TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 12, No. 8, August 2014, pp. 6017 ~ 6026
DOI: 10.11591/telkomnika.v12i8.5763

Fuzzy Sliding Mode Control of PEM Fuel Cell System for Residential Application

Mahdi Mansouri*[1], Mohammad Ghadimi[2], Kamal Abbaspoor Sani[3]
[1]Department of energy, Islamic Azad University of South Tehran branch, Tehran, Iran
[2]Department of energy, Islamic Azad University of Roudehen, Iran
[3]Department of energy, Islamic Azad University of Takestan, Iran
*Corresponding author, e-mail: Mahdi.Mansori@gmail.com[1], m.Ghadimi@riau.ac.ir[2], k-Abaspour@merc.ac.ir[3]

Abstract

Proton exchange membrane fuel cells (PEMFCs) are receiving more attention compared with other sources of power generation. Maintaining a fuel cell system requires excellent system control to receive the best operating. Therefore, in this paper a dynamic model of a (PEMFC) for residential power generation is applied. The model proposed includes the fuel cell stack model, power condition unite that consists of the methanol reformer model and DC-AC inverter model. According to power output of (PEM) fuel cell system, a fuzzy sliding mode controller which contains the characteristics of fuzzy control and sliding mode control is addressed, in order to modify the hydrogen flow feedback from the terminal load. In addition, this combined controller is used to improve stability by fuzzy reasoning to control the output variation that reduces chattering and increase the speed of tracking by reasoning of sliding mode control. Consequently, the dynamical behavior of system with FSMC is more improved as compared to the FLC and PI controller in terms of rate of hydrogen flow, output AC voltage and output power of FC and it is shown that the proposed controller can achieve better control effect than other controllers.

Keywords*: PEM fuel cell, dynamic model, fuzzy sliding mode controller, residential power*

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1. Introduction

Nowadays, the interest in Fuel Cells has increased during the past decade due to the fact that the use of fossil fuels for power has resulted in many negative consequences. Fuel cells are sources of energy that generate electrical energy from chemical reactions and are set to become the power source of the future. There are many types of fuel cells that are used in many applications such as: stationary power, transportation system, portable power, distributed generators, alternative power and application in space [1-4], but (PEMFCs) are the best kind of FC due to low operating temperature (less than 100 degree C), high power density, quick start-up capability, low weight, limited number of moving parts, null pollutant emissions, low electrolyte corrosion and long life-time. Thus, a new power source is needed that is energy efficient, has low pollutant emissions and has unlimited supply of fuel [5-6].

There are several research results on the design of PEMFC controllers that can improve the behaviour of system. For this purpose, an analytical details of how active and reactive power output of a stand-alone PEMFC power plant has been proposed in [5]. This analysis is based on an integrated dynamic model of the entire power plant including the reformer. In addition, a dynamic modeling of various components of an isolated system is presented in [7] and a PID controller is used to adjust the fuel cell inlet and oxygen pressure to maintain a constant stack output voltage. The aim of used PID type controller is control of the fuel cell voltage by varying the hydrogen and oxygen flow rates. Unfortunately, the performance of a PEMFC is very difficult to modeling analytically. So, the main challenge of controller design in order to improve performance of PEMFC system is satisfying of the stability and robustness of cells [8]. On the other hands, the Performance of PEMFC depends on existence of many variables such as operating temperatures, flow rate of hydrogen, membrane humidity, water management of the membrane, pressure and other factors. These variables influence on each other and making nonlinearity in the performance models that makes the research on PEMFC systems very difficult, so empirical model have been used [9-10]. However, controlling the rate

Received February 8, 2014; Revised April 19, 2014; Accepted May 6, 2014

of flow of hydrogen is more importance in order to improve the performance of a PEMFC stack and to follow the desired output power in stand-alone and grid connected mode. There are three reasons for this claim such as: 1. Protons generated by hydrogen oxidation at the anode and then are reduced to hydrogen at the cathode; 2. lack of the hydrogen leads to drying of the membrane and failure of chemical reaction in the cell; 3. Total pressure of FC is controlled by the flow of hydrogen. So for this purpose, researchers have proposed different methods ([9], [11-13]).

In this paper a Fuzzy sliding mode controller (FSMC) is proposed for the control of flow of hydrogen in PEMFC. Sliding mode control (SMC) is a type of variable structure control method that is designed to constrain the state variables of system within a neighbourhood of switching function. The choice of switching functions can be tuned the dynamical behaviour of system. Also, SMC has fast response characteristic to the fast load changes without sensitive to parameter variations and external disturbances. However, in SM controller one of the most important disadvantages is chattering problem and another is that dynamic equation influence on controller design. In addition, Fuzzy logic controller (FLC) possesses several advantages like robustness, model-free and is designed based on human experience. Due to this advantage, FLC has been addressed for many industrial applications [9].

The fuzzy sliding mode control (FSMC) method, which is an integration of SMC and FLC, provides a systematically design for FLC. In the term of designing of FSMC, fuzzy rules are used for tuning of sliding surface. Moreover, this method can provide robustness against model uncertainties and external disturbances and also it is capable to minimize the chattering phenomenon while assuring sliding behaviour.

The paper is organized as follows: Section 2 introduces a model for a fuel cell system consists of the FC stack, the fuel processing unit or the reformer, and the inverter. In Section 3, Fuzzy logic controller design is introduced for PEMFC and then Fuzzy Sliding Mode controller is addressed to regulate flow rate of hydrogen. The proposed controller modifies the rate of hydrogen flow for controlling the active power to the load change. Finally, in section 4, Simulation results and discussions are presented and an illustrative example confirms the advantages of our approach.

2. PEM Fuel Cell Model

2.1. Fuel Cell Static Model

In [9] introduced a model of PEMFC system for residential power generation. The chemical reactions in PEMFC system are given as:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (Anode) \tag{1}$$

$$1/2O_2 + H^+ + 2e^- \rightarrow H_2O \quad (Cathode) \tag{2}$$

The representation of a PEMFC system is shown in Figure 1.

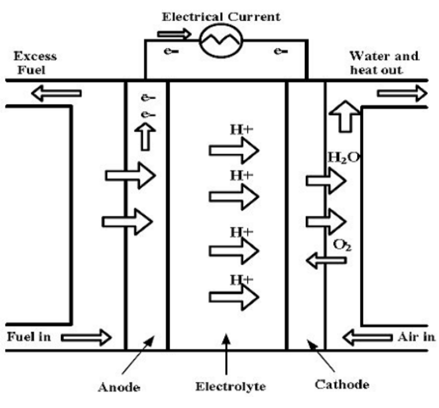

Figure 1. Schematic Diagram of PEMFC

The output voltage of a cell can be defined in the following term:

$$V_{Fc} = E_{Nerst} - V_{act} - V_{ohm} - V_{conc} \tag{3}$$

Which E_{Nerst} is the thermodynamic potential of the cell that represent reversible voltage of cell, with:

$$E_{Nernst} = 1.229 - 0.85 * 10^{-3}\left(T_{fc} - 298.15\right) + 4.31 * 10^{-5} T_{fc}[\ln\left(P_{H_2} + \frac{1}{2}\ln\left(P_{O_2}\right)\right. \tag{4}$$

Where P_{H_2} and P_{O_2} are the hydrogen and oxygen pressures, and $T_{fc}(K)$ is the operating temperature of cell. V_{act} is the voltage drop of the anode and the cathode:

$$V_{act} = 0.9514 - 3.12 * 10^{-3} T_{fc} - 7.4 * 10^{-5} T_{FC}\ln\left(C_{O_2}\right) + 1.87 * 10^{-4} T_{fc}\ln(i) \tag{5}$$

Where $i(A)$ is the electrical current and C_{O_2} is the oxygen concentration. V_{ohmic} is the ohmic voltage drop of protons through the solid electrolyte and electrons:

$$V_{ohmic} = i(R_M + R_C) \tag{6}$$

Where $R_C(\Omega)$ is the contact resistance of electron flow, and $R_M(\Omega)$ is the resistance of proton transfer through the membrane.

$$R_M = \frac{\rho_M l}{A} \tag{7}$$

$$\rho_M = \frac{181.6\left[1 + 0.03\left(\frac{i}{A}\right) + 0.062\left(\frac{T_{fc}}{303}\right)^2\left(\frac{i}{A}\right)^{2.5}\right]}{\left[\Psi - 0.634 - 3\left(\frac{i}{A}\right)\right]\exp\left[4.18\left(\frac{T_{fc} - 303}{T_{fc}}\right)\right]} \tag{8}$$

Where $\rho_M(\Omega.cm)$ is the membrane specific resistivity, $l(cm)$ is the membrane thickness, $A(cm^2)$ is the membrane active area, and Ψ is a specific coefficient for every type of membrane.

V_{conc} represents the voltage drop of the mass transportation effects, which affects the concentration of the reacting gases and can be described in the following term:

$$V_{conc} = -B\ln\left(1 - \frac{i}{i_{\max}}\right) \tag{9}$$

Where $B(v)$ is a parametric coefficient which depends on the cell and its operation state and $i_{\max}$ represent the current of cell.

The static model of the PEMFC is shown in Figure 2.

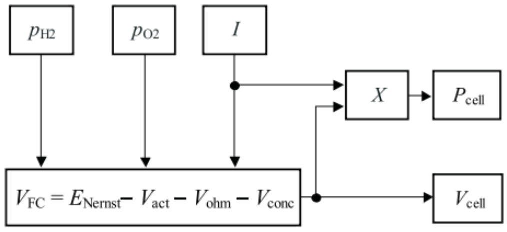

Figure 2. PEMFC Static Model

2.2. Fuel Cell Dynamic Model

The dynamical model of cell is based on simulating the relationship between the output voltage and partial pressure of hydrogen, oxygen, and current. This model of PEMFC is shown in Figure 3.

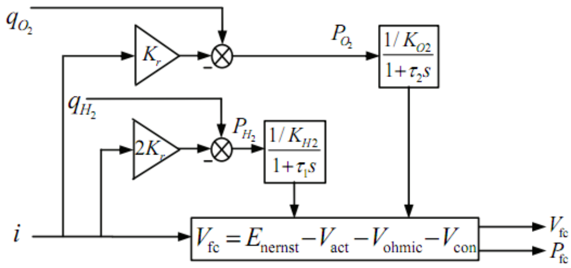

Figure 3. PEMFC Dynamic Model

The PEMFC dynamic model parameters are described as follow:

q_{H_2} : input molar flow of hydrogen (kmol/s),

q_{O_2} : input molar flow of oxygen (kmol/s),

K_{H_2} : hydrogen valve molar constant (kmol/bar/s)),

K_{O_2} : oxygen valve molar constant (kmol/bar/s),

$K_r = N_0 / 4F$: constant, (kmol/s/A),

N_0 : number of series fuel cells in the stack,

F : Farady constant 9684600 C/kmol.

2.3. Reformer Model

A developed model of PEMFC is generating of hydrogen through the methane. The reformer model is a second order transfer function. The mathematical model of the model can be written as follows [15]:

$$\frac{q_{H_2}}{q_{methane}} = \frac{CV}{\tau_1 \tau_2 s^2 + (\tau_1 + \tau_2)s + 1} \tag{10}$$

Where,

$q_{methane}$: methane flow rate [kmol/s],

CV : conversion factor [kmol of hydrogen per kmol of methane],

τ_1, τ_2 : reformer time constants [10].

2.4. DC/AC Inverter Model

The model of the inverter is given in [14]. DC/AC inverter is used to convert DC output voltage to AC. Fuel cell is DC voltage source that when it connected to the electrical load, or to the electrical grid followed by a single-phase or three-phase DC/AC inverter. Considering the fuel cell as a source of power, the inverter and load connection is shown in Figure 4.

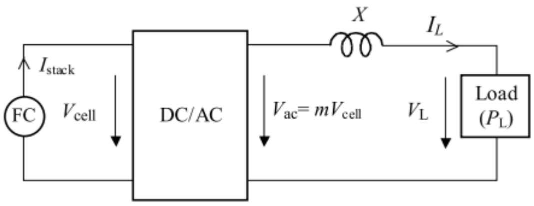

Figure 4. Fuel cell, Inverter and Load Connection Diagram

The AC output voltage as a function of the modulation index (m) can be written as:

$$V_{ac} = mV_{cell} \tag{11}$$

The AC output power, reactive output power and I_L can be written as:

$$P_{ac} = \frac{mV_{cell}V_L \sin(\delta)}{X} \tag{12}$$

$$Q_{ac} = mV_{cell} \frac{mV_{cell} - V_L \cos(\delta)}{X} \tag{13}$$

$$I_L = \frac{P_L}{V_s \cos(\theta)} \tag{14}$$

Where,

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 [VAR];
V_L : load terminal voltage [V]; 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]. and assuming a lossless inverter:

$$P_{ac} = P_{dc} = V_{cell} I_{stack} \tag{15}$$

$$I_{stack} = mI_L \cos(\theta + \delta) \tag{16}$$

PI controllers are used to control the modulation index. The transfer function of the modulation index is:

$$m = \frac{K_5 + sK_6}{s}(V_r - V_{ac}), \tag{17}$$

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 showned in Figure 5.

A relationship between the stack current and the molar flow of hydrogen can be written as:

$$q_{H_2} = \frac{N_0 I_{stack}}{2FU}, \tag{18}$$

Were U is a utilization factor. From (12), (15) and (18) we obtain:

$$\sin(\delta) = \frac{2FUX}{mV_s N_0} q_{H_2} \cong \delta \tag{19}$$

Assuming a small phase angle. Equation (18) describes the relationship between the output voltage phase angle and flow of hydrogen. These indicate that the active power as a function of the voltage phase angle can be controlled by controlling the amount of flow of hydrogen.

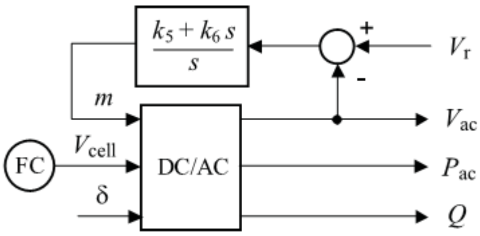

Figure 5. The DC/AC Inverter Model

The model parameters 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).

3. Control Approach

A fuzzy sliding mode controller is designed for the PEMFC. The structure of the fuzzy sliding mode control system is shown in Figure 6.

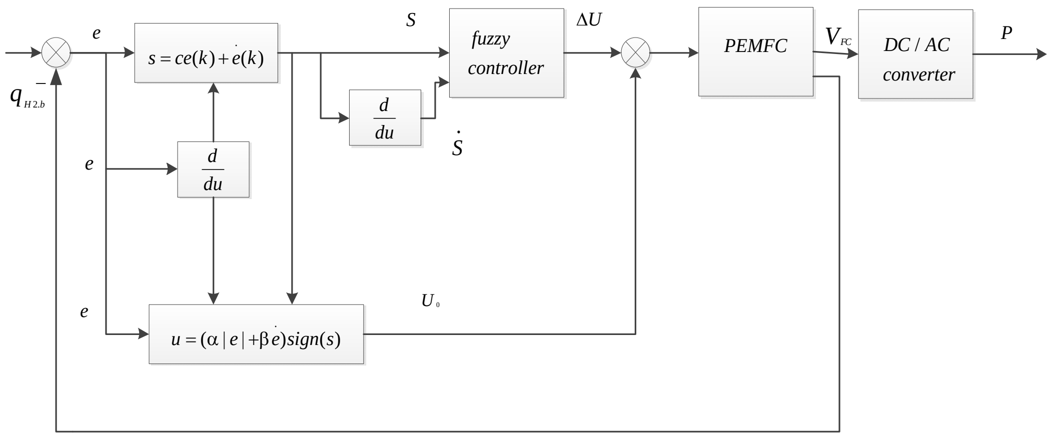

Figure 6. Fuzzy Sliding Mode Control System

3.1. Fuzzy Logic Controller Design

The FLC studied in this section has two inputs: the error and the rate of change of error with:

$$e = q_{H_2} + q_{meth,ref} - q_{H_{2,b}} \tag{20}$$

Which q_{H_2} is the hydrogen flow from the current feedback signal proportional to the terminal load, $q_{meth,ref}$ is the methane reference signal and $q_{H_{2,b}}$ is the flow of hydrogen feedback signal.

$$ce(k) = e(k) - e(k-1) \tag{21}$$

The output of the controller is fed to input of the reformer which converts fuel into hydrogen as per load demand [13].

$$U = u_{H2}(k) + u_0 \tag{22}$$

$$u_{H2}(k) = u_{H2}(k-1) + \rho.\Delta u_{H2}(k) \tag{23}$$

Each of two inputs of the FLC have five linguistic variables and the output (U) have seven variable, namely, “PB”, “PM”, “PS”, “ZO”, “NB”, “NM”, “NS”, which stand for “positive large”, “positive medium”, “positive small”, “zero”, “negative large”, “negative medium”, “negative small”. The rule base used in the FLC is illustrated in Table 1.

Table 1. Fuzzy Rule Base

u		$\dot{s}$				
		NB	NS	ZO	PS	PB
s	NB	NB	NB	NM	NM	ZO
	NS	NB	NS	NS	ZO	PM
	ZO	NB	NS	ZO	PS	PB
	PS	NM	ZO	PS	PS	PB
	PB	ZO	PM	PM	PB	PB

For instance, a rule in the rule base can be expressed by: if error is NB and rate of change of error is NB, then output is NB. In fact, in this section, MIN-Max method is implemented. Namely, the output of each rule is given by the MIN operator, while the total output is given by the MAX operator.

3.2. Sliding Mode Controller Design

As previous mentioned; the output voltage of PEMFC and active power flow from the PEMFC to the load is controlled though controlling the flow of hydrogen. Hence, we consider the error function as same as (19).

For design of controller, we assume this problem is equal to the tracking control problem with desired trajectory $x_d(q_{H_2} + q_{meth,ref})$ and the tracking error:

$$e = -(x - x_d) \tag{24}$$

The model of system with assumes $\tau_1 = \tau_2 = CV = 2,$ is:

$$\ddot{x} = -\dot{x} - {}^1\!/_4\, x + {}^1\!/_2\, u \quad (x = q_{H_{2,b}}) \tag{25}$$

A sliding surface for second order systems is determined by:

$$s(x,t) = (d/dt + \lambda)(-e), \lambda \geq 0 \tag{26}$$

To derive a control law such that the state variable remains on the sliding surface, we define a Lyapunov function:

$$V = 1/2s^2, \tag{27}$$

Sufficient condition for the stability of the system (21) in the sense of Lyapunov is:

$$\dot{V} = 1/2d/dt(s^2) \leq -\eta|s|, \eta > 0, \tag{28}$$

For the second order system (reformer model) we have:

$$s = \lambda e + \dot{e} \tag{29}$$

$$\dot{s} = \lambda\dot{e} + \ddot{e} \tag{30}$$

With assume $\lambda = 1$ we obtain:

$$s\dot{s} = (e + \dot{e})(\dot{e} - 1/2u - \dot{e} - 1/4e), \tag{31}$$

Defining controller signal as follow, we reach to condition (24):

$$u_0 = -\frac{1}{2}e + \alpha|e + \dot{e}| + \beta sgn(e + \dot{e}), \alpha, \beta > 0 \tag{32}$$

4. Simulation Results and Discussions

The PEMFC model which is noted in section 2 is implemented and tested. The model parameters are given in Table 2. This system was tested with a step change in the load as shown in Figure 6. The main goal in this implementation is to investigate the active power behaviour under effect of terminal load.

The reformer controller parameters have an important effect on the power control. In this paper, the fuzzy sliding mode controller was able to improve the variation of H_2 and O_2 flow with respect to load change. The fuzzy sliding mode controller have a faster time response and good tracking compared to the fuzzy and PI controllers, as shown in Figure 7. The variation of hydrogen flow is shown in Figure 8. As noted above, load change is a reference signal which hydrogen flow should be capable to track it significantly with minimum error and it obviously depicted in Figure 8. Consequently, the fuzzy sliding mode controller has better performance than other approach. The error variation is shown Figure 9 and the absolute of error is shown in Table 3. It is obvious that error variation with proposed approach considerably is lower than other control methods. Output voltage is shown Figure 10.

Table 2. Model Parameters

parameters	value	parameters	value	parameters	value	parameters	value
T	343K		$1.4251*10^{-6}$Kmol/sA		$7.716*10^{-6}$		2S
F	96484600 C/Kmol	U	0.8		3.37S	CV	2
R	8314.47 J/Kmol K		$4.22*10^{-5}$Kmol/s atm		6.74S	B	0.04777 A^{-1}
	0.6 V		$2.11*10^{-5}$ Kmol/s atm		18.418S	C	0.0136V
Rint	0.2778	X	0.05 ohm		0.000015		88

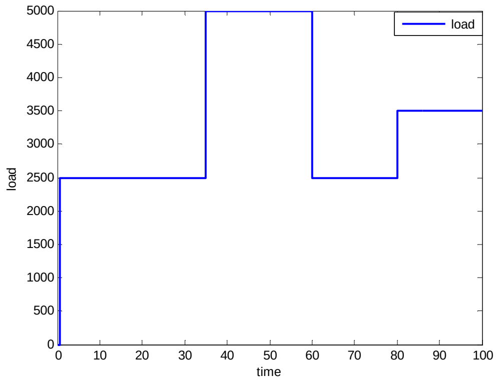

Figure 6. Load Step

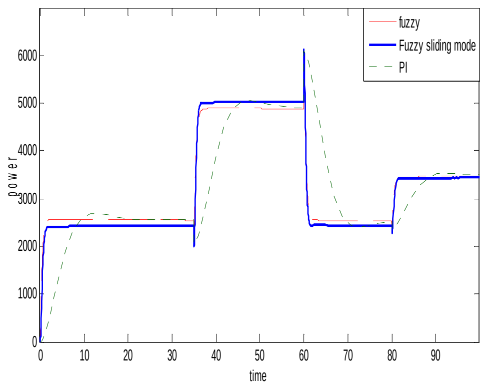

Figure 7. Power

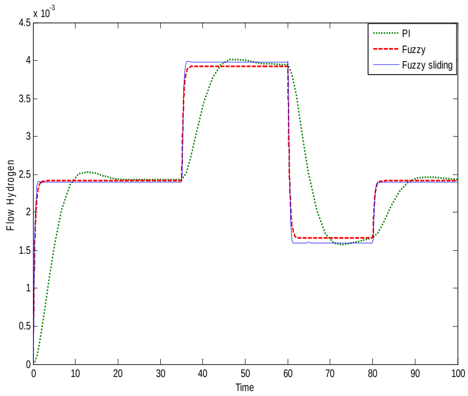

Figure 8. Hydrogen Flow

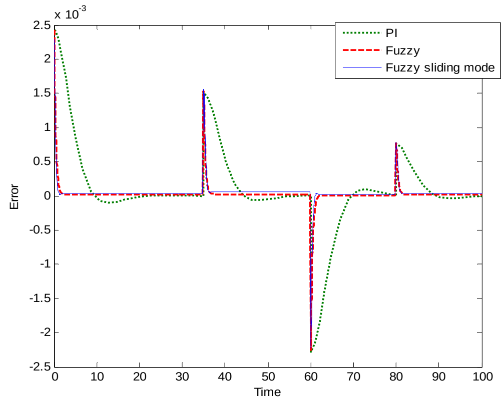

Figure 9. Erorr

Table 3. Absolut of Error

Fuzzy sliding mode	Fuzzy	PI
$6.417*10^{-5}$	$6.961*10^{-5}$	$3.743*10^{-4}$

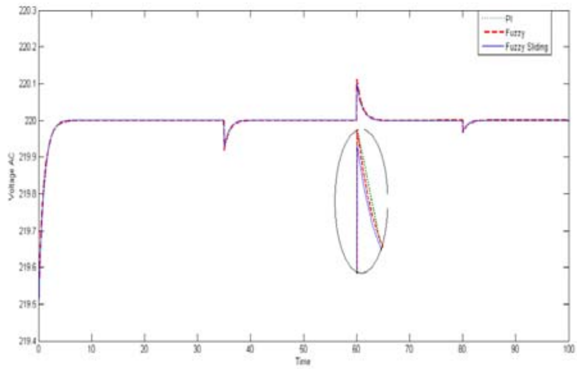

Figure 10. AC Voltage

5. Conclusion

In this paper the PEM fuel cell system model for residential generation is proposed. This model includes a dynamic fuel cell model, a methanol reformer model, power condition unit, and fuzzy sliding mode controller. The simulation results indicate that the DC-AC converter and fuel have to be controlled, and also indicate that the fuzzy sliding mode controller is effective to control the H_2 flow for power load variation. PEMFCs require good control system because need to keep the output power invariable. By using fuzzy sliding mode controller, fuel cell can fast response characteristic, and have good steady-state behaviour and strong robustness.

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