzy PIPD controller](image)

4 Fuzzy Logic Controller

Fuzzy controller synthesis started from the initial selection of membership function for individual controllers and creating the database of rules [1, 13]. For such prepared structures of regulators an initial verification simulation to set the correct assumptions were conducted. After that some intuitive changes in shape and distribution of
membership function were introduced and the
database of rules were corrected. After comparison
the selected methods of defuzzification, the method
of center of gravity proved to be the most effective.
At the end of the parameters’ optimization was
carried out, involving the selection of the scaling
reinforcement for individual regulators. Scaling
reinforcements were selected manually basing on
results of computer simulation.

4.1 Reactant supply controllers
In order to control the gas flow, the fuzzy PIPD
controller was designed (Fig. 3). In its structure, the
PI and PD actions can be distinguish. For the PD
and PI actions, membership functions are shown in
Fig. 4 and Fig. 5, respectively.

Then the rules bases for the PD and PI actions
(Table 1 and 2) were designed basis on fuel cell
operator experience. There is used the following
notation: BM – very small, M – small, S – medium,
D – big and BD – very big.

The centroid defuzzification method was used to
determine the output value from the center of
gravity of the output membership function. The
membership functions utilized in this process are
depicted in Fig. 6. For the elaborated structure of the
fuzzy PIPD, the controller tuning was carried out.
The results are shown in Table 3.

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**Table 1. Rules base for PD action**

<table>
<thead>
<tr>
<th>e(t)</th>
<th>BM</th>
<th>M</th>
<th>S</th>
<th>D</th>
<th>BD</th>
</tr>
</thead>
<tbody>
<tr>
<td>de(t)</td>
<td>BM</td>
<td>BM</td>
<td>BM</td>
<td>M</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>BM</td>
<td>M</td>
<td>S</td>
<td>D</td>
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<td></td>
<td>D</td>
<td>M</td>
<td>S</td>
<td>D</td>
<td>BD</td>
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<tr>
<td></td>
<td>BD</td>
<td>S</td>
<td>D</td>
<td>BD</td>
<td>BD</td>
</tr>
</tbody>
</table>

**Table 2. Rules base for PI action**

<table>
<thead>
<tr>
<th>e(t)</th>
<th>BM</th>
<th>M</th>
<th>S</th>
<th>D</th>
<th>BD</th>
</tr>
</thead>
<tbody>
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<td>de(t)</td>
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<td>BM</td>
<td>BM</td>
<td>M</td>
<td>S</td>
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<tr>
<td></td>
<td>M</td>
<td>BM</td>
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<td></td>
<td>BD</td>
<td>S</td>
<td>D</td>
<td>BD</td>
<td>BD</td>
</tr>
</tbody>
</table>

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**Fig. 4 Membership functions for PD input variables:**

a) e(t), b) \( \frac{de(t)}{dt} \)

**Fig. 5 Membership functions for PI input variables:**

a) e(t), b) \( \frac{de(t)}{dt} \)

**Fig. 6 Membership functions for output variable**

\( u(t) \): a) PD action, b) PI action
Table 3. Fuzzy PIPD controller settings

<table>
<thead>
<tr>
<th>Hydrogen flow</th>
<th>Oxygen flow</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PI action</strong></td>
<td></td>
</tr>
<tr>
<td>Gain of P unit</td>
<td>0,09</td>
</tr>
<tr>
<td>Gain of I unit</td>
<td>0,05</td>
</tr>
<tr>
<td><strong>PD action</strong></td>
<td></td>
</tr>
<tr>
<td>Gain of P unit</td>
<td>20</td>
</tr>
<tr>
<td>Gain of D unit</td>
<td>0,00001</td>
</tr>
</tbody>
</table>

4.2 Recirculation pump controller
The recirculation pump speed is automatic controlled by the fuzzy PIPD controller. It was assumed that the membership functions and the rule bases are the same as those presented in the gas flow control system with the exception of PD action, where the membership functions for PD input and output variables are depicted in Fig. 7 and Fig. 8.

For the elaborated structure of the fuzzy PIPD, the controller tuning was carried out. The results are shown in Table 4.

Table 4. Fuzzy PIPD controller settings

<table>
<thead>
<tr>
<th>Hydrogen flow</th>
<th>Oxygen flow</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gain of command signal</strong></td>
<td>4</td>
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<tr>
<td><strong>PI action</strong></td>
<td></td>
</tr>
<tr>
<td>Gain of P unit</td>
<td>0,02</td>
</tr>
<tr>
<td>Gain of I unit</td>
<td>0,05</td>
</tr>
<tr>
<td><strong>PD action</strong></td>
<td></td>
</tr>
<tr>
<td>Gain of P unit</td>
<td>3</td>
</tr>
<tr>
<td>Gain of D unit</td>
<td>0,0001</td>
</tr>
</tbody>
</table>

5 Simulation study
To validate the performance of the developed fuzzy control, some computer simulations have been made. In order to achieve it, an input function was prepared. The input function represents the required value of the fuel cell current density. In this function, the following changes were included: from 0% to 50%, from 50% to 100%, from 100% to 75% and from 75% to 25% of the maximal value.

Fig. 7 Membership functions for PD input variables:

a) $e(t)$, b) $\frac{de(t)}{dt}$

Fig. 8 Membership functions for PD output variable $u(t)$

Fig. 9. Mass flow rate of oxygen for fuzzy PD and PIPD controllers (reactant supply subsystem)

Fig. 10. Mass flow rate of oxygen for fuzzy PI and PIPD controllers (reactant supply subsystem)
As the result of the simulation, the desirable output function of the mass flow rate of hydrogen and oxygen was obtained. Connected this function with the simulation results of the fuzzy P, PI, PD and PIPD controllers, comparison analysis of the elaborated systems was performed. Some results of the simulation are depicted in Fig. 9, Fig. 10 and Fig. 11.

![Mass flow rate of hydrogen for fuzzy P and PIPD controllers (recirculation subsystem)](image)

**Fig. 11.** Mass flow rate of hydrogen for fuzzy P and PIPD controllers (recirculation subsystem)

### 6 Conclusion

Synthesis of the reactant gases flow control system using fuzzy logic was performed. It was useful to have appreciation how the process of the reactant supply runs. Relaying on the literature, an essential apparatus for the developed system was selected. We decided to use checked out in real systems elements. Looking for alternative ones could help us to develop better systems, but they might be unfeasible. The simulation model was also significantly simplified. The modelling of measuring apparatus was skipped and modelling of some gas parameters have been simplified. It was assumed, that the elaborated system should answer to the question, how to design the control systems for fuel cell applications. Simultaneously, it has to be so flexible, that in the future, it will be possible to use them on a real object. For this reason, the attempt to elaborate the control system using fuzzy logic was made. The structures of developed controllers were based on the classical P, PI, PD and PID algorithms. Because during research there weren’t any circumstances for choice a concrete controller, there were examined all of this algorithms.

The comparison analysis of the elaborated systems led to formulate the following conclusions:

- fuzzy PI controllers used in the reactant supply control system don’t fulfil expectations in the field of settle time,
- fuzzy P and PD controllers used in the reactant supply control system don’t fulfil expectations in the field of offset,
- fuzzy P, PD and PIPD controllers have a comparable good performance.

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**References:**


