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Simple dynamic model of a PEM-type fuel cell

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This paper presents a heuristic zero-dimensional model of a PEM-type fuel cell including dynamic states. The model is based on the static energy characteristics of the cell as a function of the voltage generated from the current drawn from the cell. The model was supplemented with a module of inertia under load change and the cleaning process. The phenomenon of cell efficiency decrease under the influence of water accumulation on the cathode side and purging of the cell, controlled by purging and short-circuiting, was also taken into account. The simulation and research results for the Horizon 300 W fuel cell are shown. Measurements and simulations were compared to demonstrate the model's high accuracy.

Key words: *fuel cell, model, static, dynamic, power*

1. Introduction

With the growing challenges of climate change, depletion of fossil fuel resources, and the need to reduce greenhouse gas emissions, the development of renewable energy technologies is becoming one of the key directions for research and technological innovation. Hydrogen, as a clean and high-energy fuel, is becoming increasingly important in the context of the energy transition. Its use in fuel cells, which enable emission-free conversion of chemical energy into electricity, is a promising alternative to conventional energy technologies.

Today, the European Union is pursuing its declared hydrogen strategy to achieve climate neutrality by 2050 [14, 22]. Hydrogen, especially so-called green hydrogen (produced using renewable energy sources), plays a key role in this transition. The strategy, also adopted by the member countries [23], includes the following actions [14]:

1. Increasing the share of hydrogen in the energy sources. Currently, hydrogen accounts for only about 2% of the EU's energy consumption, with most of it coming from fossil fuels. The Union's objective is to significantly increase the share of low-carbon hydrogen, primarily green hydrogen, in total energy consumption.
2. Green hydrogen development. The EU is emphasising the development of green hydrogen, which produces no CO_2 emissions. Although its production is currently more expensive than grey or blue hydrogen, the strategy includes investment in RES-powered electrolysers, reducing production costs through technology scaling, and support for research and innovation in electrolysis process efficiency.
3. Hydrogen applications in industry and transport. Hydrogen is expected to replace fossil fuels in sectors difficult to decarbonise, such as steel and chemical industries, heavy transport (trucks, railways, ships), energy storage, and grid stabilization.
4. Integration of energy systems. Hydrogen to act as an energy carrier and store, enabling seasonal integration of RES (e.g. surplus energy from photovoltaics in summer can be converted to hydrogen and used in winter).
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Fuel cells are being considered as one of the key technological solutions [22]. Fuel cells, and in particular Proton Exchange Membrane Fuel Cell (PEMFC) hydrogen cells, are characterized by their high efficiency, low emissions, and ability to operate over a wide power range. Thanks to these properties, they find applications in both transport (cars, buses, trains) and stationary systems (emergency power, microgrids). However, despite their numerous advantages, the widespread deployment of fuel cells faces a number of technological and economic challenges, including production costs, component durability, and optimisation of the processes inside the cell [2, 7, 17].

Fuel cells as part of machine power systems are an important element in the energy efficiency of a machine. The static and dynamic characteristics of the cell make it necessary to adapt and optimise the power supply and control systems. This is easier with whole-machine (system-level) simulation methods. In most cases, it is not necessary to develop models describing the exact phenomena taking place in the cell (including physico-chemical phenomena, gas and heat flow), but they can be replaced by simplified models based on empirical data. This approach is often used in the development of system models [6, 10, 13, 20].

The aim of this article is to present a mathematical model describing the operation of a hydrogen fuel cell of the PEMFC type. A simple model has been developed, including the dependence of the current generated by the cell on the system voltage, taking into account not only its static characteristics, but also dynamic phenomena.

2. Simple fuel cell model

The basic assumption of the model was to obtain a simple form of the model that is as easy to identify as possible (with a small number of parameters), giving the model's response to the cell's operating conditions, which is correct in terms of both static and dynamic conditions. Due to the availability of measurement data, it was decided to use an empirical model instead of a physical model, which is an acceptable method for creating simplified models [10].

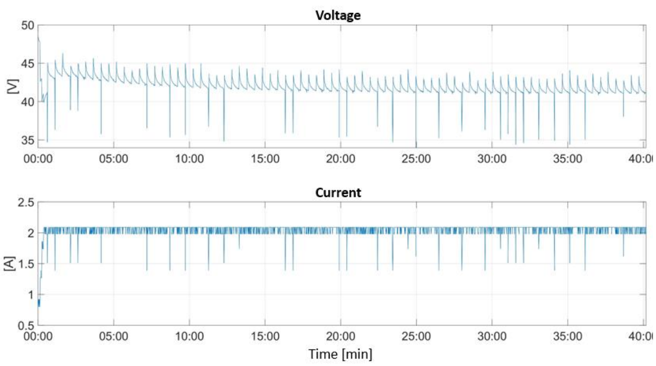

Fig. 1. Voltage and current flow for Spectronik Protium-450 fuel cell

From the testing of a Spectronik Protium-450 cell equipped with a control system that optimizes its performance (Fig. 1), it was noted that, in addition to the static characteristics of the voltage-current dependence of the cell's load, there are changes due to inertia during load spikes and changes due to the cell's cleaning process. This can be seen as periodic (with a frequency of about 60 s) voltage spikes.

It was therefore proposed that the model should take into account three phenomena: the static characteristics, the dynamic characteristics resulting from inertia under load change, and the cell cleaning characteristics. The components of the model are described below.

The simple fuel cell model is the relationship of the output voltage from the cell as a function of load (current) and time. The model, according to the assumption described above, is divided into three components:

$$\mathrm{U_{FC} = U_P + U_{Dyn} + U_{Purg}} \tag{1}$$

where: $\mathrm{U_P}$ – static fuel cell characteristic (polarization curve); $\mathrm{U_{Dyn}}$ – dynamic fuel cell characteristic; $\mathrm{U_{Purg}}$ – dynamic fuel cell characteristic during cleaning.

The first component of the model is the static characteristics of the cell. This is termed the polarization curve [1, 3]. This curve (Fig. 2) is characteristic of all PEM fuel cells and is divided into three regions: an initial activation region where the voltage decreases logarithmically with increasing current, a ohmic region where increasing current causes a linear decrease in voltage and a mass transport region where further increases in current lead to an exponential decrease in voltage. There are many simplified models describing these characteristics [1, 3, 9, 15]. These are based on a simple description of the physical phenomena occurring in the cell. The proposed model, however, adopts a much simpler approach based on an approximation of test results.

$$\mathrm{U_P = f(I)} \tag{2}$$

where: I – current, A.

The second component of the model is related to the dynamic response of the cell during a step change in load. As tests have shown (Fig. 3), with a step increase in load change, the system needs time to decrease the voltage (with respect to the polarization curve) and then asymptotically return to the polarization curve [11]. With a step decrease in load, the opposite occurs – a temporary increase in voltage relative to the polarization curve. As described in the articles [8, 11, 18, 20], this is due to the inertia of the phenomena occurring in the cell, mainly related to mass transport both to the membrane region and in the membrane structure. The phenomenon can therefore be described as:

$$\mathrm{U_{Dyn} = -k_{Dyn} \cdot \frac{dU}{dt}} \tag{3}$$

where: $\mathrm{k_{Dyn}}$– model parameters – fuel cell inertia.

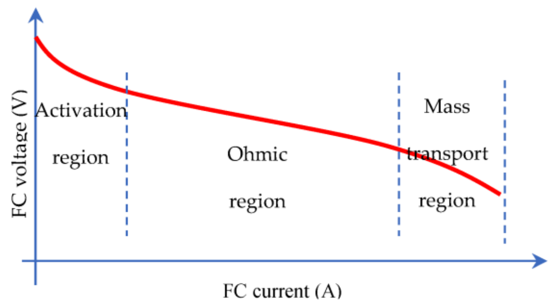

Fig. 2. Nonlinear U = f(I) characteristic of the fuel cell [3]

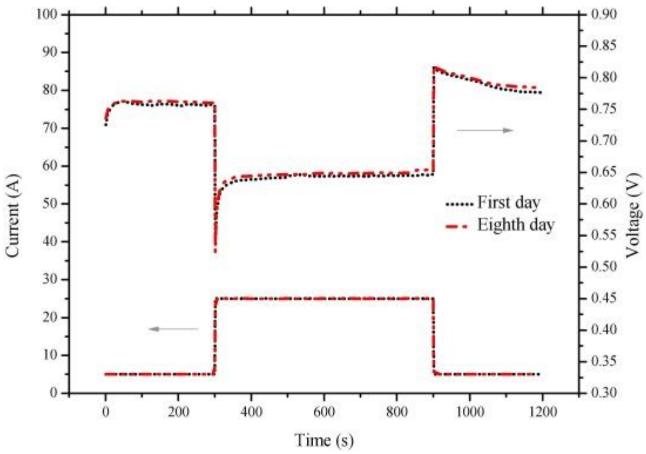

Fig. 3. Dynamic response of the fuel cell [11]

The final component of the model is the segment responsible for changing the polarization curve as a result of cleaning the cell. The effectiveness of the membrane depends, among other things, on the amount of accumulated water (or water vapor) on its surface and in its surroundings. This vapor is generated by the oxidation of hydrogen on the cathode side, but some of it enters the anode side, obstructing the flow of hydrogen to the membrane, reducing its efficiency. To prevent this phenomenon, periodic cleaning of the anode side is used [4, 5, 11, 16]. This is done by short-circuiting the cell (to evaporate the water) and opening the through-valve (purge) and blowing off a small amount of hydrogen with the water vapor. The result of this action is a temporary increase in the cell's efficiency, followed by a slow return to the basic polarity curve (Fig. 4). The frequency of purging and its intensity are selected to suit the design parameters and operating conditions of the cell.

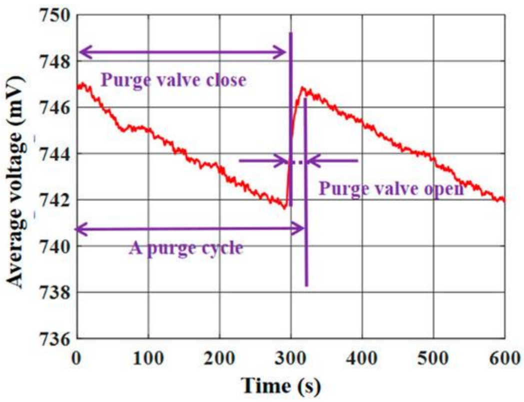

Fig. 4. The voltage variation of the average single cell under traditional long-cycle purge intervals [11]

In the developed model, the following function was adopted to describe this action:

$$U_{Purg} = \Delta U_{max} + \Delta U_{tot} \cdot \left(\frac{1}{e^{k_C \cdot t}} - 1\right) \tag{4}$$

where: ΔU_{max} – maximum increase over polarization curve; ΔU_{tot} – total possible drop of characteristic under polarization curve; k_C – model parameter; t – time form last cleaning process.

It should also be remembered that the implementation of cleaning causes a step change in the load of the cell. During a short-circuit, a much higher current flows through the cell (resulting from the low resistance of the cell). This change must therefore be taken into account in the calculation according to the formula:

$$I = \begin{cases} I_{Load}, & \text{Purge} = \text{off} \\ I_{Short}, & \text{Purge} = \text{on} \end{cases} \tag{5}$$

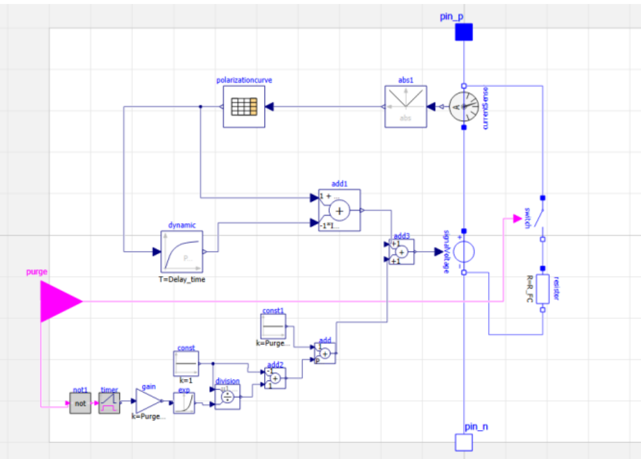

Fig. 5. Fuel cell model implementation in Modelica

The above model was implemented in the Modelica environment. Figure 5 shows the developed model, which is a component of an electrical circuit connected by pins (pin_p and pin_n) to an electrical circuit. A data matrix interpolation element using the continuous derivative method is responsible for the static model. Below this is the element responsible for the inertia of the system under dynamic load changes and at the bottom is the cell cleaning model. The model thus prepared was subjected to an identification process.

3. Model identification

3.1. Object research

The developed model, implemented in the Modelica environment, requires parameter identification. To this end, tests were carried out on a selected cell model equipped with an integrated control system performing the purification function automatically. Details are provided below.

The object of the study is a PEMFC Horizon 300 type cell from Horizon (Fig. 6). It is a cell consisting of 60 open-cathode cells with a nominal power of 300 W. Detailed data are provided in Table 1.

Table 1. Parameters of Horizon 300 fuel cell [21]

Fuel cell	Horizon 300
Type	PEM
No. of cells	60
Architecture	Open cathode
Coolant	Air cooled
Rated power	300 W
Rated current	8.3A
Voltage output	32–54 VDC
Start-up time	< 30 s
Hydrogen gas	Dry, 99.999% purity
Delivery pressure	0.4–0.5 bar
Fuel consumption	3.9 dm^3/min

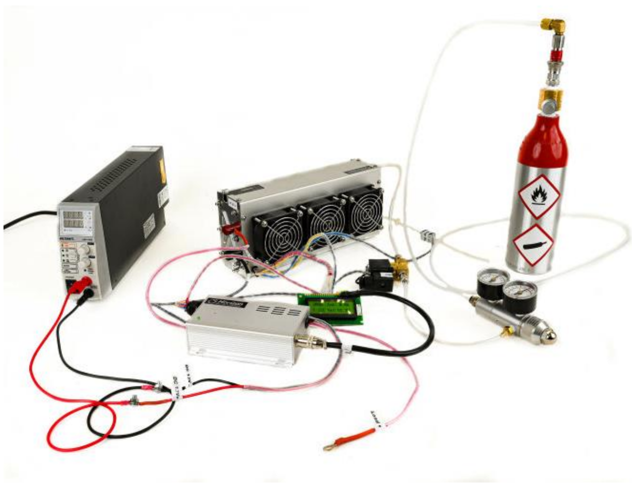

Fig. 6. Object of the research – Horizon-300W fuel cell [21]

3.2. Test stand

The research was carried out at the Lublin University of Technology. The hydrogen cell was supplied from a 0.4-litre bottle via a Spectronik EMPR regulator. The cell was connected to a current load EA-EL 3080-60 B, allowing the electrical load of the cell to be varied. Control of the cell was performed by a system that was an integral part of the cell. Current and voltage were measured using an oscilloscope, Tektronix TBS1052C 50 MHz, with a data recording card and current probe, Tektronix TCP0030A, plus an amplifier, Tektronix TCPA300. A schematic of the test bench is shown in Fig. 7 and Fig. 8. Measurements were taken at a frequency of 1 kHz. The measurement error of the voltage was 0.003 V, and the current was 0.01 A.

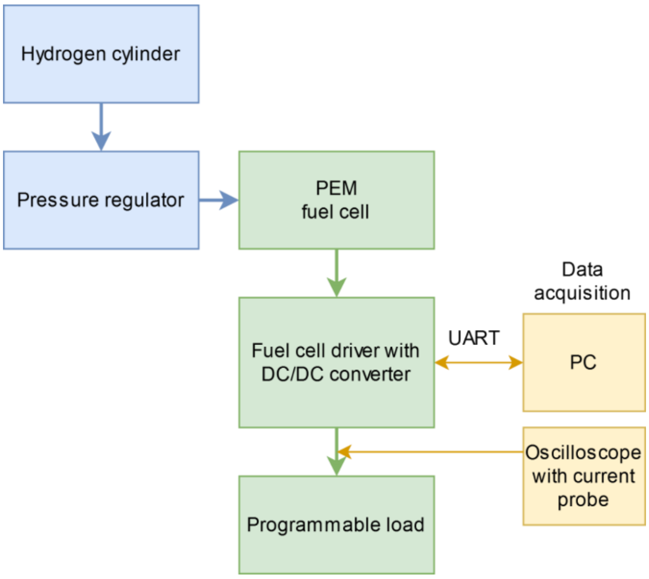

Fig. 7. Test stand block diagram

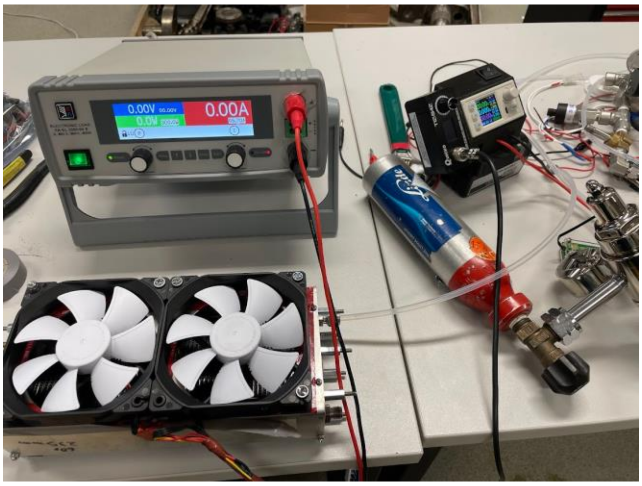

Fig. 8. Test stand

3.3. Methodology

The identification tests were divided into 2 parts. In the first, tests were carried out under steady-state conditions, and in the second, under dynamic conditions.

The first part involved determining the polarization curve of the cell when the purification system was switched off. For this purpose, the cell was loaded with a specific current and, after stabilization of its operation (a period of 1 minute), the voltage was measured. Measurements were carried out with increasing and decreasing load on then the average value was drawn.

The second part of the research was carried out in a set resistance system allowing for a step change in the load of the fuel cell between 65 and 130 W. Variations were performed with a current load on a 10 second cycle: 5 s – 65 W load, 5 s – 130 W load. In one cycle, there was both a step increase and a step decrease of the load. In addition, a purge circuit operating at 1 Hz was active in this experiment.

3.4. Analysis

The first part of the study involved the determination of the polarization curve. The result is shown in Fig. 9. The shape of the curve is consistent with the literature data [1, 3, 13, 16]. It should be noted that the power obtained is significantly less than that declared by the manufacturer. The maximum power, located at the end of the ohmic part of the curve (see Fig. 2), was 150 W (30 V · 5 A) against a rated 300 W (see Table 1). This is due to the high degradation of the cell. The test unit was used for six years as part of the activities of the Student Scientific Club of Aerospace Propulsion in the Shell Eco-marathon competition.

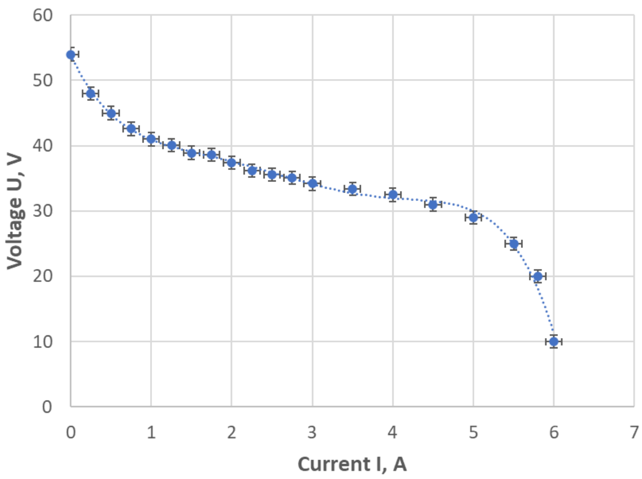

Fig. 9. Static characteristic of fuel cell – polarization curve

The second part of the research included load cycling and the operation of the cleaning system. Four load cycles were carried out. The results are presented in Fig. 10 and Fig. 11. The inertia of the system can be seen – when the load is activated, the voltage momentarily drops below the base value and the current increases, while when the load is deactivated, there is a momentary increase in voltage. The operation of the purge system causes, after the circuit output current drops due to a short circuit, a jump in the efficiency of the cell – an increase in both voltage and current, followed by a slow decrease in both values to the level of the polarization curve.

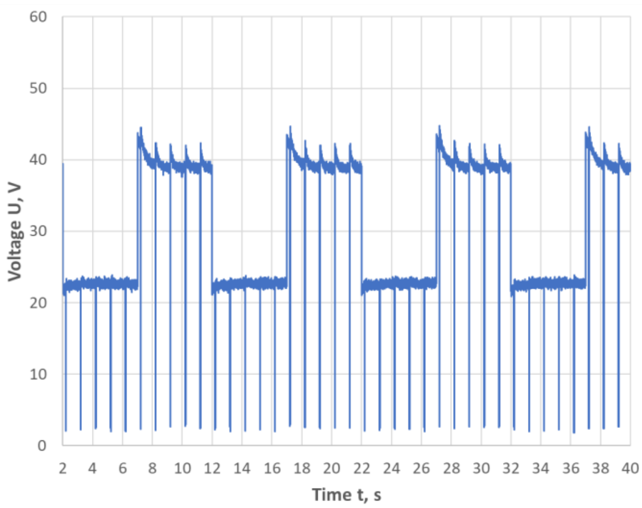

Fig. 10. Voltage during changed load conditions

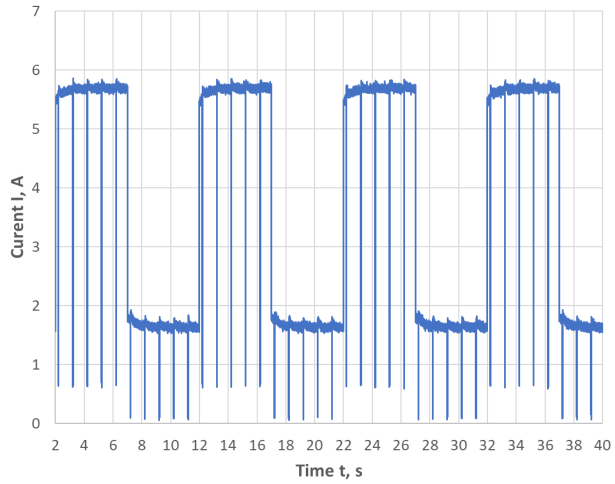

Fig. 11. Current during changed load conditions

3.5. Model parameters identification

As the model developed in Modelica used the derivative continuity approximation module to determine the polarization curve, it was therefore not necessary to determine the parameters of this model. The characteristics based on the test results shown in Fig. 9 were used for further calculations.

Figures 12–15 show the results of the measurements compared with the simulation results of the developed model. The blue line shows the bench measurements, the green line the model without the cleaning module (only with the dynamic module), and the orange line the results of the full model.

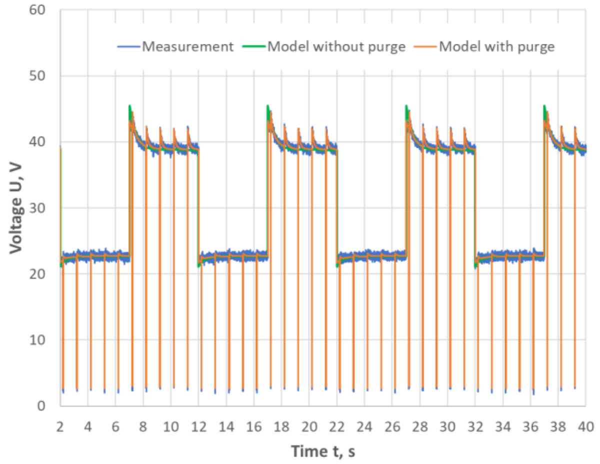

Fig. 12. Voltage measurement and simulation during changed load conditions

The identification of the dynamic model parameters and the cleaning were divided into two separate operations, but based on the same set of measurement data. Using the results of the bench tests described above, the identification of the dynamic model parameter was carried out using the least squares method, with the focus on obtaining a correct representation of the system inertia. A model with a concordance of R = 0.853 was obtained, although this was compared with the tests of the system with active cleaning. Figures 12–15 show the effect of the cell inertia.

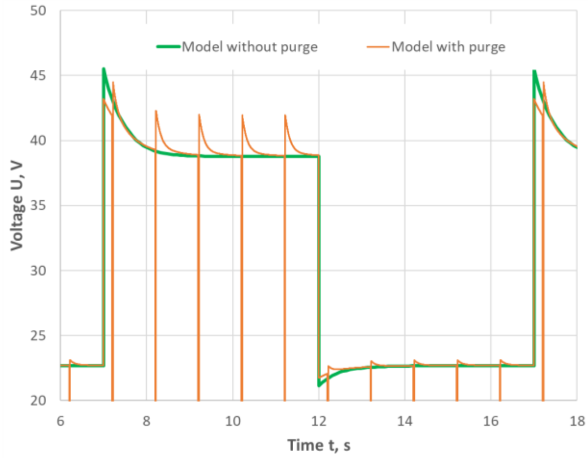

Fig. 13. Voltage simulation with and without active cleaning module during changed load condition

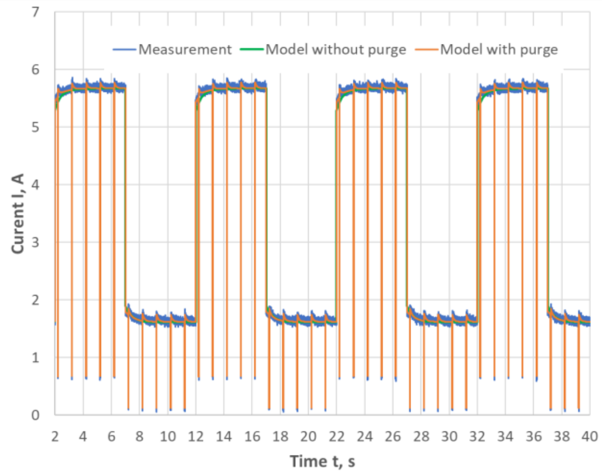

Fig. 14. Current measurement and simulation during a changed load condition

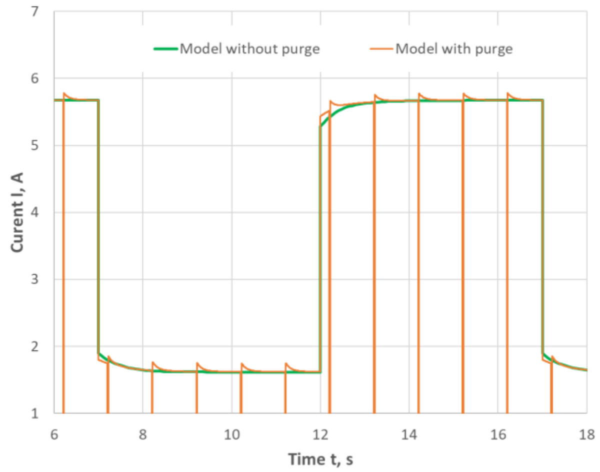

Fig. 15. Current simulation with and without active cleaning module during changed load condition

After the identification of the dynamic model, the identification of the cleaning model was performed. Again, the least squares method was used, with the simulation work performed on the model with the dynamic module parameters already identified. In this case, a much higher compliance performance R = 0.958 was obtained. Figures 13 and 15 show the difference in the behaviour of the model with the cleaning module on and off. Cleaning, as reported in the literature described in chapter 2 of this article, leads to a periodic increase in the capacity of the cell, despite the occurrence of temporary interruptions in the energy supply to external systems. The purpose of the purification process is to remove water accumulating on the cathode side. Water blocks the flow through the membrane, which causes a decrease in cell efficiency. Water accumulation also causes membrane degradation and a decrease in service life. Therefore, this process is carried out despite the fact that it causes fuel losses (fuel is blown into the atmosphere). According to publications [4, 5, 11, 16], this reduces the overall efficiency of the cell by about 10%, but extends its service life more than threefold.

The parameters of both models are shown in Table 2.

Table 2. Parameters of the dynamic and cleaning module

Parameter	Value
k_{Dyn}	0.541
ΔU_{max}	3.00
ΔU_{tot}	3.12
k_c	10.03

4. Summaries

A simple fuel cell model was developed, describing both the static characteristics of the polarization curve and also the dynamics of the model during load changes and the change in cell performance after the cleaning process. The model was developed as an empirical model by simplifying a physical description of the phenomena occurring inside the fuel cell. However, based on measurement data, a model with very high correlation with measurement results was obtained. A correlation of R = 0.958 was obtained.

The polarization curve obtained during the tests shows a significant reduction in cell performance resulting from wear and tear. The drop in power relative to the catalogue parameters is approximately 50%. During sudden load changes, there is a temporary deviation from the polarization curve of approximately 15% (with an increase in load, the voltage drops by 3.5 V from the nominal 23 V, and with a decrease in load, the voltage increases by 7.3 V from the nominal 28 V). Stabilization occurs after approximately 2 seconds.

Cleaning the cell causes a temporary increase in efficiency (increase in voltage relative to the polarization curve) of approximately 7%, with a return to the nominal value occurring after just 0.7 seconds.

Thanks to its simplicity, this model can be very easily identified for any fuel cell and thus provides a tool for simulation and optimizing control systems and powerplant systems using the cell as an energy source. The introduction of a cleaning model also allows the energy efficiency optimization of the cell by selecting the frequency of cleaning occurrence.

Acknowledgements

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Nomenclature

PEM, PEMFC proton exchange membrane fuel cell
U voltage
I current
t time

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