

# Piecewise Control Method of Oxygen Flow in PEM Fuel Cell

Jerzy Garus and Adam Polak

**Abstract** The paper presents a method of control of an oxygen flow in the PEM fuel cell without recirculation. The proposed procedure of finding an optimal value of the oxygen flow basis on comparing a current voltage of the cell with a reference one obtained from a static model of the PEM fuel cell. Simulation results show that such value of the flow is obtained for a limited number of steps. It allows to reduce the oxygen usage assuring safe operation of the fuel cell.

**Keywords** PEM fuel cell · Oxygen flow · Control

## 1 Introduction

Nowadays renewable energy sources are intensively searched. This approach has its roots in the belief of scientists and industry representatives on the imminent exhaustion of fossil fuels and environmental safety. Fuel cells are the perfect solution to both of these issues. They are completely ecologically clean and do not require fossil fuels to work [1, 2].

An evidence of the growth of interest in this source of energy in last decades is the increasing number of scientific publications as well as implementations of the power supply systems which have found a variety of applications, including electric energy sources for unmanned vehicles, cars, submarines, space objects, etc. [1–3].

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There are many types of the fuel cells, but the most promising one seems to be the proton exchange membrane (PEM) fuel cell. It requires providing hydrogen and oxygen for correct operation and produces electricity, heat, and water as products. One of the main subsystems responsible for proper operation of the fuel cell system is an oxygen supply subsystem. Most often oxygen is obtained from the atmospheric air and the oxygen supply subsystem consists of a blower or a compressor [4] causing the air flow through a cathode channel of the fuel cell and providing the sufficient amount of oxygen for the oxidation reaction and removal of produced water, and sometimes also the excess heat. In the case of lack of access to the air, pure oxygen is used and the oxygen supply subsystem is constructed in two different ways [3]. In the first one, oxygen is circulated through a closed loop by an oxygen recirculation pump. It needs to use a controller responsible for maintaining a constant gas pressure in the cathode channel and providing a continuous circulation of oxygen in the system. An advantageous of such a solution is possibility of complete oxygen utilization, but disadvantageous a need of additional equipment like the oxygen recirculation pump and dryers or water condensers increasing a total weight and size of the system. The second solution is the oxygen supply subsystem with an open cathode, wherein the excess oxygen is blown out of the cell. In such a way, part of oxygen is not used causing a loss in the overall balance of the fuel cell system operation but there is no need for installation of any additional equipment. However, in such a case control of the oxygen flow is more complicated because not only a proper amount of the oxygen for the reaction has to be provided but also a sufficient flow of the oxygen in the cathode must be ensured in order to remove water being the reaction product. Therefore, it is necessary to apply a control procedure allowing to choose the flow of oxygen depending on an operating state of the fuel cell. This case is considered in the paper.

The work consists of six sections. A mathematical model of the PEM fuel cell is written in section two. Then in next two sections a behavior of the fuel cell for different oxygen flows and a proposed control strategy are described. In section five some simulation tests and obtained results are presented. Conclusions are given in the last section.

## 2 PEM Fuel Cell Mathematical Model

PEM fuel cells obtain the energy from electrochemical reaction that take place inside them. Separating the half reaction to anode and cathode it is possible to harness the released energy to do electric work. The reactions that take place inside fuel cells are as follows:



An overall reaction is:



Electric energy generated by the fuel cell comes from a difference between the Gibbs free energy of formation of the product (water) and the Gibbs free energy of formation of the reactants (oxygen and hydrogen) [1]:

$$2\Delta G = G_{\text{product}} - G_{\text{reactants}} \tag{4}$$

It is convenient to analyze the energy equation in the molar notation, hence the formulae (4) takes a form:

$$\Delta g = g_{\text{product}} - g_{\text{reactants}} \tag{5}$$

During the chemical reaction that take place in the PEM FC one mole of molecular hydrogen and half a mole of molecular oxygen are consumed by the cell per one mole of the produced water. Therefore (5) for PEM FC can be expressed as follows:

$$g_{\text{H}_2\text{O}} - g_{\text{H}_2} - \frac{1}{2}g_{\text{O}_2} \tag{6}$$

For a mole of reacting hydrogen,  $2N$  of electrons flow through an external electric circuit ( $N$ —the Avogadro constant) and charge transferred between the electrodes is equal to:

$$-2Ne = -2F \tag{7}$$

where:  $e$ —the charge of a single electron,  $F$ —the Faraday constant.

The electric work  $W_{\text{el}}$ , related to transferred charge, done by the fuel cell is equal to:

$$W_{\text{el}} = -2FE \tag{8}$$

where  $E$  is the electromotive force of the fuel cell.

Assuming that the cell operates without losses, the electric work would be equal to the change of the Gibbs free energy of formation:

$$W_{\text{el}} = \Delta g \quad (9)$$

Hence, the electromotive force  $E$ , of the hydrogen fuel cell operating in standard pressure, can be expressed by the following equation:

$$E = \frac{-\Delta_g}{2F} \quad (10)$$

However, there is also a dependency between the Gibbs free energy of formation and the pressure of the reactants and the products. For PEM FC, it is taken into account in the Nernst equation and is expressed as [1, 2]:

$$E = E^0 + \frac{RT_{\text{op}}}{2F} \ln \left( \frac{P_{\text{H}_2} P_{\text{O}_2}^{\frac{1}{2}}}{P_{\text{H}_2\text{O}}} \right) \quad (11)$$

where  $E^0$  is the electromotive force of the fuel cell at standard pressure,  $T_{\text{op}}$  is the operating temperature of the cell and  $P_{\text{H}_2}$ ,  $P_{\text{O}_2}$ ,  $P_{\text{H}_2\text{O}}$  are the partial pressure of hydrogen, oxygen, and produced water, respectively.

Modeling of the PEM FC operation it is required to take into account voltage losses which occur during operation. The losses are distinguished according to their causes, but generally, they are regarded as: activation losses, concentration losses, and ohmic losses [2, 4, 5].

## 2.1 Activation Losses

The activation losses are caused by the limited speed of reactions that take place on the electrodes. A part of the generated electric energy is used to maintain the speed of the reaction which is determined by the load current. These losses are described by the empirical equation introduced by Tafel in 1905 and used since now by researches [6]:

$$\Delta V_{\text{act}} = A \ln \left( \frac{i}{i_0} \right) \quad (12)$$

where:  $i_0$ —exchange current density,  $A$ —coefficient which depends on the catalyst material and the reactants composition.

In the hydrogen fuel cell, the activation losses existing on the cathode are much greater than losses appearing on the anode, thus in practical applications the last ones are neglected. Also losses associated with the fuel crossover, because of their insignificant effect on the operating voltage, are omitted [1].

## 2.2 Ohmic Losses

The ohmic losses are proportional to the current and the internal resistance of the fuel cell according to the following formulae [1]:

$$V_{\text{ohmic}} = IR \quad (13)$$

The resistance  $R$  can be treated as a sum of the resistance of the path through which the electrons flow, (i.e., electrodes and bipolar plates), and the ionic resistance of the PEM. The Eq. (13) can be written in current density terms as follows:

$$\Delta V_{\text{ohmic}} = ir \quad (14)$$

where:  $i$  is the current density in mA/cm<sup>2</sup>, and  $r$  is the area-specific resistance given in kΩ cm<sup>2</sup>.

## 2.3 Concentration Losses

The mass transport losses, also named the concentration losses, are caused by reactants pressure gradient appearing in gases supply manifolds, flow channels, and gas diffusion layers once a current is being drawn from the cell. A decreased partial pressure of the reactants at the catalyst site leads to the reduction of the fuel cell voltage. There are many theoretical approaches presenting models of the transport losses, but the following one is lately regarded to be of the most value [1, 7]:

$$\Delta V_{\text{trans}} = m \exp ni \quad (15)$$

The constants  $m$  and  $n$  in (15) depend not only on a construction of the gas flow channels and diffusion layers but also a composition of the reactants.

## 2.4 Operating Voltage Equation

Taking into account all the voltage losses, the operating voltage of the fuel cell at given current density can be calculated as follows [6, 8, 9]:

$$V = E - \Delta V_{\text{ohmic}} - \Delta V_{\text{act}} - \Delta V_{\text{trans}} \quad (16)$$

Substitution (12), (14), and (15) into (16) gives the expression:

$$V = E - ir - A \ln\left(\frac{i}{i_0}\right) - m \exp(ni) \quad (17)$$

Excluding the constant  $i_0$  from the activation losses (12) and including it into the constant value of the real open circuit voltage  $E_{\text{oc}}$ :

$$E_{\text{oc}} = E + A \ln(i_0) \quad (18)$$

leads (17) to the dependency:

$$V = E_{\text{oc}} - ir - A \ln(i) - m \exp(ni) \quad (19)$$

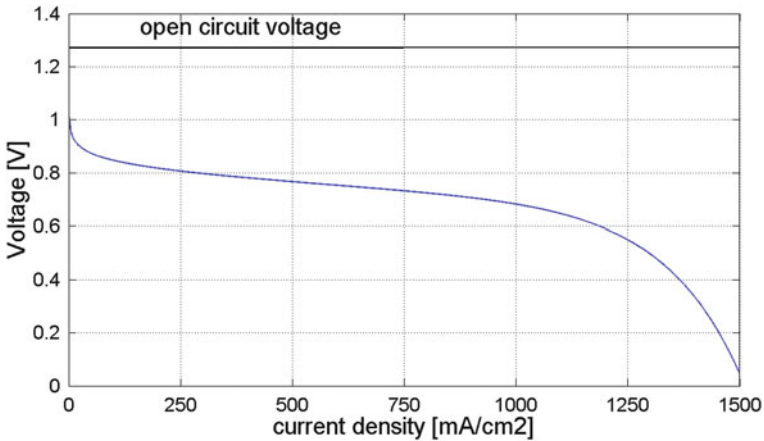
The above theoretical form of the polarization curve is quite simple and easy to implement into a control system of the PEM FC.

An operating voltage of a whole fuel cell stack  $V_{\text{st}}$  can be calculated from the following expression:

$$V_{\text{st}} = N_{\text{cell}} \cdot V \quad (20)$$

where  $N_{\text{cell}}$  is the number of cells in the stack.

The parameters of the Eq. (19) are obtained with help of the identification method described in [10]. The equations with the obtained parameters have a form:



**Fig. 1** PEM fuel cell steady-state model (polarization curve)

$$U = 1.01 - 47 \times 10^{-6} \times i - 0.0347 \times \ln(i) - 2 \times 10^{-4} \times \exp(4.9 \times 10^{-3} \times i) \quad (21)$$

and it's graphical representation is shown in Fig. 1.

## 2.5 Fuel Cells Behavior in Different Oxygen Flows

PEM fuel cell for proper operation requires sufficient amount of oxygen delivered successfully to the positive electrode of the cell. The amount of the consumed oxygen is dependent on the cell current and results directly from the reaction (3) occurring in the cell. Dependency (22) presents the oxygen usage to perform the reaction in the cell [1]

$$O_{2,usage} = \frac{1}{4F} = \frac{i \cdot A_{FC}}{4F} \quad (22)$$

where  $I$  is the fuel cells' current,  $A_{FC}$  is the fuel cell's active area ( $cm^2$ ).

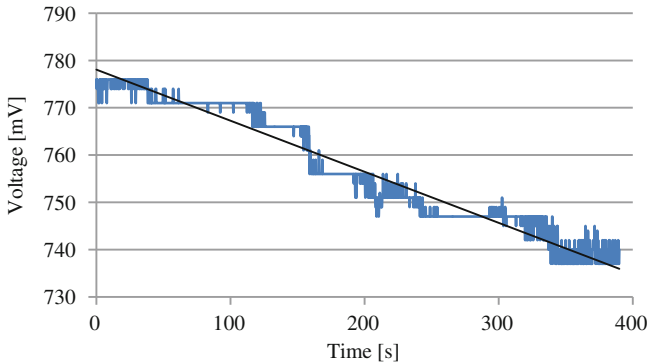
The Eq. (22) depicts the amount of oxygen, which is used to maintain the chemical reaction inside the cell at the rate determined by the cell's current. In the PEM fuel cell, the additional amount of oxygen flow is required to flush the produced water out of the cell before it starts to condense. Therefore, the total oxygen flow required for the proper operation of the cell can be expressed as follows:

$$\dot{m}_{O_2,mol} = k \cdot O_{2,usage} \quad (23)$$

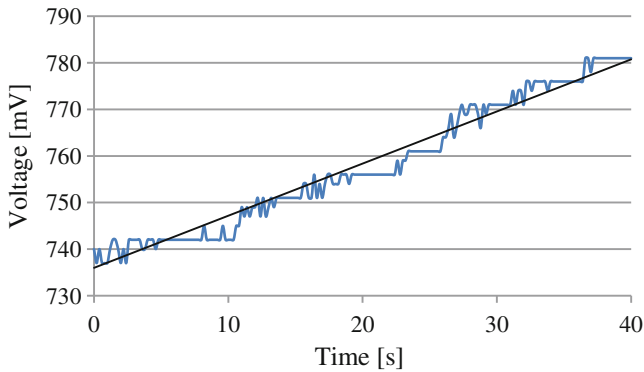
where:  $k$  is the oxygen flow coefficient and  $\dot{m}_{O_2,mol}$  is the actual oxygen flow expressed in mol/s.

In the reviewed literature, there was not found the analytical way to determine the optimal oxygen flow coefficient that ensures safe and stable operation of the cell. It is significant aspect especially in fuel cell systems that do not use the oxygen from air but use the oxygen from any storage devices. However, the minimal and at the same time safe for fuel cell oxygen flow coefficient, was experimentally estimated. Depending on the size of the fuel cell, the current density, the temperature, and the reactants partial pressure inside the cell, as well as the architecture of the oxygen flow channels of the cell, the optimal oxygen flow coefficient varies from 1.1 to 4 [11, 12].

In order to use a simulation means to validate the control method it is necessary to model the fuel cell response to different oxygen flows. For that purpose the



**Fig. 2** PEM fuel cell response to low oxygen flow (from  $k = 2$  to  $k = 1.1$ ); *blue line*—measured data, *black line*—linear interpolation)



**Fig. 3** PEM fuel cell response to the change of the flow coefficient from  $k = 1.1$  to  $k = 2$  (*blue line*—measured data, *black line*—linear interpolation)

experimentally gathered data from the PEM fuel cell system was used. The measurements of voltage change of the PEM fuel cell and its linearization during low oxygen flow (oxygen flow coefficient set to 1.1) are presented on Fig. 2.

The response to increased oxygen flow was also recorded and is presented on Fig. 3. The oxygen flow was increased from  $k = 1.1$  to  $k = 2$ .

From the measurements of the fuel cell response to a different oxygen flows it is possible to determine the general dependencies describing the voltage change in case of different oxygen flows. The equation for estimation the  $DU$  (the voltage change in discrete time intervals  $T$ ) in case of different oxygen flow coefficients presents dependency (24)



$$\Delta U = a \cdot T \tag{24}$$

where:  $a$  is the voltage change coefficient,  $T$  is the assumed time interval. The  $a$  coefficients for the data presented on Figs. 2 and 3 are  $a = -0.108$  mV/s,  $a = 1.118$  mV/s respectively.

For the modeling purpose, the possible values of the oxygen flow coefficient were limited to the range  $k \in \langle 1; 5 \rangle$ . Moreover, according to the laboratory tests the optimal oxygen flow coefficient was estimated to the value of  $k_{opt} = 1.345$ . Furthermore, the linear relationship of the parameter from Eq. (24) and the oxygen flow coefficient was assumed. For those assumptions the parameter  $a$  is calculated as follows:

$$a = \begin{cases} 0.44 \cdot k - 0.592 & \text{for } 1 < k < k_{opt} \text{ and } U_{act} - U \leq 0 \\ 1.707 \cdot k - 2.296 & \text{for } k \geq k_{opt} \text{ and } U_{act} - U < 0 \\ 0 & \text{for } k \geq k_{opt} \text{ and } U_{act} - U = 0 \end{cases} \tag{25}$$

where  $U_{act}$  and  $U$  are the current voltage of the cell and the calculated voltage of the cell from (21), respectively.

### 3 Control Strategy for Oxygen Flow

The oxygen flow control algorithm should deliver to the fuel cell sufficient amount of oxygen for the reaction and for the product water removal. For the optimal usage of oxygen it is necessary to continuously track the actual current and the voltage of the cell and set the oxygen flow to the minimal value that will guarantee the proper operation of the cell, which will be assessed by comparison of the voltage of the fuel cell with the reference one obtained from the model. Due to the high inertia of the fuel cell and the air supply subsystem for fuel cell that is operating at constant current, for control of oxygen flow a method of successive approximations at regular intervals can be implemented. The control method involves:

- by any change of the electric current drawn from the cell to set the predefined initial value of oxygen flow coefficient  $k_0$ ,
- finding the optimal value of the oxygen flow coefficient by method of successive approximations in fixed intervals  $T$ ,
- completion of the search for the optimal oxygen flow when the step reaches a value less than assumed  $\epsilon$ .

The search for the optimal flow rate of oxygen is accomplished by changing the value of the oxygen flow coefficient in the steps obtained from the following Eq. (25):

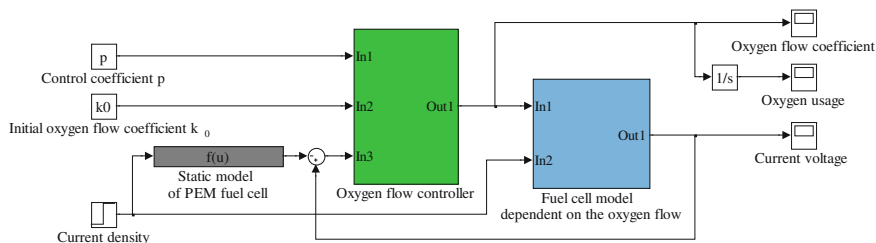
$$k_i = \begin{cases} k_{j-1} + \frac{k_0}{p^j} & \text{for } U_{\text{act}} - U < 0 \\ k_{j-1} - \frac{k_0}{p^j} & \text{for } U_{\text{act}} - U = 0 \end{cases} \quad (26)$$

where:  $j$  is the number of the current iteration,  $p$  is the constant control coefficient.

## 4 Simulation Tests and Results

The simulation tests of the proposed control strategy of the oxygen flow through the cathode of the PEM fuel cell were performed in MATLAB/Simulink environment. Figure 4 presents the simulation model.

The model allows to run the tests for different initial oxygen flow, and for different control coefficient. It also allows to visualize the change of the oxygen flow, the oxygen usage and the current voltage of the cell. The tests were performed for the conditions presented in Table 1. Simulations were performed for different values of the control coefficient, so it is possible to rate the control method of the oxygen flow for various values of this coefficient. The results of the simulations are presented on Figs. 5, 6, 7, 8, 9 and 10. From results of the simulation it can be concluded that the selection of the appropriate value of the control coefficient has a significant impact on the quality of the obtained results of the regulation.



**Fig. 4** Oxygen flow control system of the PEM fuel cell—simulation model created in MATLAB/Simulink environment

**Table 1** Parameters of the performed simulations

Parameters	Units	Values
$i$	$\text{mA}/\text{cm}^2$	300
$p$	–	1.25, 1.5, 1.75, 2, 2.2, 2.4, 2.6, 2.8, 3
$k_0$	–	1.7, 2
$T$	s	100

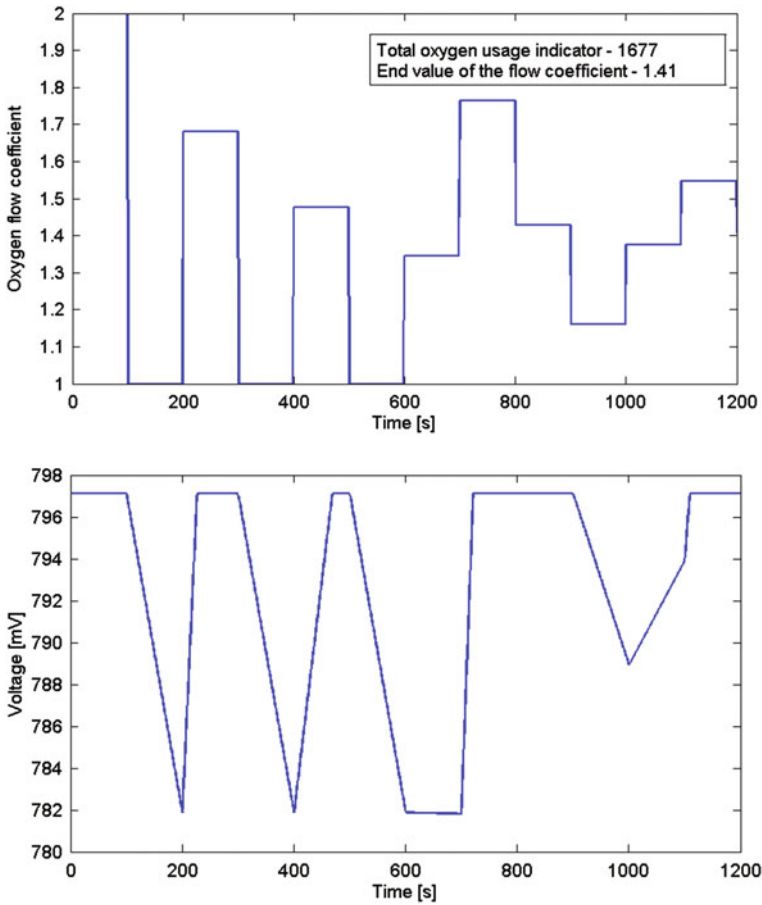
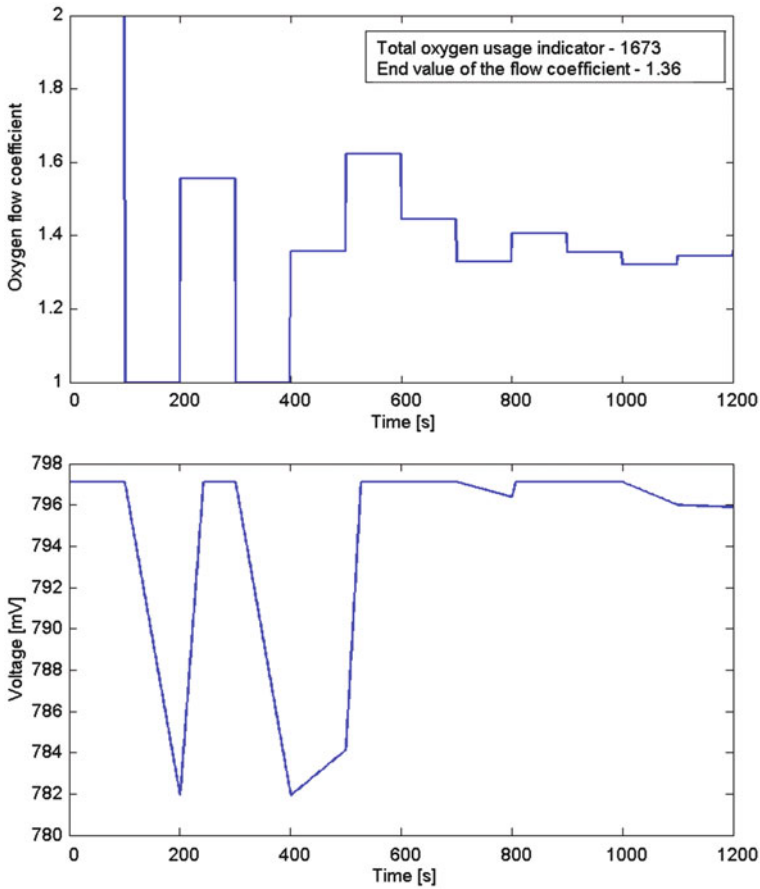


Fig. 5 Oxygen flow coefficient and voltage at the output of the PEM fuel cell for  $p = 1.25$

The quality of the regulation is measured as an accuracy of setting the oxygen flow coefficient. Setting the control coefficient on a too low value causes that the regulation steps are very small, therefore the adjustment time is greatly extended. On the other hand, small value of the control coefficient allows for accurate adjustment of the oxygen flow coefficient. Conversely, if the control coefficient is too high, the regulation steps are large, which can also cause the proposed regulation method never come close enough to the optimal oxygen flow. This phenomenon is dangerous in two ways. In the case of setting a value less than the optimum value, it would lead to water condensation inside the cathode channel of



**Fig. 6** Oxygen flow coefficient and voltage at the output of the PEM fuel cell for  $p = 1.5$

the fuel cell and in consequence a significant reduction of the cell voltage and even the failure of the cell. In contrast, setting the flow to a much higher value than the optimum result in excessive oxygen consumption and consequently low oxygen utilization.

Also, the initial oxygen flow has an influence on the results of the proposed control algorithm. For the same control coefficient and for the different initial oxygen flows, the results of the simulations differ each other. Figure 10 presents the results of the simulation for the initial oxygen flow coefficient set to 1.7 and the

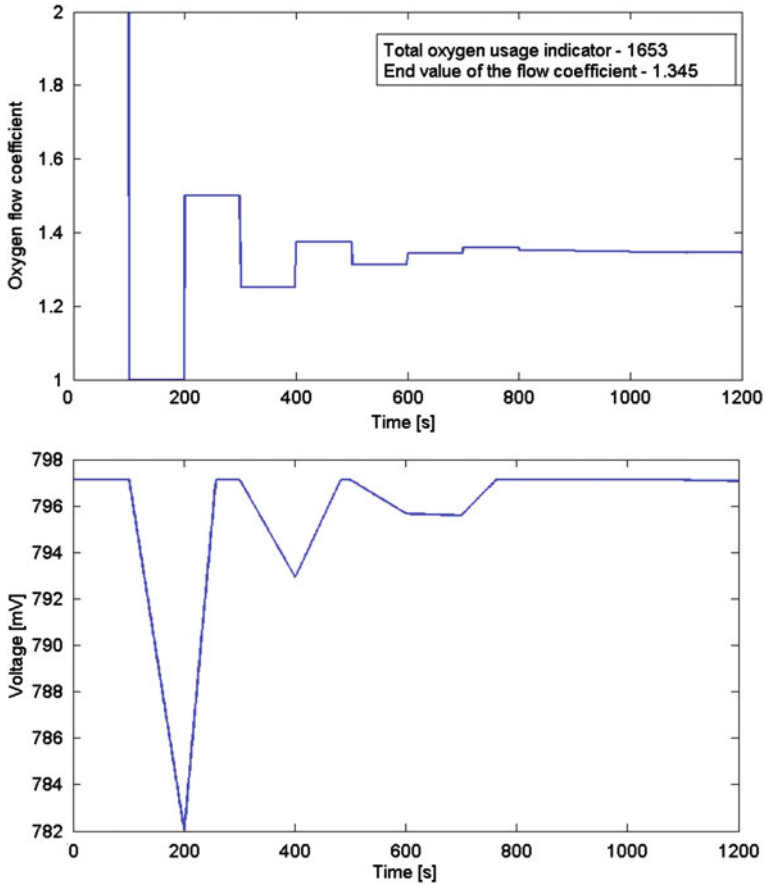


Fig. 7 Oxygen flow coefficient and voltage at the output of the PEM fuel cell for  $p = 2$

control coefficient set to 2.4. Comparison the results presented on Figs. 8 and 10 shows the influence of the initial oxygen flow on the value of the oxygen flow coefficient at the end of regulation, which in the case presented on Fig. 10 is tuned for higher value.

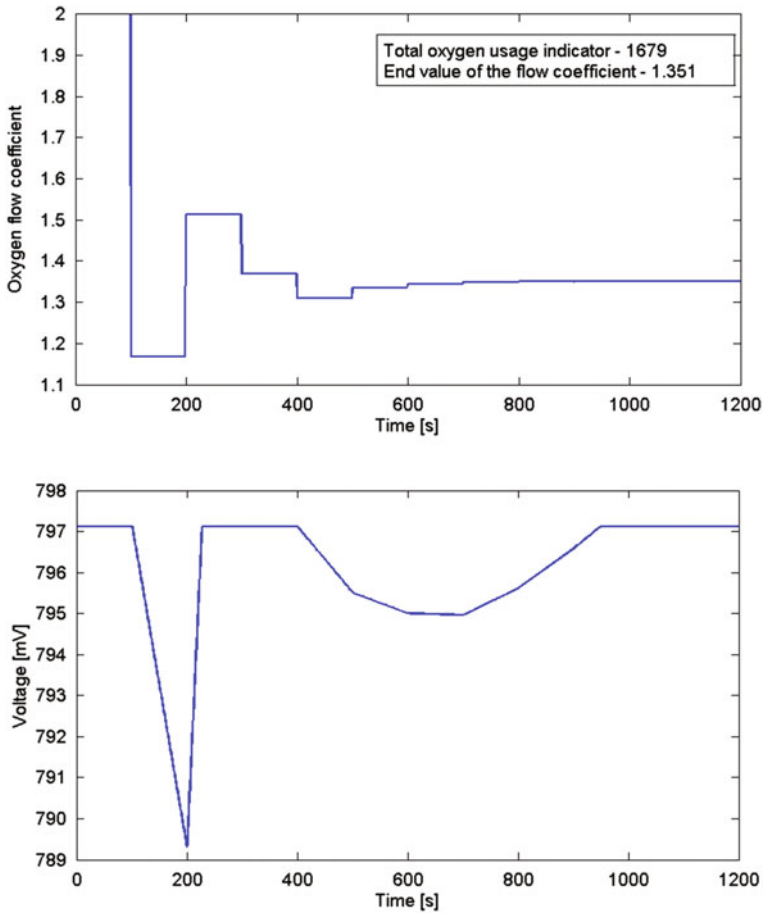


Fig. 8 Oxygen flow coefficient and voltage at the output of the PEM fuel cell for  $p = 2.4$

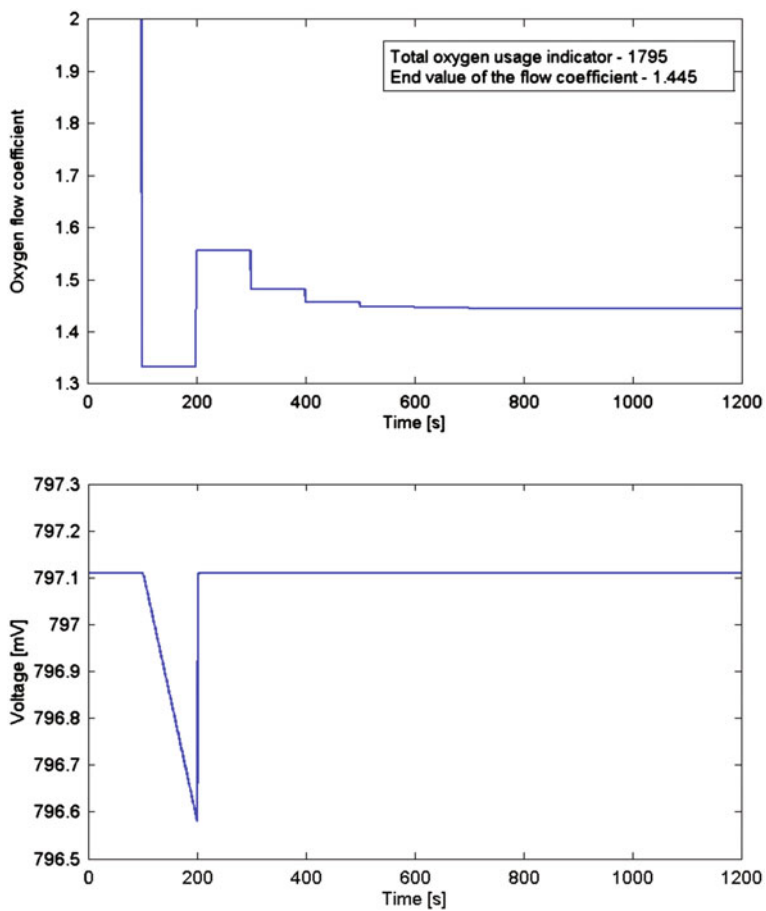
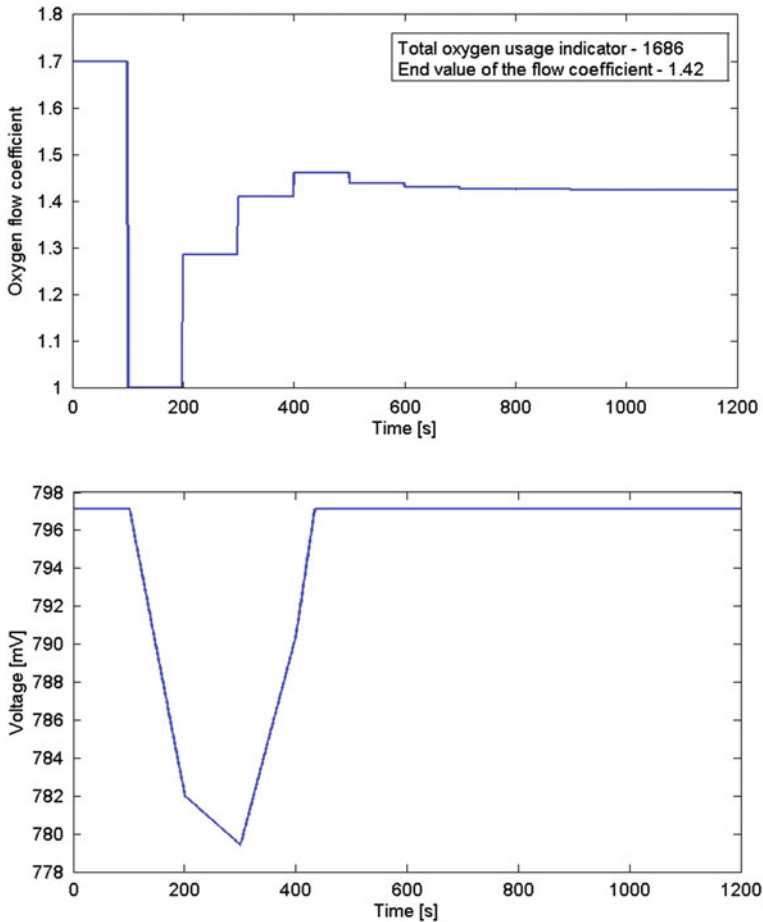


Fig. 9 Oxygen flow coefficient and voltage at the output of the PEM fuel cell for  $p = 3$



**Fig. 10** Oxygen flow coefficient and voltage at the output of the PEM fuel cell for  $p = 2.4$  and the initial oxygen flow coefficient set to 1.7

## 5 Conclusions

The main task of the oxygen subsystem of the PEM fuel cell is to deliver oxygen in an amount which assures maintaining speed of the oxidation reaction at level determined by the electric current drawn from the cell. Another important task is to flush out water being the product of the reaction. Both of them are achieved by setting the oxygen flow rate at the proper value. Most often that value is calculated as a product of the amount of oxygen consumed in the oxidation reaction and the oxygen excess flow coefficient  $k$ . The oxygen flow is usually overestimated due to the value of the coefficient is constant in time.



The paper presents a method of determination of the oxygen flow taking into account that the coefficient  $k$  is varying in time. In every step of the control procedure a new value of the coefficient  $k$  is calculated. Performed simulations confirmed the correctness of the proposed procedure for estimating the proper value of the oxygen flow coefficient. The results showed that the most significant impact on the quality of control has the initial value of oxygen flow coefficient  $k_0$ .

The further investigations will focus on the verification of the effectiveness of the described control method by means of experiment on the real PEM fuel cell.

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