Experimental study of fuel cell properties based on current-voltage characteristic

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Abstract. Demand for stable and easily-accessible energy is constantly growing. It is obvious that renewable energy sources cannot meet all the needs of modern human civilization. Thus, it is extremely important to find an effective and environmentally safe way of extracting energy from natural resources. Fuel cells could make such opportunities available, combining high efficiency and low greenhouse gas emissions. But since fuel cells are at the initial stage of development, it is required to conduct a lot of research for improving their performance. This article introduced a simple but powerful method for diagnosing fuel cells. It has been shown that correctly processed data from the current-voltage curve can provide a quick analysis of the performance parameters of fuel cells.

1. Introduction

A fuel cell is an electrochemical device in which electrical energy is generated by electrochemical reactions between the oxidant and the fuel. Driving forces of the reactions are gradients of partial pressures of gases in a fuel cell.

The paper proposes a method for studying properties of single fuel cells by examining a current-voltage characteristic of the element.

The following chemical reactions are valid for an ideal hydrogen fuel cell:

— hydrogen oxidation occurs at the anode:

$$2H_2 \rightarrow 4H^+ + 4e^-$$

— the reduction of oxygen with the release of water occurs at the cathode:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

The total equation can be represented in the following form:

$$2H_2 + O_2 \rightarrow 2H_2O$$

The most common types of fuel cells are fuel cells with solid electrolytes [1]. This class includes fuel cells with a polymeric proton exchange membrane PEMFC.

A transfer of the ion charge in the case of proton exchange membranes is carried out by hydrogen ions. A distinctive feature of proton-exchange membranes is the low operating temperature $t < 100^\circ C$ [2].

One of the main parameters characterizing the efficiency of FC is voltage on the cell. Under standard conditions, OCV (open circuit voltage) of an ideal hydrogen fuel cell is 1.23 V [3].

According to the Nernst equation, OCV of a fuel cell can be expressed as follows [4]:

$$E = E^0 - \frac{RT}{nF} \ln Q$$

where

- $E$ is the cell potential
- $E^0$ is the standard cell potential
- $R$ is the gas constant
- $T$ is the absolute temperature
- $n$ is the number of electrons transferred
- $F$ is the Faraday constant
- $Q$ is the activity of the reactant
\[ E = \frac{-\Delta G}{N F} + \frac{R T}{N F} \ln \frac{\alpha_{\text{red}}}{\alpha_{\text{ox}}}, \]  

Here \( \Delta G \) - Gibbs free energy of the redox reaction, \( J / \text{mol} \); \( F \) - Faraday constant, \( C / \text{mol} \); \( N \) - number of electrons are involved in the electrochemical reaction; \( R \) - gas constant, \( J / (\text{mol} \cdot \text{K}) \); \( T \) - temperature, \( K \); \( \alpha \) - an activity of oxidized and reduced forms.

The actual voltage, \( V \) differs from the theoretical voltage due to various losses. Thereby, for a real fuel cell we have [4]:

\[ V = E - V_{\text{act}} - V_{\text{ohm}} - V_{\text{con}} \]  

Here \( V_{\text{act}} \) - activation losses, \( V \); \( V_{\text{ohm}} \) - ohmic losses, \( V \); \( V_{\text{con}} \) - concentration (mass transport) losses, \( V \).

Thus, in order to increase the power of the fuel cell, it is important to determine separately each type of losses. In [2], the above equation for the study of PEMFC was described in a convenient for the researcher form:

\[ V = E_{\text{OCV}} - b \log \left( \frac{i + i_{\text{tot}}}{i_{\text{tot}}} \right) - R i - m [\exp(n i) - 1] \]  

Here \( E_{\text{OCV}} \) - open circuit voltage, \( V \); \( i \) - current density, \( \text{mA/cm}^2 \); \( b, i_{\text{tot}}, R, m, n \) - empirical coefficients.

The summands \( R i, b \log \left( \frac{i + i_{\text{tot}}}{i_{\text{tot}}} \right), m [\exp(n i) - 1] \) represent respectively ohmic, activation and mass transport losses.

The activation losses are associated with the activation energy of the system and the rate of the chemical reaction and can be reduced by the use of catalysts [3]. The losses associated with the electronic conductivity of the membrane can also be referred to activation ones [5].

The mass transport losses are associated with the presence of a partial pressure gradient of the reagents that is caused by consumption of the gasses on the catalyst. It happens due to insufficient supply and removal of reagents and products of the reaction respectively [3].

The ohmic losses are specified by transition of energy of the ion and electron currents to thermal energy in a fuel cell, as well as by the resistance of interconnects and other current-carrying parts.

2. Methods
The purpose of the experiment is to build the current-voltage and current-power characteristics of the fuel cell which consists of a proton exchange membrane made of Nafion. The source of fuel is the balloon with pure hydrogen. The schematic diagram of the experimental setup and its appearance are shown in Figures 1 and 2, respectively.

\[ \text{Figure 1. Schematic diagram of the experimental setup} \]
The membrane must be moistened during operation to ensure proton conductivity since in the absence of water the sulfate group of the electrolyte does not dissociate [3]. In addition, with humidification, the rate of degradation of FC is reduced. In order to moisten the membrane, a bubbler with distilled water is provided, which is washed with distilled water before use.

"AKTAKOM ATN-8030" is used as a monitoring instrument. The measurements were carried out in current stabilization mode under normal conditions.

The experiment was carried out by setting the current intensity on the load and reading the voltage and power at constant parameters of the gases entering the fuel cell. The readings from the device were taken after the voltage had been stabilizing for 3 minutes.

The results of the measurements are shown in Figures 3 to 4. In order to process the results of the experiment, the software "Microsoft Office Excel" was used.

3. Results and conclusions
Using the method of least squares, the values of the coefficients of equation (3) were obtained. The results of the calculations are presented in Tables 1 to 2, in Figures 5 to 6.
Table 1. Empirical coefficients of equation (3)

| $b$      | $i_{los}$ | $R$   | $m$         | $n$   |
|----------|-----------|-------|-------------|-------|
| 0.0832   | 0.6026    | 0.0124| $1.280 \times 10^{-87}$ | 24.5  |

Table 2. Actual and simulated voltage values

| Actual voltage, $V_{actual}$, V | Simulated voltage, $V_{simulated}$, V |
|---------------------------------|--------------------------------------|
| 0.950                           | 0.949                                |
| 0.950                           | 0.940                                |
| 0.910                           | 0.910                                |
| 0.870                           | 0.883                                |
| 0.867                           | 0.862                                |
| 0.847                           | 0.844                                |
| 0.832                           | 0.827                                |
| 0.810                           | 0.811                                |
| 0.800                           | 0.797                                |
| 0.777                           | 0.782                                |
| 0.767                           | 0.769                                |
| 0.742                           | 0.740                                |
| 0.000                           | 0.000                                |

Figure 5. Model of voltage drop

Figure 6. Different types of voltage drops

It can be seen from Fig. 6 that the activation voltage losses, in other words, losses associated with low reaction rates are predominant at low currents. Significant ohmic resistances are observed, and at relatively low currents, the ohmic losses start to exceed the activation ones, which is an atypical case for polymer fuel cells. The value of $R = 12.5$ ohm-cm$^2$ revealed in the experiment is extremely high for PEMFC and requires special attention.

The behavior of the polarization curve at currents above 8 mA/cm$^2$ is typical for an insufficient partial pressure of fuel at the anode to maintain a given power, which is confirmed by the sharply increased mass transport losses (Figure 6). In our case, the observed voltage drop is due to the insufficient supply of hydrogen into the fuel cell.

Thus, based on the results obtained, the following conclusions can be drawn:
1. Differentiation of voltage losses by types in the proposed model makes it possible to identify the most problematic factors of electricity generation in fuel cells:
   — to reduce the activation losses, it is necessary or to choose a different type of catalyst, or increase the temperature in the fuel cell process;
   — high ohmic losses indicate a low value of the ionic conductivity of the electrolyte, considerable resistance of the interconnects and conductive parts. In order to reduce the ohmic losses, it is necessary to use more advanced materials with high conductivity values, and also to select the optimum temperature regime of operation;
   — to reduce mass-transport losses, it is necessary to ensure timely supply of reagents and removal of reaction products, as well as optimum moisture content in the fuel.

2. Development of the regression equation for the polarization curve from the current-voltage characteristic is an effective way of structural analysis of a fuel cell and is a preliminary stage before an in-depth study of the problem.

3. Simulation of the PEMFC characteristics conducted according to the recommendations of the authors [2] is provided with high accuracy - the coefficient of determination $R^2 = 0.99945$ even with fast changes in voltage.

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