A fuzzy logic controller for a hybrid PV/FC green power system

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Abstract: Design and utilisation of a fuzzy logic controller (FLC) for a hybrid photovoltaic (PV) and proton exchange membrane fuel cell (PEMFC) renewable power system is studied in this paper. The FLC is designed and utilised to compensate load changing effects as well as to establish a sustainable energy source by eliminating the effects of the changes on the source side. As well known, the output power of the PV source is directly affected from the sunlight. Therefore, changing solar irradiation levels of sunlight must be compensated as well not to affect the load side power balance. A DC/AC converter is used to control the power flow from the hybrid PV-PEMFC source to the load side by maintaining a sustainable source of power. All of the system components are modelled in Matlab/Simulink environment and combined with the FLC model, which is also developed in Matlab/Simulink environment by using functional blocks of the Simulink.

Keywords: fuzzy logic control; FLC; photovoltaic; PV; fuel cell; FC; renewable energy.

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1 Introduction

Fuzzy logic has found applications in so many areas (Maiers and Sherif, 1985) including control and power systems (Momoh et al., 1995; Warwick et al., 1997; El-Hawary, 1998). Due to the ability of fuzzy logic (FL) to be able to be utilised in a way that similar to human thoughts and decision processes, the application areas of FL have been widespread in many different disciplines. However, the application of the FLC in non-linear systems with imprecise data and behaviour is more meaningful because of its flexible and adaptable structure.

Since the level of solar irradiation coming to photovoltaic (PV) arrays may change during day time depending on the weather conditions and is not predictable, FL controllers or decision-makers can be used to control the power output of the PV arrays. Actually, the power generated by the PV arrays is also a function of the instant load power (Altas and Sharaf, 2008), which is also unpredictable and requires load estimation methods to be treated clearly.

FL has been used in various parts of PV systems such as maximum power tracking (Cheikh et al., 2007; Gounden et al., 2009), DC-DC and/or DC/AC interfacing converters

(Wu et al., 2000; El-Shatter et al., 2006) and power quality compensators (Thapar et al., 2003).

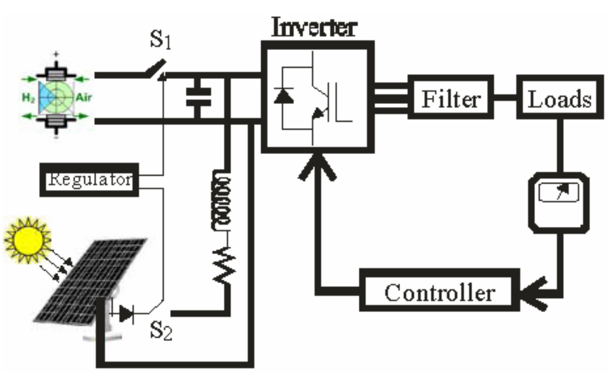
In this study, FL has been used as a controller and a decision-maker in different parts of a renewable green energy utilisation scheme. As a controller, the FL is used to control bus voltage magnitudes and frequencies to be kept at desired constant values. The FL is used as a fuzzy decision-maker in load-power-battery matching problem. Since the solar irradiation (SX) and ambient temperature affect the power output of the PVAs, a decision-maker is required to make a selection between PV and fuel cell (FC) systems and other backup units.

One of the main parts of the scheme where the FL is used as a controller is the power matching decoupled interface devices such as DC/DC and AC/DC converters (Kasa et al., 1999). The power matching of PV array – load combination and control issues of the DC/DC and DC/AC converters are the major research topics underway (Muljadi, 1997), besides the power quality problems (Barbosa et al., 1998) in renewable energy systems.

In this study, a PV/FC hybrid system supplying power to three phase AC loads is considered. The voltage at the load terminals are kept constant at 380 V using both PI and FL controllers. FL controller is employed to satisfy an acceptable total harmonic distortion (THD) in standard limits. A decision-maker makes the selection between the PVA and the FCs whenever the power generated by the PVA is insufficient or sufficient to establish a sustainable energy source for the user.

All of the subsystem components (PV, FC, FLC, PI, DC/AC converter, three phase loads, regulator) used in the solar PV/FC powered renewable green energy scheme are modelled individually using the Matlab/Simulink operational blocks.

Figure 1 PV/FC renewable energy source (see online version for colours)



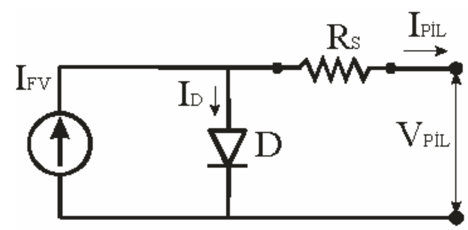
2 PV/FC hybrid energy scheme

A general basic view of the PV/FC hybrid energy scheme is shown in Figure 1. The hybrid energy system feeds three phase loads over a controlled DC/AC inverter. Actually, the DC voltage outputs of the PV array and FC sources are also controlled and kept constant at the input terminals of the three-phase inverter. The output voltage and the frequency of the inverter also must be remained constant at the values required by loads. The FL controllers proposed and utilised in this study are operated with a strategy so that the changes in solar irradiation are compensated before the inverter as the changes in load power are compensated by controlling the inverter. Due to switching processes on load side and by DC-DC and DC/AC converters, the harmonics in the system become higher than related standard values. The proposed controllers are also employed to reduce the harmonic effects and keep the THD at acceptable standard values.

2.1 An equivalent model of PV array

The equivalent circuit shown in Figure 2 is used to model the PV cells used in the proposed PV array. This model consists of a current source, a resistor and a reverse parallel connected diode.

Figure 2 PV solar cell's equivalent circuit



The PVA model developed and used in Matlab/Simulink environment is based upon the circuit given in Figure 2, in which the output voltage is expressed as in (1) and other equations shown in equations (2)–(8).

$$V_{pil} = \frac{A \times k \times T_{pil}}{e} \ln\left(\frac{I_{ph} + I_0 - I_{pil}}{I_0}\right) - R_S \times I_{pil} \qquad (1)$$

where the symbols are defined as follows:

I_{pil} cell output current (A)

V_{pil} sell output voltage (V)

I_{ph} photocurrent, function of irradiation level and junction of temperature (A)

I_0 reverse saturation of current of diode

R_S series resistance of cell

e electron charge ($1.6021917 \times 10^{-19}$C)

k Boltzmann constant (1.380622×10^{-23} J/°K)

T_{pil} reference cell operating temperature

A curve fitting factor (100) (Altas and Sharaf, 2008).

The values of the parameters used in the unified PV array model are given in Table 1.

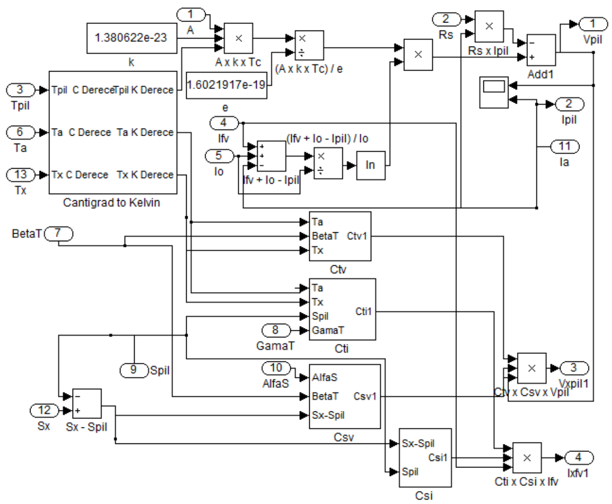
Table 1 Constants of PV solar cell

T_a:	25°C	β_T:	0.005	α_S:	0.3
S_{pil}:	100 mW/cm^2	γ_T:	0.02		

The output voltage of PV solar cell as given in (1), depends on cell operating temperature (T_{PV}) and the photocurrent (I_{pil}), which is a function of solar irradiation level (Sx). Using Figure 2 and equation (1) as the reference initial base model, the effect of the changing solar irradiation level and operating temperature are included in the modelling of the PV cell in Matlab/Simulink and shows in Figure 3 (Altas and Mengi, 2008).

Simulink PV model has a lot of subsystems. The mathematical expressions of these subsystems are given by equations (2)–(8).

Figure 3 Simulink PV model



$$C_{TV} = 1 + \beta_T \left(T_a - T_x\right) \tag{2}$$

$$C_{TI} = 1 + \frac{\gamma_T}{S_{pil}}\left(T_x - T_a\right) \tag{3}$$

$$C_{SV} = 1 + \beta_T \times \alpha_s \left(S_x - S_{pil}\right) \tag{4}$$

$$C_{SI} = 1 + \frac{1}{S_{pil}}\left(S_x - S_{pil}\right) \tag{5}$$

$$\alpha_s = \frac{\Delta T_{pil}}{S_x - S_{pil}} = \frac{T_{pil} - T_a}{S_x - S_{pil}} \tag{6}$$

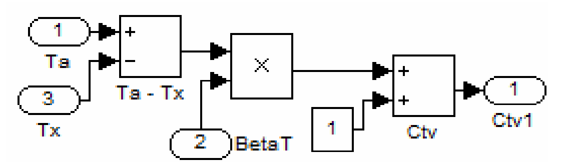
$$V_{Xpil} = C_{TV} \times C_{SV} \times V_{pil} \tag{7}$$

$$I_{XFV} = C_{TI} \times C_{SI} \times I_{FV} \tag{8}$$

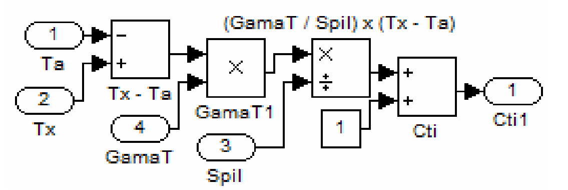
where

- C_{TV} temperature-voltage coefficient
- C_{SV} irradiation-voltage coefficient
- C_{SI} irradiation-current coefficient
- C_{TI} temperature-current coefficient
- β_T temperature coefficient for PV cell voltage
- T_a PV cell operating temperature (K)
- T_x ambient temperature (K)
- γ_T temperature coefficient for PV cell current
- S_{pil} reference solar irradiation level
- S_x solar irradiation level at different times.
- α_s temperature coefficient of PV cell due to the variations in solar irradiation level
- V_{Xpil} PV array output voltage (V)
- I_{XFV} cell output current (A).

Figure 4 The model of the temperature variation effects on PV cell voltage and current (a) temperature variation effect on voltage (b) temperature variation effect on current

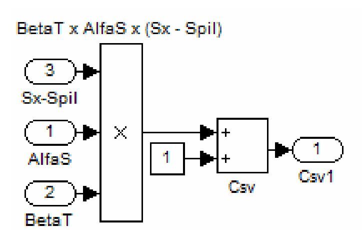


(a)

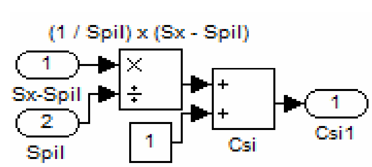


(b)

Figure 5 The model of the effects of solar irradiation variation on PV cell voltage and current (a) the effect of the solar irradiation on voltage (b) the effect of the solar irradiation on current



(a)

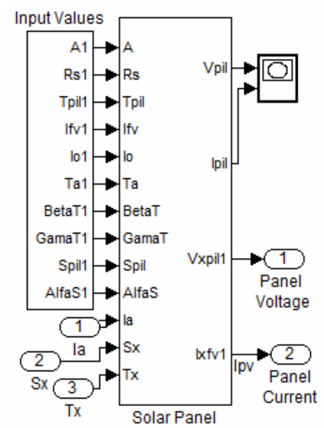


(b)

The Simulink model of the PV array is an extended version of the PV cell model. A single PV cell model voltage is multiplied by the number of cells in series to obtain the voltage required by the load. The power matching of the PV array with the load is done by the number of PV cells in parallel. The effects of the cell temperature and solar irradiation level are included as shown in Figure 4 and Figure 5.

The whole system has been arranged as a single block by combining the sub systems as given in Figure 6. Besides the PV cell block, data block has been added to the model just to make the input parameters to be entered easily.

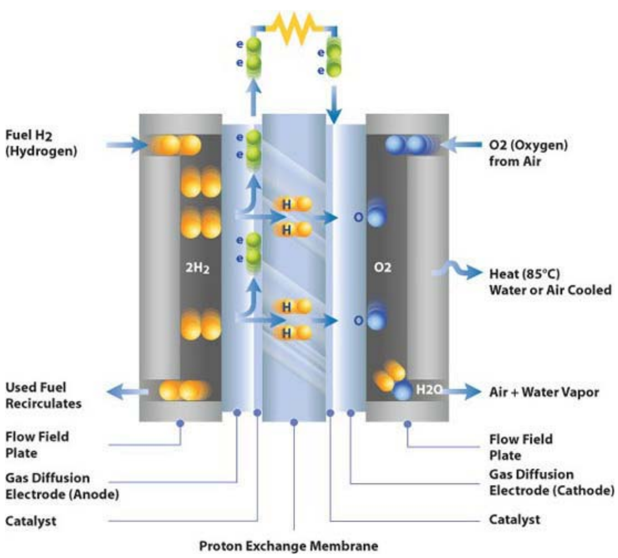
Figure 6 The unified PV array model with the additional data block



2.2 PEM FC system

The fundamental structure of a proton exchange membrane (PEM) FC can be described as two electrodes (anode and cathode) separated by a solid membrane acting as an electrolyte as shown in Figure 7.

Figure 7 Schematic of a single typical proton exchange membrane fuel cells (see online version for colours)



Hydrogen fuel flows through a network of channels to the anode, where it dissociates into the protons that, in turn, flow through the membrane to the cathode and electrons that are collected as electrical current by an external circuit linking the two electrodes. The oxidant (air in this study) flows through a similar network of channels to the cathode where oxygen combines with the electrons in the external circuit and the protons flowing through the membrane, thus producing water. Total cell reaction of a PEM FC is as follows:

- Anode reaction (oxidation half reaction):

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{9}$$

- Cathode reaction (reduction half reaction):

$$O_2 + 4H^+ + e^- \rightarrow 2H_2O \tag{10}$$

- Total cell reaction:

$$2H_2 + O_2 \rightarrow 2H_2O + \text{electricity} + \text{heat} \tag{11}$$

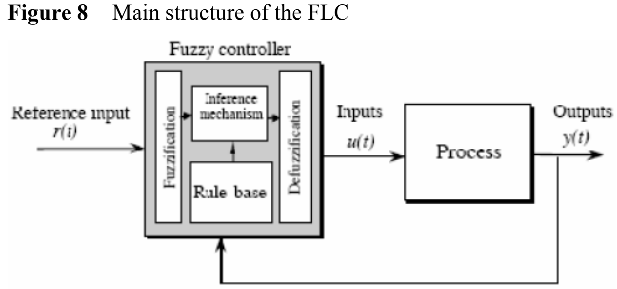
The products of this process are water, DC electricity and heat. Electrons flowing from anode to cathode provide power to the load. A number of cells, when connected in series, make up a stack and deliver sufficient electricity. The behaviour of a cell is highly non-linear and depends on a number of factors such as current density, cell temperature, membrane humidity, and reactant partial pressure. The cell voltage decreases with increasing current. A PEM FC generally performs best at temperatures around 70–80°C, at a reactant partial pressure of 3–5 atm, and a membrane humidity of 100% (Ural et al., 2007).

2.3 The fuzzy logic controller (FLC)

Automatic control is one of the major application areas of FL. A compact block diagram is given in Figure 8 to show input-output processes and internal process algorithm of a FL controller.

As shown in Figure 8, the FLC system consists of three subsystems, which are the fuzzification, rule base and defuzzification. Fuzzification, the first component of the FLC, converts the exact inputs to fuzzy values. These fuzzy values are sent to rule base unit and processed with fuzzy rules. These derived fuzzy values are sent to defuzzification unit. In this unit, the fuzzy results are converted to exact values.

Figure 8 Main structure of the FLC



These subsystems are shown in Figure 9 to Figure 12. The triangle membership function is defined in equation (12) and its Simulink subsystem is shown in Figure 9.

$$\mu_{A\ddot{U}}(x) = \max\left(\min\left(\frac{x - x_1}{x_T - x_1}, \frac{x_2 - x_1}{x_2 - x_T}\right), 0\right) \tag{12}$$

Generally, the FLCs input values are the control error and the variation of this error in one sampling time. According to these variables, a rule table is produced in the FLCs rule base unit.

The FLC is designed in the Matlab/Simulink environment as shown in Figure 13. Thereby, the user can interfere the controller more efficiently and can make the necessary settings easily (Altas and Sharaf, 2008; Mengi and Altas, 2008).

Figure 9 Triangle membership function

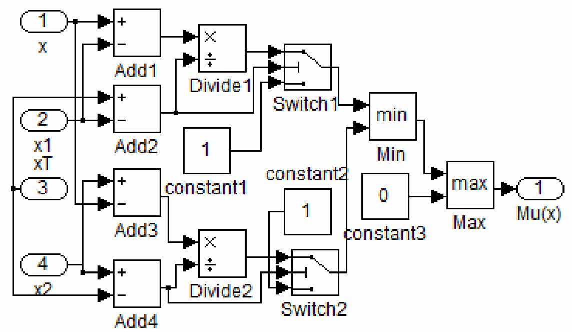


Figure 10 Fuzzification unit

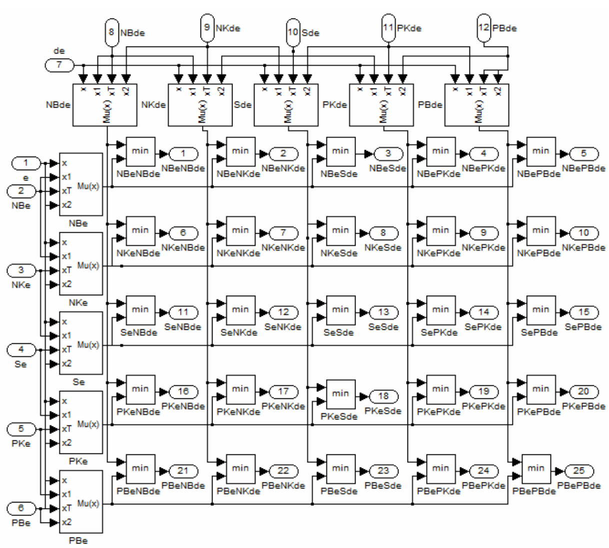


Figure 11 Fuzzy rules

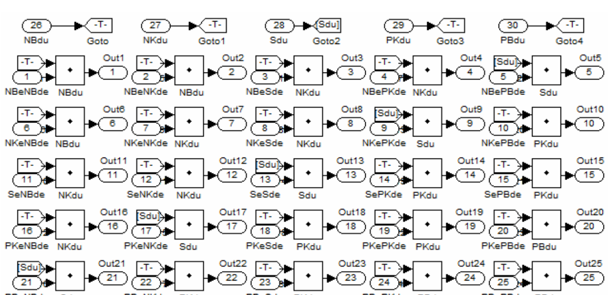


Figure 12 Defuzzification unit

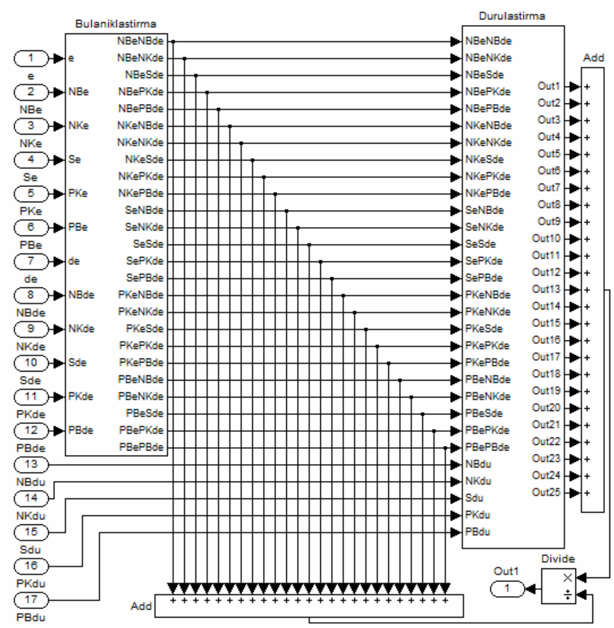


Figure 13 FLC with input and output values

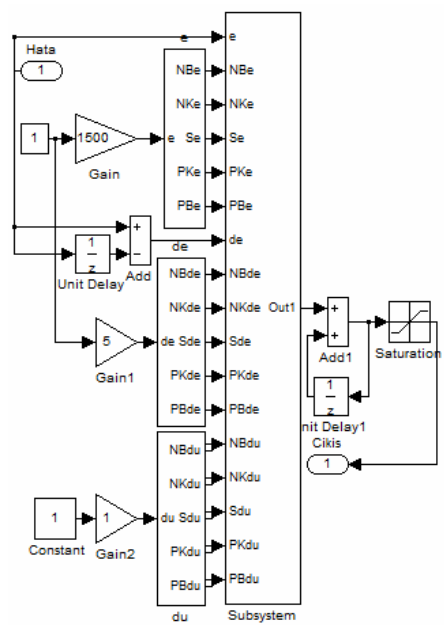


Figure 14 The variations of S_x

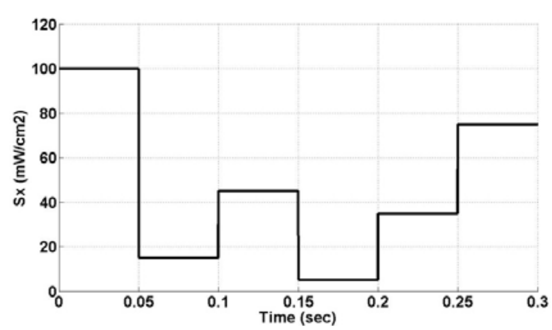
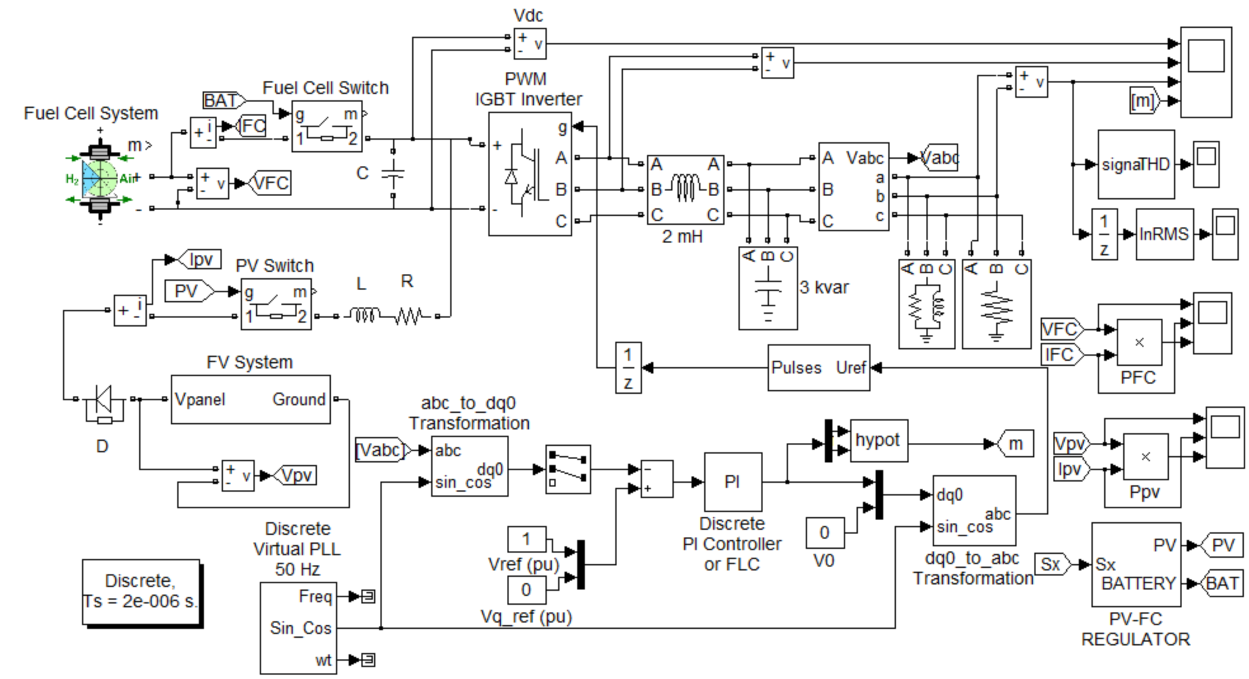


Figure 15 The Simulink model of the PV/FC hybrid renewable energy system (see online version for colours)



3 System simulation

The simulated system is shown in Figure 15 where an 80 kW PV array is constructed by connecting 20 module branches in parallel with each branch having 40 modules in series. A 55 kW FC source is established by connecting five modules in series. Each one of the FC module has 52 A and 210 V nominal value. Required regulator, inverter, filters, reactive resistance loads with 30 kW, 15 kW and 10 kVAr; measurement units, switches and controllers are all shown in Figure 15.

During the simulation process the voltage on the loads are fixed at the value of 380 V. Three phase voltages at the output terminals of the inverter are converted to d–q axis layouts and then the derived V_d and V_q values are used by FLC to control the voltages. Besides, a phase locked loop (PLL) approach is used to keep the frequency at desired value, such as 50 Hz.

The regulator used in the hybrid power system is a device that measures the variation of the solar irradiation level and the output voltage of the PVA so that a decision can be generated whether the PVA or the FC is to be used. This decision process is a mechanism that uses either an on-off control technique or a FL decision algorithm. Such that when the solar irradiation level (S_X) is less than a specific value the load power is supplied by FC unit. Otherwise, the PV array continues to deliver power to the loads. In order to reduce the harmonic effects on the system, a filter used and total harmonic corruption is measured. The S_X is changed as shown in Figure 14. The ambient temperature is 25°C.

4 Discussion and result analysis

In Figure 16–Figure 19, the result obtained using the PI controller is shown. The DC side voltage, and the AC voltage between the phases a and b at the output terminals of the inverter are given in Figure 16. The modulation index variations are also shown. The waveforms of the AC voltages at the load terminals are very similar to sinusoid form. The RMS voltage on the load terminals reaches the value of 380 V at 0.03 s with the PI type controller in Figure 17. The maximum overshoot voltage is measured as 392.1 V. The THD value is less than 5% at steady state operation. PV and FC current, voltage and power variations are shown in Figure 18 and Figure 19.

Figure 16 The results of PI controller

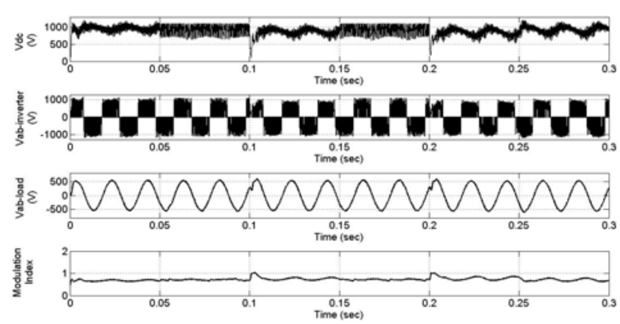
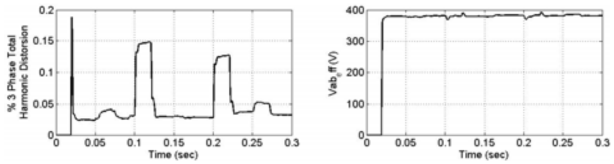
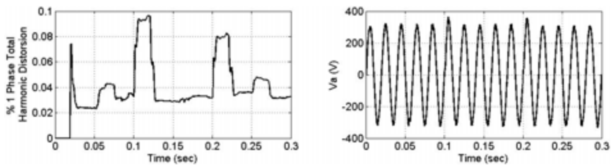


Figure 17 (a) and (b) 1 and 3 phased THD and load voltage variation



(a)



(b)

Figure 18 Fuel cell current, voltage and power

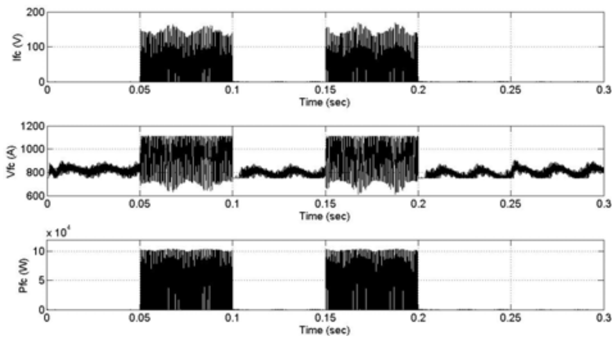
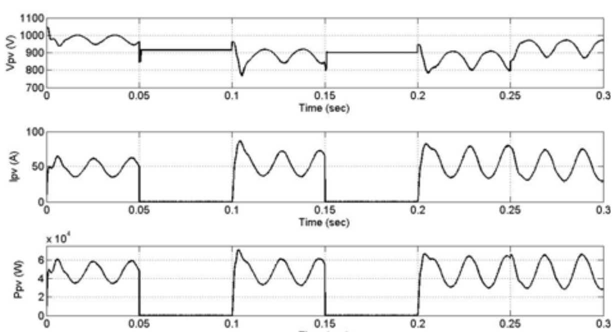


Figure 19 PV current, voltage and power



The results obtained using the FLC is shown in Figure 20 to Figure 23. In the Figure 20, the DC output voltage, the inverter's output voltage between the phases a and b, the load voltage between the phases a and b, and the variation of the modulation indexes are shown. The RMS voltage at the load terminals reaches the value of 380 V at 0.03 s with the FLC type controller in Figure 21. The maximum overshoot value is 388.1 V, and the THD value is less than 5%. PV and FC current, voltage and power variations are shown in Figure 22 and Figure 23. The magnitude changes on the loads shown in Figure 24.

When the solar irradiation level is less than the value of 20 mW/cm^2 the regulator switches the power source from the PVA to FC.

Figure 20 The results of FLC controller

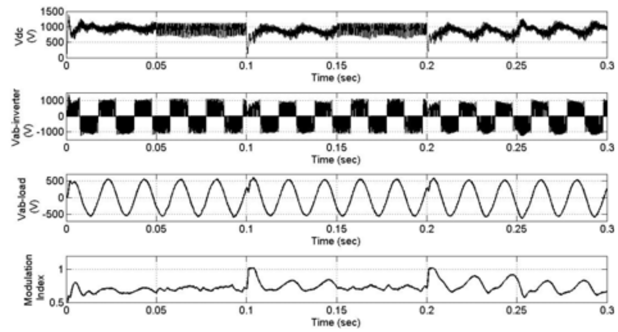


Figure 21 1 and 3 phased total harmonic distortion and load voltage variation

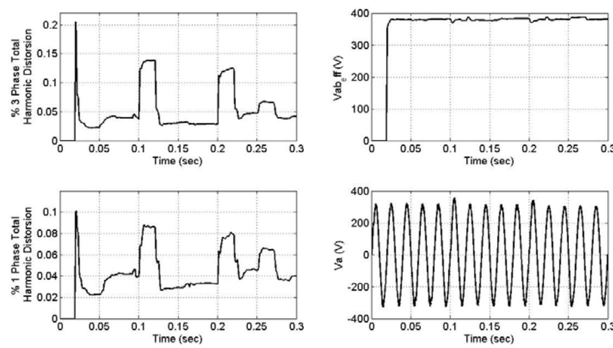
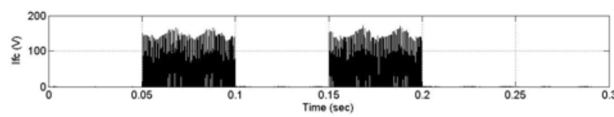
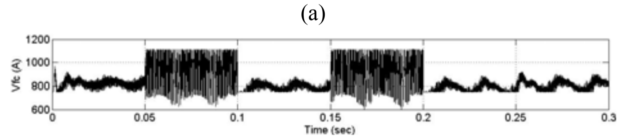


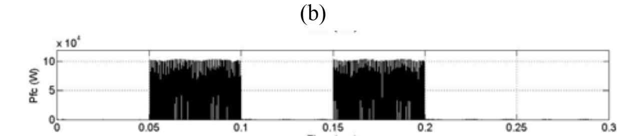
Figure 22 Fuel cell current, voltage and power (a) fuel cell current (b) fuel cell voltage (c) fuel cell power



(a)



(b)



(c)

Figure 23 PV current, voltage and power

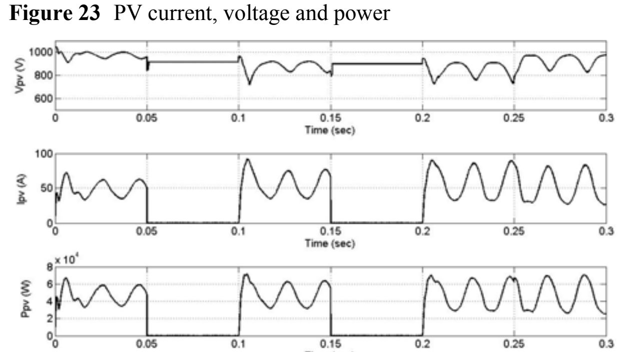
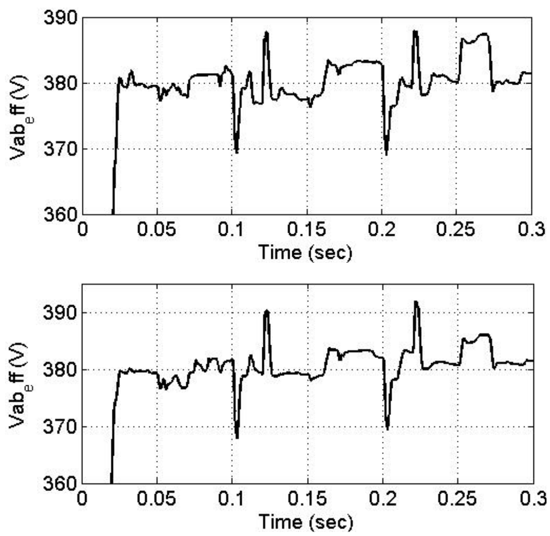


Figure 24 Variations of V_{ab_eff} with PI and FLC



5 Conclusions

Since the input solar energy to the PV arrays is not constant and unpredictable depending on the weather conditions, the power generated by such systems are not constant. Therefore, the power transferred from the PVA system to the loads must be controlled for a good generated power load matching. Hence, a FL controller is designed and used to control power transfer from renewable sources to the load or utility grid while maintaining the power quality. A simulation model of the proposed system is developed and used in Matlab/Simulink resulting in reasonable and acceptable outputs. The results obtained with FL controller are compared with those obtained using a PI controller.

References

Altas, I.H. and Mengi, O.O. (2008) 'AA ve DA yuklerini Besleyen FV/Aku grubunun Matlab/Simulink ortamında modellenmesi ve simulasyonu', *Elektrik – Elektronik ve Bilgisayar Muhendisligi Sempozyumu (ELECO 2008)*, pp.135–139, Bursa, Turkey.

Altas, I.H. and Sharaf, A.M. (2008) 'Novel maximum power fuzzy logic controller for photovoltaic solar energy systems', *Renewable Energy*, Vol. 33, pp.388–399.

Barbosa, P.G., Rolim, L.G.B., Watanabe, E.H. and Hanitsch, R. (1998) 'Control strategy for grid connected DC-AC converters with load power factor correction, generation, transmission and distribution', *IEE Proceedings*, Vol. 145, No. 5, pp.487–491.

Cheikh, M.S.A., Larbes, C., Kebir, G.F.T. and Zerguerras, A. (2007) 'Maximum power point tracking using a fuzzy logic control scheme', *Revue des Energies Renouvelables*, Vol. 10, No. 3, pp.387–395.

El-Hawary, M.E. (1998) *Electric Power Applications of Fuzzy Systems*, IEEE Press.

El-Shatter, T.F., Eskander, M.N. and El-Hagry, M.T. (2006) 'Energy flow and management of a hybrid wind/PV/fuel cell generation system', *Energy Conversion and Management*, Vol. 47, Nos. 9–10, pp.1264–1280.

Gounden, N.A., Peter, S.A., Nallandula, H. and Krithiga, S. (2009) 'Fuzzy logic controller with MPPT using line commutated inverter for three phase grid connected photovoltaic systems', *Renewable Energy*, Vol. 34, pp.909–915.

Kasa, N., Iida, T. and Iwamoto, H. (1999) 'An inverter using Buck-boost type chopper circuits for popular small scale photovoltaic power system', *The 25th Annual Conference of the IEEE Industrial Electronics Society (IECON '99)*, Vol. 1, pp.185–190.

Maiers, J. and Sherif, Y.S. (1985) 'Applications of fuzzy set theory', *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. SMC-15, No. 1, pp.175–189.

Mengi, O.O. and Altas, I.H. (2008) 'Ruzgar enerji sistemlerinde gerilim genligi denetiminin bulanık mantikla gerceklenmesi', *Otomatik Kontrol Ulusal Toplantısı (TOK 2008)*, pp.835–840, Istanbul, Turkey.

Momoh, J.A., Ma, X.W. and Tomsovic, K. (1995) 'Overview and literature survey of fuzzy set theory in power systems', *IEEE Transactions on Power Systems*, Vol. 10, No. 3, pp.1676–1690.

Muljadi, E. (1997) 'PV water pumping with a peak-power tracker using a simple six-step square-wave inverter', *IEEE Transactions on Industry Applications*, Vol. 33, No. 3, pp.714–721.

Thapar, A., Saha, T.K. and Dong, Z.Y. (2003) 'A fuzzy logic based recognition technique for power quality categorization', *R. Duke The Australasian Universities Power Engineering Conference*, Christchurch, New Zealand.

Ural, Z., Gencoglu, M.T. and Gumus, B. (2007) 'Dynamic simulation of a PEM fuel cell system', *Proceedings 2nd International Hydrojen Energy Congress and Exhibition (IHEC 2007)*, Istanbul, Turkey.

Warwick, K., Ekwue, A. and Aggarwal, R. (1997) *Artificial Intelligence Techniques in Power Systems*, IET.

Wu, T.F., Chang, C.H. and Chen, Y.K. (2000) 'A fuzzy logic controlled single stage converter for PV powered lighting system applications', *IEEE Transactions on Industrial Electronics*, Vol. 47, No. 2.