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FUZZY LOGIC CONTROL OF FUEL CELL SYSTEM FOR RESIDENTIAL POWER GENERATION

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This paper presents a dynamic model of a fuel cell system for residential power generation. The models proposed include a fuel cell stack model, reformer model and DC/AC inverter model. Furthermore a fuzzy logic (FLC) controller is used to control the active power of PEM fuel cell system. The controller modifies the hydrogen flow feedback from the terminal load. Simulation results confirmed the high performance capability of the fuzzy logic controller to control power generation.

K e y w o r d s: polymer-electrolyte fuel cell, dynamic model, residential power, fuzzy controller

1 INTRODUCTION

Proton exchange membrane (PEM) fuel cells is one of the promising technologies for alternative power source of residential power generation in future. However, a fuel cell system is large, complex and consumptive. Designing and building prototypes is difficult and expensive. The alternative is modelling the fuel cell system and its simulation. The modelling of the fuel cell is very important for the power system because it facilitates the understanding of the involved phenomena. Many models have been proposed to simulate fuel cells in the literature [1-6], which have generally their own specificities and utilities, following the studied phenomena.

The model proposed in this paper includes the electrochemical and fluid dynamic aspects of chemical reactions inside the fuel-cell stack. Furthermore, voltage losses due to ohmic, activation, and concentration losses are accounted for. Therefore, this dynamic PEMFC model complements the existing models such as the ones developed in [5, 6]. The model is suitable for power generation. To study the transient response of a grid-independent PEM fuel cell power plant, this paper proposes an electrochemical model for a 30 kW fuel cell which incorporates an external reformer to generate hydrogen from methane.

Fuel cells are dc voltage sources connected to the electric power load through DC/AC inverters. A method to connect the proposed PEMFC model to a grid - independent through an interface block is presented. The fuel-cell model, an external reformer and its interface block are implemented in MATLAB and incorporated with a power control analysis package.

Finally, a fuzzy logic based controller is designed for this purposes because of the numerous advantages it has high performance, higher than other types of controllers. The most important aspect is the cost of the controller design and implementation. The proposed controller modifies the hydrogen flow for controlling the active power to the load change.

2 FUEL CELL STATICS MODEL

Hydrogen PEM fuel cells transform chemical energy into electrical and thermal energy by the simple chemical reaction [1-3]

$$H_2 + 1/2\,O_2 \rightarrow H_2O + \text{heat} + \text{electrical energy} \tag{1}$$

In order to get an electric current out of this reaction, hydrogen oxidation and oxygen reduction are separated by a membrane which is conducting protons from the anode to the cathode side. The semi reactions on both electrodes are

$$\begin{aligned} &H_2 \rightarrow 2\,H^+ + 2\,e^- &&\text{anode}\\ &O_2 + 4\,e^- \rightarrow 2\,O_2^- &&\text{cathode} \end{aligned} \tag{2}$$

While the protons are transported through the membrane, electrons are carried by an electric circuit in which their energy can be used. Modelling of fuel cells is getting more and more important as powerful fuel cell stacks are getting available and have to be integrated into power systems. In [5, 6] Jeferson M. Corrêa introduced a model for the PEMFC . The model is based on simulating the relationship between the output voltage and partial pressure of hydrogen, oxygen, and current.

The output voltage of a single cell can be defined by the following expression [5, 6]

$$V_{FC} = E_{Nernst} - V_{act} - V_{ohm} - V_{conc} \tag{3}$$

where, E_{Nernst} is the thermodynamic potential of the cell and its represents reversible voltage; V_{act} is the voltage drop due to the activation of the anode and of the

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cathode; V_{ohm} is the ohmic voltage drop – a measure of the ohmic voltage drop associated with the conduction of the protons through the solid electrolyte and electrons through the internal electronic resistances; V_{conc} represents the voltage drop resulting from the concentration or mass transportation of the reacting gases [5]. The first term in (3) represents the FC open circuit voltage, while the three last terms represent reduction of the useful voltage of cell for a certain operating condition. Each one of the terms in (3) can be calculated by the following equations, using the parameters listed in Tab. 1 [6].

2.1 Cell Reversible Voltage

The reversible voltage of the cell is calculated starting from a modified version of the equation of Nernst, with an extra term to take into account the changes in temperature with respect to the standard reference temperature 30 °C [5]

$$E_{Nernst} = \frac{\Delta G}{2F} + \frac{\Delta S}{2F}(T - T_{ref}) + \frac{RT}{2F}\left[\ln(p_{\mathrm{H2}}) + \frac{1}{2}\ln(p_{\mathrm{O2}})\right] \tag{4}$$

where ΔG is the change in the free Gibbs energy (J/mol), F is the constant of Faraday (96.487 °C), ΔS is the change of the entropy (J/mol), R is the universal constant of the gases (8.314 J/K mol), p_{H2} and p_{O2} are the partial pressures of hydrogen and oxygen (bar), respectively. Variable T denotes the cell operation temperature (K) and T_{ref} the reference temperature. Using the standard pressure and temperature (SPT) values for ΔG and ΔS, (4) can be simplified to [5]

$$E_{Nernst} = 1.229 - 0.85 \times 10^{-3}(T - 298,15) + 4.31 \times 10^{-5}T\left[\ln(p_{\mathrm{H2}}) + \frac{1}{2}\ln(p_{\mathrm{O2}})\right] \tag{5}$$

2.2 Activation Voltage Drop

As shown in [5], the activation overpotential, including anode and cathode can be calculated by

$$V_{act} = -\left[\xi_1 + \xi_2 T + \xi_3 T \ln(c_{\mathrm{O2}}) + \xi_4 \ln(I_{stack})\right] \tag{6}$$

Here I_{stack} is the cell operating current (A), and ξ_i's represent parametric coefficients for each cell model, whose values are defined based on theoretical equations with kinetic, thermodynamic, and electrochemical foundations [5], and c_{O2} is the concentration of oxygen in the catalytic interface of the cathode mol/cm, determined by

$$c_{\mathrm{O2}} = \frac{p_{\mathrm{O2}}}{5.08 \times 10^6 e^{-498/T}}$$

2.3 Ohmic Voltage Drop

The ohmic voltage drop results from the resistance to the electrons transfer through the collecting plates and carbon electrodes, and the resistance to the protons transfer through the solid membrane. In this model, a general expression for resistance is defined to include all the important parameters of the membrane.

$$V_{ohmic} = I_{stack}(R_m + R_c) \tag{7}$$

Here R_c represents the resistance to the transfer of protons through the membrane, usually considered constant. and

$$R_m = \rho_M \frac{l}{A}$$

ρ_M is the specific resistivity of the membrane for the electron flow (Ωcm), A is the cell active area (cm^2) and l is the thickness of the membrane (cm), which serves as the ectrolyte of the cell.

The following numeric expression for the resistivity of the Nafion membranes is used [5] after introducing: the current density $J_{stack} = I_{stack}/A$ and the relative temperature $\theta = T\,(\mathrm{K})/303$ K

$$\rho = \frac{181.6\left[1 + 0.03 J_{stack} + 0.062\theta^2 J_{stack}^{3.5}\right]}{\left[\psi - 0.634 - 3J_{stack}\right] e^{4.18(1-\theta)}} \tag{8}$$

where $\frac{181.6}{\Psi - 0.634}$ is the specific resistivity (Ωcm) at no current and at 30 °C, [5].

2.4 Concentration or Mass Transport Voltage Drop

To determine an equation for this voltage drop, a maximum current density is defined J_{max} under which the fuel is being used at the same rate of the maximum supply speed. The current density cannot surpass this limit because the fuel cannot be supplied at a larger rate. Typical values for are in the range of 500 – 1500 mA/cm^2. Thus, the voltage drop due to the mass transport can be determined by

$$V_{con} = -B \ln\left(1 - \frac{J}{J_{\max}}\right) \tag{9}$$

where B (in volts) is a parametric coefficient which depends on the cell and its operation state, and J represents the actual current density of the cell (A/cm^2).

The static model of the PEM fuel cell is shown in Fig. 1, and the parameters are given in Tab. 1.

3 FUEL CELL SYSTEM MODEL

In [7-9] Sharkh, Rahman, and Alam introduced a model of PEMFuel cell system for residential power generation. This model has been modified to introduce a static model show in Fig. 1 the new model is shown in Fig. 4.

Tab. 1. Model parameters [5, 6].

T	343 K
A	333 cm^2
L	178 μm
B	0.016 V
R_C	0.3 mΩ
ζ_1	-0.948
ζ_2	$0.00286+0.0002\ln A + 4.3\times10^{-5}\ln(c_{\mathrm{H2}})$
ζ_3	7.6×10^{-5}
ζ_4	-1.93×10^{-4}
Ψ	23
J_{max}	1500 mA/cm^2
J_n	1.2 mA/cm^2

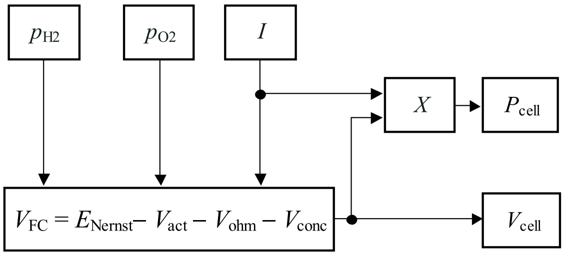

Fig. 1. PEMFC static model

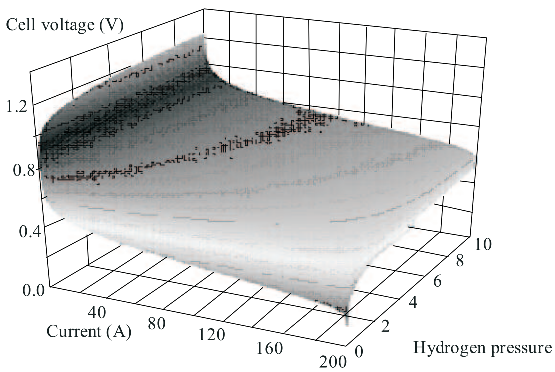

Fig. 2. Typical PEMFC cell voltage response surface with simultaneous changes in the inlet partial pressure of hydrogen and current at a constant stack temperature of 70 °C

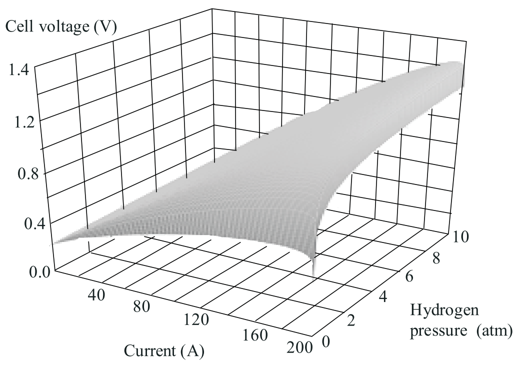

Fig. 3. Typical PEMFC cell power response surface with simultaneous changes in the inlet partial pressure of hydrogen and current at a constant stack temperature of 70 °C

3.1 Fuel Cell Dynamic Model

This model is based on simulating the relationship between the output voltage and partial pressure of hydrogen, oxygen, and current. A detailed model of the PEM fuel cell is shown in Fig. 4.

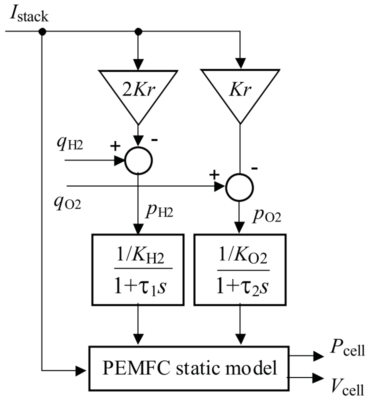

Fig. 4. PEMFC dynamic model

The model parameters are as follows:

q_{H2}	input molar flow of hydrogen (kmol/s),
q_{O2}	input molar flow of oxygen (kmol/s),
p_{H2}	hydrogen partial pressure (bar),
p_{O2}	oxygen partial pressure (bar),
K_{H2}	hydrogen valve molar constant (kmol/bar/s)),
K_{O2}	oxygen valve molar constant (kmol/bar/s),
N_0	number of series fuel cells in the stack,
I_{stack}	stack current (A),
K_r	$= N_0/4F$ – constant, (kmol/s/A)
F	Farady constant 9684600 C/kmol.

3.3 Reformer Model

In [7, 8] the authors introduced a simple model of a reformer that generates hydrogen through reforming methane. The model is a second-order transfer function. The mathematical form of the model can be written as follows

$$\frac{q_{\mathrm{H2}}}{q_{methane}} = \frac{CV}{\tau_1\tau_2 s^2 + (\tau_1+\tau_2)s + 1} \tag{11}$$

where, CV is the conversion factor (kmol of hydrogen per kmol of methane), $q_{methane}$ is the methane flow rate (kmol/s) and τ_1, τ_2 are the reformer time constants (s).

3.4 DC/AC inverter Model

In this paper, only a simple model of a DC/AC inverter is considered for the following reasons: the dynamic time constant of inverters is of the order of microseconds or at the utmost milliseconds. The time constants for the reformer and stack are of the order of seconds. The model of the inverter is given in [9], where the output voltage and output power are controlled using the inverter modulation index and the phase angle δ of the AC voltage. Considering the fuel cell as a source, the inverter and load connection is shown in Fig. 5.

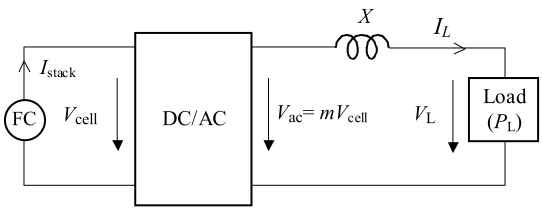

Fig. 5. Fuel cell, Inverter and load connection diagram [9]

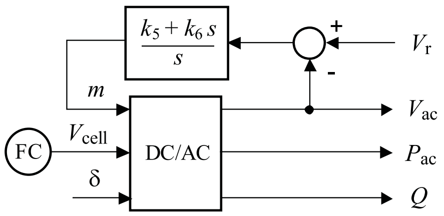

Fig. 6. The DC/AC inverter model [9]

Here the model parameter are as follows

V_{ac}	AC output voltage of the inverter (V)
m	inverter modulation index
δ	phase angle of the AC voltage (rad)
P_{ac}	AC output power from the inverter (W)
Q_{ac}	reactive output power from the inverter (W)
V_L	load terminal voltage (V)
X	reactance of the line connecting the fuel cell to the load
I_L	load current (A)
θ	load phase angle (rad)
P_L	load power (W)
I_{stack}	stack current (A)

The output voltage and the output power as a function of the modulation index and the phase angle δ – providing the phase angle of the load voltage V_L is set to zero – can be written as

$$V_{ac} = m\,V_{cell} \tag{12}$$

$$P_{ac} = \frac{m\,V_{cell} V_L \sin(\delta)}{X} \tag{13}$$

$$Q_{ac} = m\,V_{cell}\frac{m\,V_{cell} - V_L\,\cos(\delta)}{X} \tag{14}$$

$$I_L = \frac{P_L}{V_s\,\cos(\theta)} \tag{15}$$

and assuming a lossless inverter

$$P_{ac} = V_{cell} I_{stack}, \tag{16}$$

we get

$$I_{stack} = mI_L cos(\theta + \delta). \tag{17}$$

PI controllers are used to control the modulation index. The transfer function of the modulation index can be expressed as

$$m = \frac{K_5 + sK_6}{s}(V_r - V_{ac}), \tag{18}$$

were K_5, and K_6 are the PI gain, and V_r is the reference voltage signal. The block diagram of the inverter with the PI controllers is illustrated in Fig. 6.

According to electrochemical relationships, a relationship between the stack current and the molar flow of hydrogen can be written as

$$q_{\text{H2}} = \frac{N_0 I_{stack}}{2FU}, \tag{19}$$

were U is a utilization factor. From (13), (18) and (19)

$$\sin(\delta) = \frac{2FUX}{mV_s N_0} q_{\text{H2}} \doteq \delta, \tag{20}$$

assuming a small phase angle. Equation (20) describes the relationship between the output voltage phase angle and hydrogen flow. Equations (13) and (20) indicate that the active power as a function of the voltage phase angle can be controlled by controlling the amount of hydrogen flow.

4 FUZZY LOGIC CONTROLLER

The active power flow from the PEMFC to the load is controlled though controlling the flow of hydrogen. The proposed fuzzy logic controller controls the active power by controlling the hydrogen flow. The fuzzy controller consists of five different steps (Fig. 7) [10, 11].

Step (i) definition of input-output variables of controller

Step (ii) design of fuzzy control rule

Step (iii) fuzzification

Step (iv) inference

Step (v) defuzzification

The fuzzy controller inputs are the error e(k), and change of error ce(k). The output of the controller is the duty ratio of the hydrogen flow uH2(k). The error, change of error, and the output of the controller are given as follows

$$e(k) = q_{\text{H2}} + q_{meth,ref} - q_{\text{H2},b}. \tag{22}$$

Here q_{H2} is the flow hydrogen from the current feedback signal proportional to the terminal load Fig. (6), $q_{methane}$ is the methane reference signal and $q_{H2,b}$ is the hydrogen flow feedback signal.

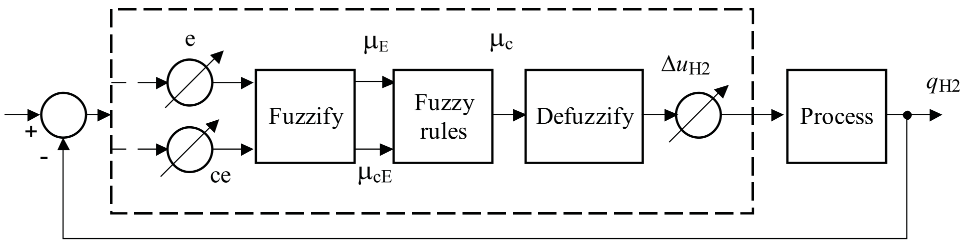

Fig. 7. The block diagram of a fuzzy logic controller

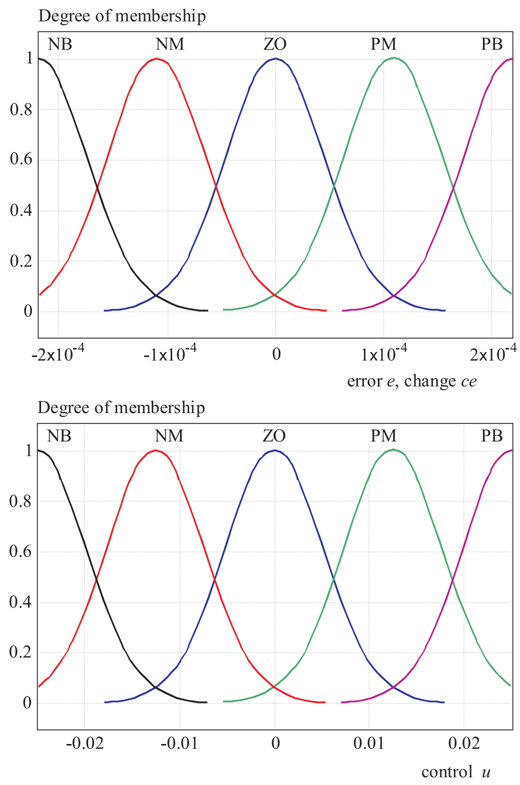

Fig. 8. Membership function for error (e), error change (ce) and control (u)

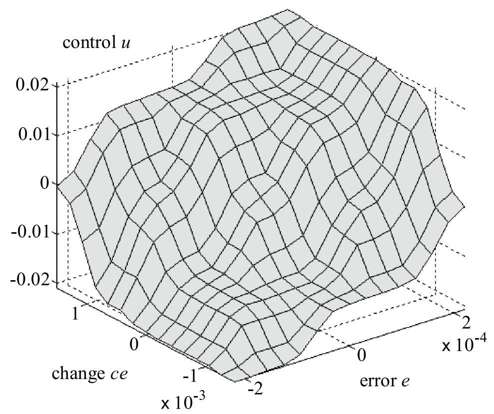

Fig. 9. The 3-dimensional representation of control input u_{H2} for fuzzy variables (e, ce)

$$ce(k) = e(k) - e(k-1) \tag{23}$$

$$u_{\mathrm{H2}}(k) = u_{\mathrm{H2}}(k-1) + \rho \Delta u_{\mathrm{H2}}(k). \tag{24}$$

Here $\Delta u_{\mathrm{H2}}(k)$ is the inferred change of duty ratio by fuzzy controller and ρ is the gain factor of the controller [6, 7].

Fig. 8 shows the basic fuzzy partition of the membership function for error, change of error, and change of control action. And fuzzy variables are expressed by linguistic variables such as "positive big (PB)" "positive medium (PM)","zero (ZO)", "negative medium (NM)" ,"negative big (NB)". Table 2 shows the fuzzy model based on fuzzy rules [7].

Example fuzzy rules are:

Rule 1: If $e(k)$ is PM and $ce(k)$ ZO then $\Delta u_{\mathrm{H2}}(k)$ is PM

Rule 2: If $e(k)$ is NB and $ce(k)$ NM then $\Delta u_{\mathrm{H2}}(k)$ is NB

The inference method used is basic and simple, it is developed from the minimum operation function rule as a fuzzy implementing function. The membership function of e, ce and u_{H2} are given by μ_{Ei}, μ_{CEi}, $\mu_{H2i}\mu_{Ci}$.

The commonly use min-max method is given for $i = 1 \dots n$ as

$$\mu_{Ri}(e, ce) = \min \Big[\mu_{ei}(e), \mu_{cei}(ce) \Big] \tag{25}$$

$$\mu_{Ci}(u_{\mathrm{H2}}) = \max \Big[\mu_{Ri}(e, ce), \mu_{u\mathrm{H2}i}(u_{\mathrm{H2}}) \Big] \tag{26}$$

The centroid defuzzification method determines the output value from center of gravity of the output membership function and is given by the expression

$$\Delta u_{H2} = \frac{\sum\limits_{i=0}^{n} \mu_{Ci}(u_{\mathrm{H2}i}) u_{\mathrm{H2}i}}{\sum\limits_{i=0}^{n} \mu_{Ci}(u_{\mathrm{H2}i})} \tag{27}$$

Based on Tab. 2 and Fig. 8, the 3-dimensional representation of control input for fuzzy variables $u_{\mathrm{H2}}(e, ce)$ is shown in Fig. 9.

Table 2. Linguistic control rule

Error	Change of Error				
U	NB	NM	ZO	PM	PB
NB	NB	NB	NM	NM	ZO
NM	NB	NM	NM	ZO	PM
ZO	NM	NM	ZO	PM	PM
PM	NM	ZO	PM	PM	PB
PB	ZO	PM	PM	PB	PB

5 SIMULATION RESULTS

The model parameters are given in Table 3.The model of the fuel cell system for residential power generation and fuzzy logic block diagram is shown in Fig. 10. It is tested with a step change in the load as shown in Fig. 11. These abrupt changes in the active and reactive power are for testing the dynamic response of the system and do not necessarily represent the change in residential load.

In a practical system, the response time of the reformer can be longer than tens of seconds [11, 12]. Therefore the reformer controller parameters have a significant effect on the active power control. In this simulation the fuzzy logic controller was able to modify the hydrogen flow for controlling active power to the load change, Fig. 12. The fuzzy logic controller is characterized by a faster time response compared to the PID controllers used in Fig. 13. The change of the current is illustrated in Fig. 14. This change is very sensitive to variation of the active power load. Fig. 15 shows the change of hydrogen flow. This change is similar to the change of the active power. The reactive power Q_{ac} follows immediately the change of the reactive power load because the reactive power is

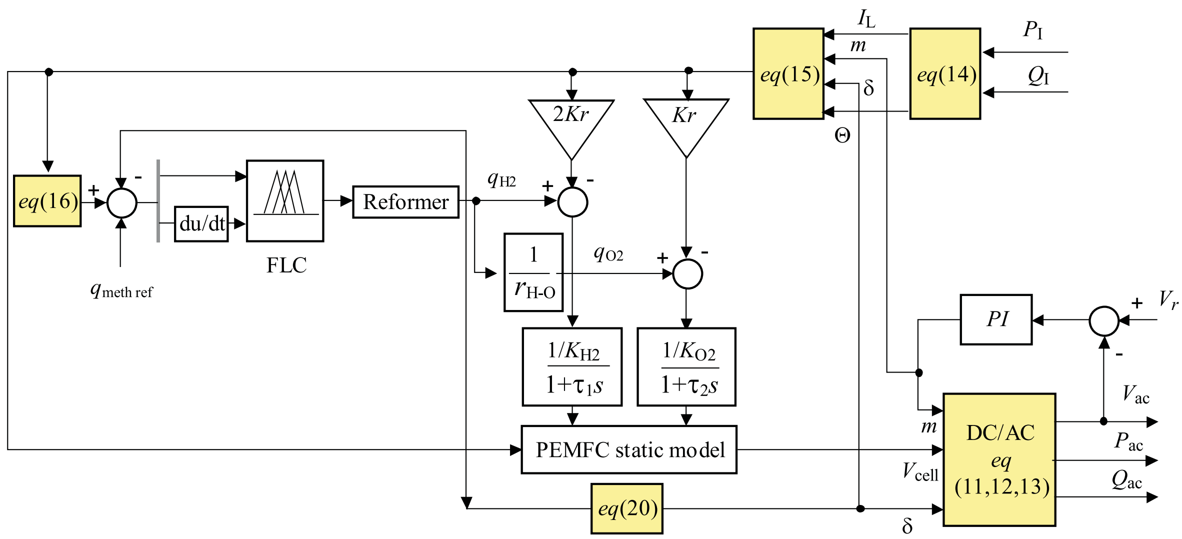

Fig. 10. PEM fuel cell system and fuzzy logic block diagram

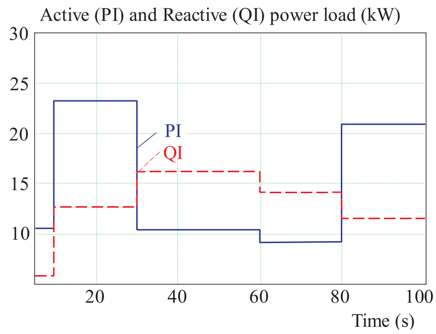

Fig. 11. Load step changes

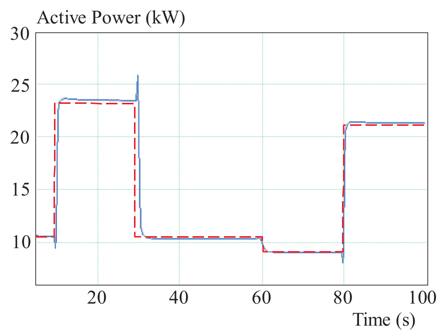

Fig. 12. Active output power change – with fuzzy logic controller

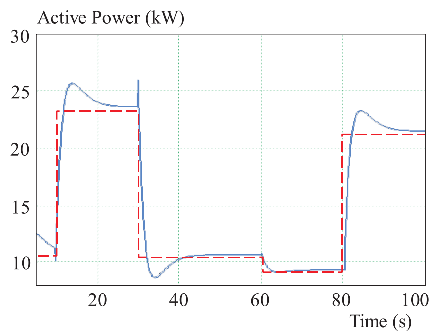

Fig. 13. Active output power change – with PID controller

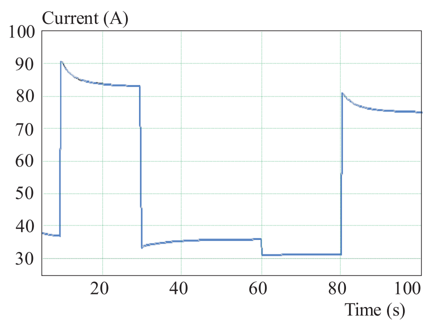

Fig. 14. Current change

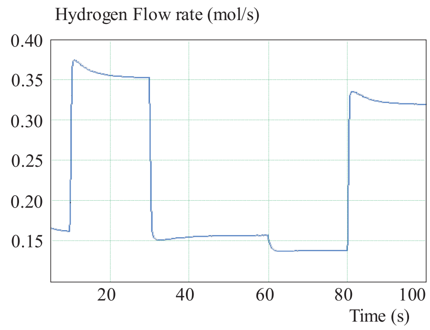

Fig. 15. Hydrogen flow rate change

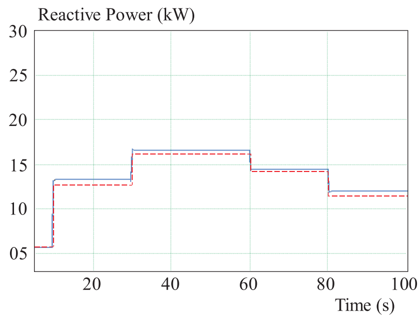

Fig. 16. Reactive output power change

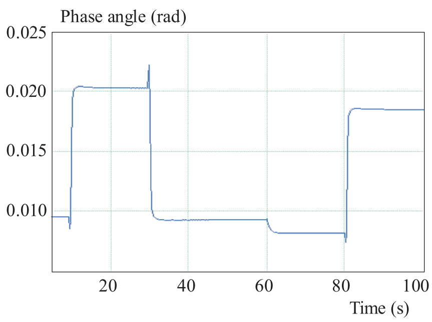

Fig. 17. Output voltage phase angle change

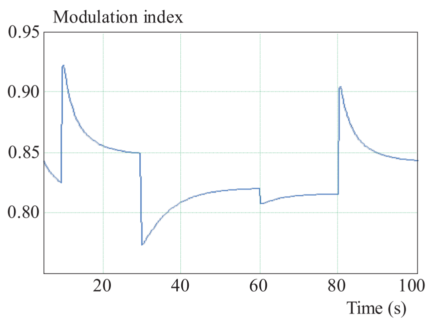

Fig. 18. Modulation index change

controlled directly from DC/AC inverter and the response of DC/AC inverter is not considerable, Fig. 16. We notice that the reactive power value is superior to the reactive power. This is due to inductive effect losses of the line (x). The change of the output voltage phase angle and modulation index are illustrated in Figs. 15 and 16.

Tab. 3. System parameters [8, 9].

Conversion factor CV	2
Faraday's constant F	9684600 C/kmol
Universal gas constant R	8.31447 J/mol/K
Number of cells N_0	333
Hydrogen valve constant K_{H2}	4.22×10^{-5} kmol/s/A
Oxygen valve constant K_{O2}	2.11×10^{-5} kmol/s/bar
Hydrogen time constant τ_{H2}	3.37 s
Oxygen time constant τ_{O2}	6.74 s
Utilization factor U	0.8
PI gain constants K_5, K_6	10
H_2-O_2 flow ratio $r_{\mathrm{H\text{-}O}}$	1.168
Methane reference signal q_{ref}	0.000015 kmol/s
Reformer time constants τ_1, τ_2	2s, 2s
Line reactance X	0.05 Ω
Voltage reference signal V_r	240 V

6 CONCLUSION

In this paper the fuel cell system model for residential generation is proposed. The proposed model includes a dynamic fuel cell model, a gas reformer model, DC/AC inverter model, and fuzzy logic controller unit block. Then the developed model is tested using a computer-simulated step change in the load active and reactive power demands. The simulation results indicate that the converter and fuel quantities have to be controlled simultaneously to control the active and reactive power. They also indicate that the fuzzy logic controller is very effective to control the hydrogen flow for active power load variation.

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