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MODELING AND ANALYSIS OF A SMALL PHOTOVOLTAIC FUEL CELL HYBRID SYSTEM

***Balasubramanian, G., Dr. Singaravelu, S. and Manivannan, A.**

Department of Electrical Engineering, Annamalai University, Annamalainagar-608 002, India

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ABSTRACT

This paper presents hybrid power generation systems which consist of following main components: photovoltaic arrays (pv), an electrolyzer system and proton exchange membrane fuel cells (PEMFC). The hybrid scheme inherently adapts to the changes in irradiation or load. An easy and accurate method of modeling photovoltaic arrays is proposed. The model and fuzzy based control strategies are combined to form intelligent controllers that are more accurate and robust. The model based controller is designed such that the reference signal for PWM generator of the converter can be adjusted to achieve maximum power generation from the photo voltaic system. The proposed fuzzy logic controller shows better performances compared to the P&O and PI MPPT based approach. The model is implemented in the MATLAB/Simulink platform. Results from the simulations bring out the suitability of the proposed hybrid scheme in remote areas.

INTRODUCTION

In recent years, renewable energy sources become more significant source of energy. Among the renewable energy sources, solar energy is sustainable with less carbon emissions (Mayssa Farhat and Lassaad Sbita, 2011; Tafticht *et al*., 2008). The output power of a PV array varies according to the sunlight conditions such as solar irradiation, shading and temperature. Special emphasis has been given on the development and implementation of fuel cell systems. Fuel cells may be considered as continuous chemical reaction which convert fuel and oxidant chemical potential into electrical energy. The key advantage of fuel cells compared to the conventional electrical power generation technologies are: higher efficiency, quiet operation suitable for residential application, and almost zero levels of produced pollutant gases. The power generated by a PV system is highly dependent on weather conditions. For example, during cloudy periods and at nights, a PV system would not generate any power.Fuel cells power are complementary at these times. The hybrid PV-fuel cells system therefore has higher availability to deliver continuous power and results in a better utilization of power conversion and control equipment than with of the individual sources. The hybrid scheme comprises one set of fuel cells and a parallel connected fixed frequency pulse width modulation (PWM) inverter fed from the solar panels .The DC bus collects the total power from the PV array and fuel cells. The performance of the PV array and fuel cells are individually studied and integrated on a common DC bus through the necessary power electronic interface. Figure 1 describes the scheme of PV-Fuel cells with the proposed fuzzy logic controller. To obtain maximum power from photovoltaic array, photovoltaic power system usually requires maximum power point tracking (MPPT) controller (Yun Tiam Tan *et al*., 2004).Various approaches have been reported to implement MPPT such as perturb and observe (P&O) method (Sullivan and Powers, 1993; Femia, 2004), the incremental conductance method, constant voltage method and short-circuit current method (Koutroulis *et al*., 2001). Using this method the maximum power point can be found for specified solar irradiation and temperature condition but they display oscillatory behaviour around the maximum power point under normal operating conditions. Moreover the system will not respond quickly to rapid changes in temperature or irradiance. On the other hand the conventional PI controllers are fixed-gain feedback controllers. Therefore they cannot compensate the parameter variations in the process and cannot adapt changes in the environment. PI-controlled system is less responsive to real and relatively fast alterations in state and so the system will be slower to reach the set point. Recently intelligent based schemes have been introduced (Abdulhadi Varnham *et al*., 2007; Damak1 *et al*., 2009; Krishna Kumar, 2009). Among the intelligent based methods fuzzy logic

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****Corresponding author:* Balasubramanian, G.,**
Department of Electrical Engineering, Annamalai University, Annamalainagar-608 002, India

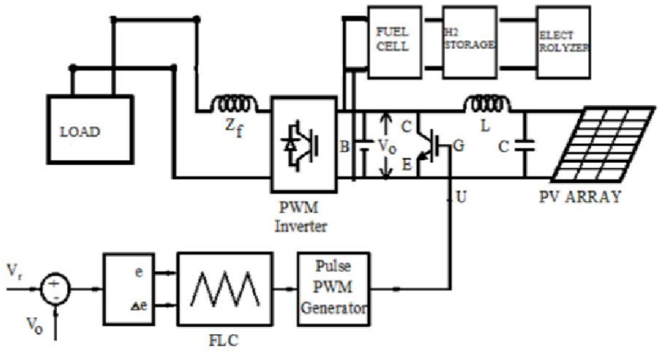

Fig. 1. Schematic diagram of hybrid scheme

controller has its own merits such that the MPPT algorithm can be easily formed. The shape of the membership function of the fuzzy logic controllers can be adjusted such that the gap between the operation point and maximum power point can be optimized. The hybrid PV-fuel cells system therefore has higher availability to deliver continuous power and results in a better utilization of power conversion and control equipment than with of the individual sources. Hence this paper investigates one such hybrid scheme comprise PV array and fuel cells with an intelligent control technique using fuzzy logic.

MODEL OF A PV ARRAY

A PV cell can be represented by an equivalent circuit (Villalva *et al.*, 2009) as shown in Fig. 2. The characteristics of this PV cell can be obtained using standard equation (1).

$$I = I_{PV} - I_O\left[\exp\left(\frac{V+R_S I}{V_t a}\right) - 1\right] - \frac{V+R_S I}{R_p} \tag{1}$$

I_{PV} = photovoltaic current
I_O = saturation current
V_t = N_S k T/q, thermal voltage of array
Ns = cell connected in series
T = is the temperature of the p-n junction
k = Boltzmann constant
q = electron charge
R_S = equivalent series resistance of the array
R_P = equivalent parallel resistance of the array
a = diode ideality constant

Fig. 2 shows the single diode model. A single solar cell will produce only a limited power. Therefore it is usual practice in order to get desired power rating the solar cells are connected in parallel and series circuits which form a module. Such modules are again connected in parallel and series to form a solar array or panel to get required voltage and current.

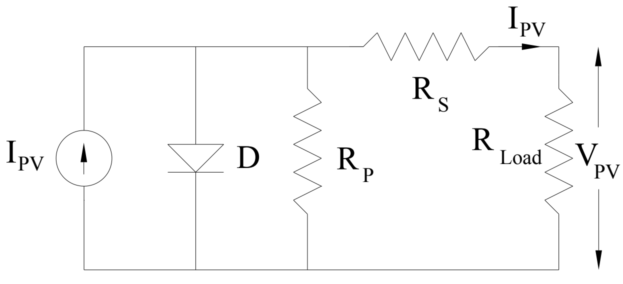

Fig. 2. Equivalent circuit of PV cell

The equivalent series and parallel resistance of the array are denoted by the symbol R_S and R_P respectively in the equivalent circuit. From the general *I-V* characteristic of the practical photovoltaic device one can be observe that the series resistance R_S value will dominate in the voltage source region and the parallel resistance R_P value will dominate in the current source region of operation. The general equation of a PV cell describes the relationship between current and voltage of the cell. Since the value of shunt resistance R_P is high compared to value of series resistance R_S the current through the parallel resistance can be neglected. The light generated current of the photovoltaic cell depends linearly on the solar irradiation and is also influenced by the temperature (Patel and Agarwal, 2008) given by the equation (2)

$$I_{PV} \;=\; \left[I_{PV,n} + K_I\,\Delta_T\right]\frac{G}{G_n} \tag{2}$$

$I_{PV,n}$ = is the light generated current at nominal condition (25^0C and 1000 W/ m^2)
Δ_T = T – T_n
T = actual temperature [K]
T_n = nominal temperature [K]
K_I = current coefficients
G = irradiation on the device surface [W/m^2]
G_n = nominal irradiation

The current and voltage coefficients K_V and K_I are included as shown in equation (3) in order to take the saturation current I_O which is strongly dependent on the temperature.

$$I_O = \frac{I_{sc,n}+K_I\Delta_T}{exp\left(\frac{V_{oc,n}+K_V\Delta_T}{aV_t}\right)-1} \tag{3}$$

K_V = voltage coefficients
K_I = current coefficients

The output voltage is increased (where the current remain unchanged) proportionally on number of identical PV modules connected in series (N_{ser}). Similarly the output current is increased (where the voltage remain unchanged) proportionally on number of identical PV modules connected in parallel (N_{par}). It can be noted that the equivalent series and parallel resistance are directly proportional to the number of series modules and inversely proportional to the number of parallel modules respectively. The equation for array composed of N_{ser} x N_{par} given by equation (4)

$$I = I_{PV}N_{par} - I_O N_{par}\left[\exp\left(\frac{V+R_S\left(\frac{N_{ser}}{N_{par}}\right)I}{V_t a N_{ser}}\right) - 1\right] - \frac{V+R_S\left(\frac{N_{ser}}{N_{par}}\right)I}{R_P\left(\frac{N_{ser}}{N_{par}}\right)} \tag{4}$$

Table 1.

I_{mp}	4.40 A	V_{oc}	21.20 V
V_{mp}	17.00 V	a	1.3
P_{max}	74.8 W	R_{se}	0.511 Ω
I_{sc}	5.02 A	R_{sh}	44.25 Ω
N_s	36	K_v	-74.7 mv/°C
$I_{O,n}$	9.83×10^{-8}A	K_I	2.80 mA/°C

The parameter of solar array (KCP-12075 at 25°C, 1000W/m^2) used for theoretical and simulation setup is given in Table 1.

PEMFC MODEL

characteristic of a PEM fuel cells presented can be divided into three regions (Li Wei, 2009), which are governed by different over-voltages. Activation over-voltages dominate at low current densities. The middle of the region is governed by the ohmic losses and bending down of the polarization curves due to the concentration over-voltages. The cell voltage model was studied empirically and physically by many researchers. The output voltage of each cell was defined with (7) as a function of the thermodynamic equilibrium potential (E) corresponding to the overall chemical reaction expressed in (8), the activation over-voltage (η_{act}) and the ohmic over-voltage (η_{ohm}).

$$P_{fc} = nV_{fc} I_{fc} = n I_{fc}(E_{Nernst} - \eta_{act} + \eta_{ohm}) \qquad (5)$$

$$H_2(g) + ½ O_2(g) \longrightarrow H_2O(l) + \text{electric} \qquad (6)$$

$$E_{Nernst} = 1.229 - 0.85 * 10^{-3}(T - 298.15) + (4.308*10^{-5})\ T\ [\ln (PH_2) + 0.5 \ln (PO_2)] \qquad (7)$$

$$\eta_{act} = \xi_1 + \xi_2 T + \xi_3 T[\ln (CO_2)] + \xi_4 T[\ln (i)] \qquad (8)$$

$$\eta_{ohm} = -i(R^{electronic} + R^{proton}) = -iR^{internal} \qquad (9)$$

$$R^{proton} = r_m\ l/A \qquad (10)$$

$$r_m = \frac{181.6[1 + 0.03(i/A) + 0.062(T/303)^2 (i/A)^{2.5}}{\left[\lambda m - 0.634 - 3\left(\frac{i}{A}\right)\right] \exp\left(4.18\left[\frac{T-303}{T}\right]\right)} \qquad (11)$$

Where P_{fc} is the stack power, n is the cell number, V_{fc} is the cell voltage, I_{fc} is the cell current, E is the open circuit voltage, η_{act} is the activation over voltage, η_{ohm} is the ohmic overvoltage, T is the temperature, PH_2 is the hydrogen reactant partial pressure, PO_2 is the oxygen reactant partial pressure, A is the active cell area, i is the current, CO_2 is oxygen concentration at the cathode, r_m is the membrane specific resistivity for the flow of hydrated protons, l is the thickness of the polymer membrane, λ_m is the membrane water content, ξ_i are the empirical coefficient for calculating activation over voltages. According to (5)-(11), the electricity model is applicable for PEMFC stack of various configuration and operating conditions.

ELECTROLYZER MODEL

The Electrolyzer model is based on a combination of fundamental thermodynamics, heat transfer theory, and empirical electrochemical relationships. The electrode kinetics of an electrolyzer cell can be modeled using empirical current voltage relationship. The electrochemical reaction of water electrolysis is given by

$$H_2O(l) + \text{electrical energy} = H_2(g) + ½ O_2(g)$$

The actual flow of rates of hydrogen and oxygen production or water consumption in an electrolyzer cell can be calculated by

$$mH_2 = 2mO_2 = mH_2O = \eta_F \frac{Ns\ I}{nF} \qquad (12)$$

where mH_2 is hydrogen production rate, mO_2 is the oxygen production rate, mH_2O is water consumption rate, η_F is Faraday's efficiency, N_s is number of series cell, I is the input current to the electrolyzer, n is the electron per mole, F is Faraday's constant.

GAS STRORAGE TANK MODEL

The hydrogen storage model is based on the ideal gas law, the mathematical model for the hydrogen pressure p in a storage tank can be calculated from

$$P = nRT/V \qquad (13)$$

Where p is the hydrogen pressure inside the tank, n is the number of moles, R is the universal gas constant, T is the temperature of the gas and V is the volume of the tank.

DC-DC BOOST CONVERTER

A dual stage power electronic system comprising a boost type dc-dc converter and an inverter is used to feed the power generated by the PV array to the load. To maintain the load voltage constant a DC-DC step up converter is introduced between the PV array and the inverter. The block schematic of the proposed scheme is shown in Fig.3.

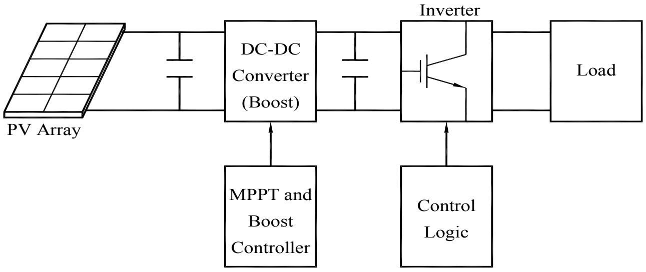

Fig. 3. System configuration for PV-based system feeding power to the load

In this scheme a PV array feeds DC-DC converter used in step-up configuration. The voltage across the DC-DC converter is fed to a single-phase, six-step, quasi-square-wave IGBT inverter a single-phase fixed amplitude and fixed frequency supply is obtained to feed an isolated load. For a dc-dc boost converter, by using the averaging concept, the input–output voltage relationship for continuous conduction mode is given by

$$Vo/Vin = 1/(1 - D) \qquad (14)$$

Where, D = duty cycle. Since the duty ratio "D" is between 0 and 1 the output voltage must be higher than the input voltage in magnitude. It should be noted that the control logic of such dc-dc converter has to be different when it is fed from a stiff DC source. The duty ratio of the chopper is found to increase linearly with increase in cell temperature and hence the intensity. It has been observed that when a PV array is connected to a boost converter, increasing the duty cycle increases the average PV array current and as a result, PV array voltage decreases. Thus, an increase in duty-cycle result in shifting the operating point to the left on the V-I characteristics of the PV array. Similarly decreasing the duty cycle decreases the average PV array current and as the PV array voltage increases resulting in shifting the operating point of PV array to the right. As the inverter DC voltage varies with irradiation to obtain constant amplitude and constant frequency supply from the inverter, a closed loop fuzzy controller is incorporated to automatically vary the duty-cycle of the DC-DC converter to obtain constant DC voltage at the inverter input terminals. The inverter output is then applied to an isolated load.

FUZZY LOGIC MPPT CONTROLLER

The conventional PI controllers are fixed-gain feedback controllers. Therefore they cannot compensate the parameter variations in the process and cannot adapt changes in the environment. PI-controlled system is less responsive to real and relatively fast alterations in state and so the system will be slower to reach the set point. On the other hand P&O method for MPPT tracking will not respond quickly to rapid changes in temperature or irradiance. Therefore the fuzzy control algorithm is capable of improving the tracking performance as compared with the classical methods for both linear and nonlinear loads. Also, fuzzy logic is appropriate for nonlinear control because it does not use complex mathematical equation. The block diagram of fuzzy logic controller (FLC) is shown in Fig.4. The two FLC input variables are the error E and change of error CE. The behavior of a FLC depends on the shape of membership functions of the rule base. In this paper a fuzzy logic control scheme (Fig.5) is proposed for maximum solar power tracking of the PV array with an inverter for supplying isolated loads. They have advantages to be robust and relatively simple to design since they do not require the knowledge of the exact model. On the other hand the designer needs complete knowledge of the PV-fuel cell hybrid system operation.

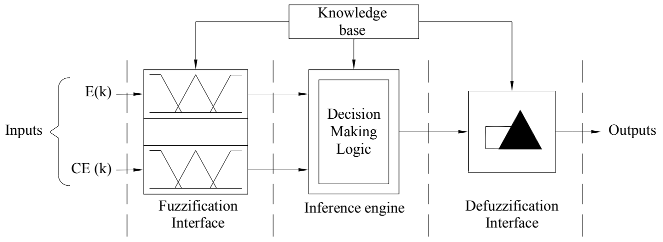

Fig. 4. Block of Fuzzy controller

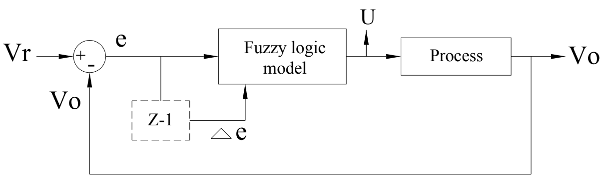

Fig. 5. Fuzzy logic control scheme

Fuzzification

The membership function values are assigned to the linguistic variables using seven fuzzy subset called negative big (nb), negative medium (nm), negative small (ns), zero(zr), positive small (ps), positive medium (pm), positive big (pb). Fuzzy associative memory for the proposed system is given in Table 2. Variable e and Δe are selected as the input variables, where e is the error between the reference voltage (Vr) and actual voltage (Vo) of the system, Δe is the change in error in the sampling interval. The output variable is the reference signal for PWM generator U. Triangular membership functions are selected for all these process. The range of each membership function is decided by the previous knowledge of the proposed scheme parameters.

Table 2. Fuzzy associative memory for the proposed system

e	Δe						
	nb	nm	ns	zr	ps	pm	pb
nb	nb	nb	nb	nm	nm	ns	zr
nm	nb	nb	nm	nm	ns	zr	ps
ns	nb	nm	nm	ns	zr	ps	pm
zr	nm	nm	ns	zr	ps	pm	pm
ps	nm	ns	zr	ps	pm	pm	pb
pm	ns	zr	ps	pm	pm	pb	pb
pb	zr	ps	pm	pm	pb	pb	pb

Inference engine

Inference engine mainly consist of Fuzzy rule base and fuzzy implication sub blocks. The inputs are now fuzzified are fed to the inference engine and the rule base is then applied. The output fuzzy set are then identified using fuzzy implication method. Here we are using MIN-MAX fuzzy implication method.

Defuzzification

Once fuzzification is over, output fuzzy range is located. Since at this stage a non-fuzzy value of control is available a defuzzification stage is needed. Centroid defuzzification method (Timothy and Ross, 1997) is used for defuzzification in the proposed scheme.

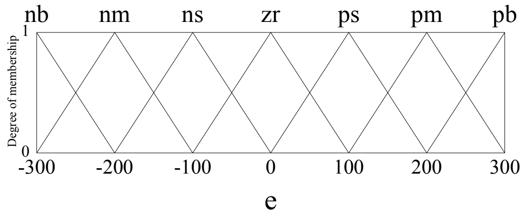

Fig 6 (a): Membership function plots for 'e'

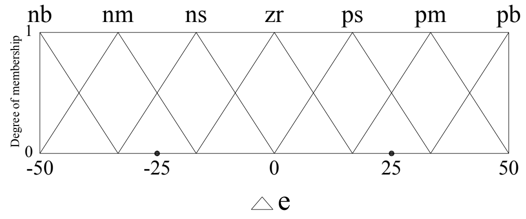

Fig 6(b): Membership function plots for 'Δe'

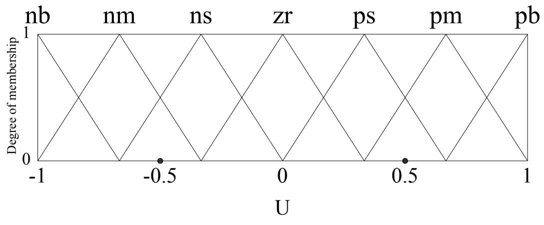

Fig 6(c): Membership function plots for 'U'

The membership function of the variables error, change in error and change in reference signal for PWM generator are shown in Fig. 6a-6c respectively.

RESULTS AND DISCUSSION

A MATLAB based modeling and simulation scheme along with MPPT and fuzzy logic controller is proposed which are suitable for studying the *I-V* and *P-V* characteristics of a PV array under a non-uniform irradiation and different temperature. In addition, the fuel cells reactant pressure, temperature, and pressure of electrolyser, as well as the conversion efficiency of the power conversion devices are well analyzed through simulation. The fuzzy logic controller based results are compared with the conventional techniques such as P&O and PI controlling methods which validate it merits.

Simulation of Photovoltaic characteristics

The behavior the PV cells and its characteristics are discussed in this section. It is found that the set of *P-V* & *I*-V characteristics are highly nonlinear and dependent on solar irradiance of the PV array. The combination of V and I that maximizes the output depends on irradiation and is also affected by the temperature of the cell. Fig. 7(a) shows *I-V* characteristics of a PV cell. It can be observed that as the cell temperature remain constant; the PV output voltage remains nearly constant while the PV output current increases with increasing solar intensity. Fig. 7(b) & Fig. 7(c) shows *P-V* & *I*-V characteristics of a PV cell respectively. Fig. 7(d) shows *P-V* curve plotted for different values of temperature.

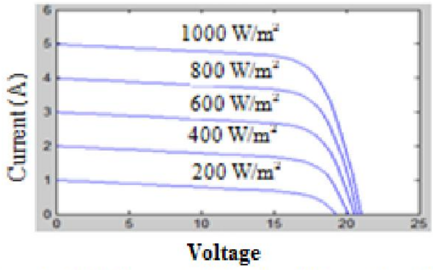

Fig 7 a): I-V Characteristics for different irradiations

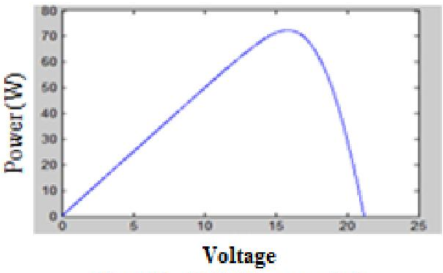

Fig 7 b): P-V Characteristics

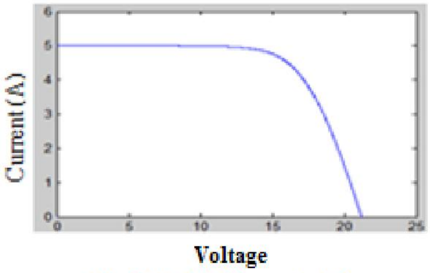

Fig 7 c): I-V Characteristics

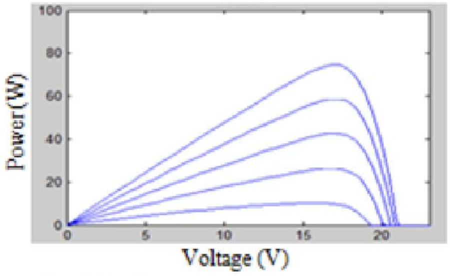

Fig 7(d): P-V Characteristics for different temperature

Simulation of P&O, PI and Fuzzy logic MPPT Controllers

An extensive simulation work ensured realized MATLAB environment is performed. Some selected results are presented with a comparison between system incorporating different configurations as P&O, PI and Fuzzy MPPT controllers. To highlight the proposed system good performances, the following simulation were presented for fast solar irradiance (Larbes *et al.*, 2009) from 500 to 1000 W/m^2 at fixed temperature of 25°C and fast decrease and increase in temperature variations from 40°C to 20°C and 20°C to 40°C respectively at fixed solar irradiance of 1000w/m^2. From the simulation results, it can be deduced that the fuzzy controller is faster than P&O controller and PI in the transitional state, and present also much smother signal with less fluctuation in steady state.

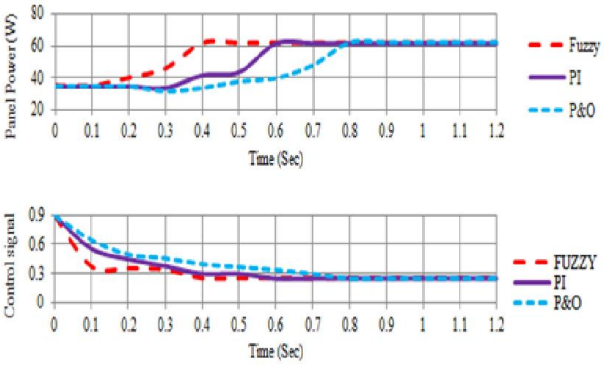

Fig 8 Response of the PV panel for a fast solar irradiance from 500 to 1000W/m^2 at 25°c

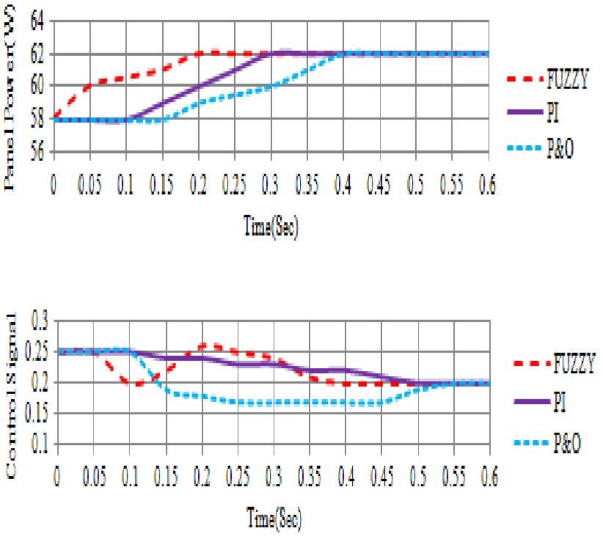

Fig 8: Response of the PV panel for a fast temperature variation from 40°c to 20°c at a solar irradiance of 1000W/m^2

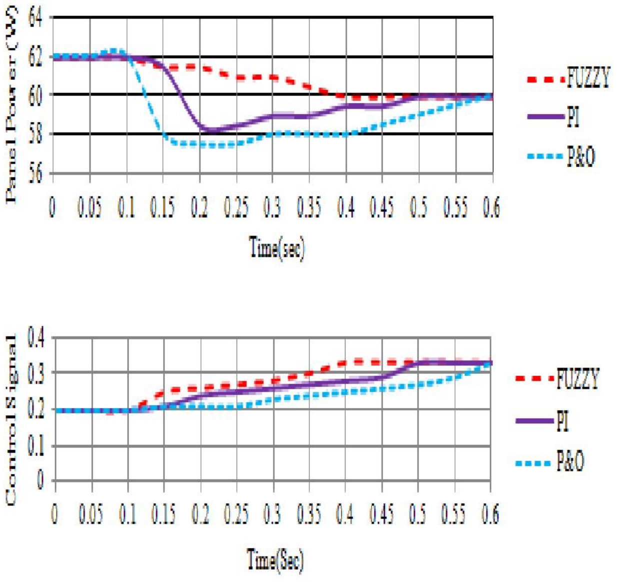

Fig 9: Response of the PV panel for a fast temperature variation from 20°c to 40°c at a solar irradiance of 1000W/m^2

The simulated single phase voltage and current waveform at the output of the inverter shown in Fig. 10(a). The simulated current waveform (Fig. 10(b)) shows, even though the load is applied at 0.8 seconds the voltage across the load remains constant.

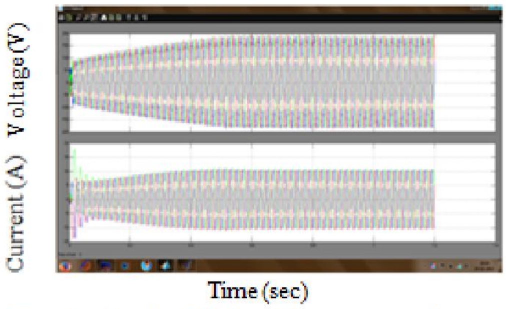

Fig 10 (a): Simulated Voltage & current waveform at output of the inverter under nominal load

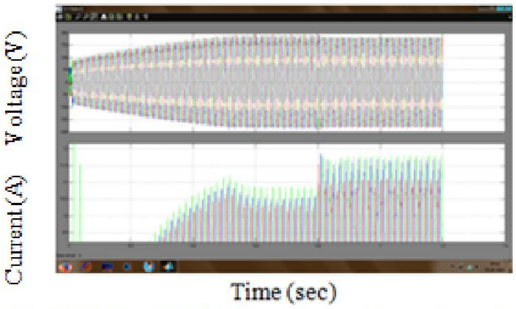

Fig 10 (b): Simulated Voltage & current waveform at output of the inverter under sudden change in load

Conclusion

A simple power electronic controller for interfacing photovoltaic arrays with DC-DC converter has been developed. By applying the pulse width modulation (PWM) control scheme with appropriate MPPT algorithm to the power switches and the DC-DC converter can draw maximum power from photovoltaic array. The Performance of PV/fuel cells hybrid power generation depends on a variety of external and internal operating conditions. Solar radiation and ambient temperature are the external factors. In addition, the fuel cells reactant pressure, temperature, and pressure of electrolyser, as well as the conversion efficiency of the power conversion devices are internal factors. The results obtained from the simulation studies of the proposed scheme are reliable, thus validating the power circuit and control circuits of the inverter. So, the fuzzy logic control is an effective tool to track and extract maximum power to the isolated load. An intelligent fuzzy controller performance, ensure the perspective of matching power to achieve the stable operation in real-time of the PV-Fuel cells hybrid power generation system. The hybrid PV-fuel cells system therefore has higher availability to deliver continuous power and results in a better utilization of power conversion and control equipment than with of the individual sources.

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REFERENCES

Mayssa Farhat and Lassaad Sbita, “Advanced Fuzzy MPPT Control Algorithm for Photovoltaic System”, *Science Academy Transactions on Renewable Energy Systems Engineering and Technology*, 2011, vol. 1, no. 1, pp. 29-36, Mar. 2011.

Tafticht, T., K. Agbossou, M.L. Doumbia, and A. Cheriti, “An Improved Maximum power point tracking method for photovoltaic system”, *Renewable energy*, vol.33, pp. 1508-1516, 2008.

Yun Tiam Tan, Daniel S. Kirschen, and Nicholas Jenkins, “A Model based PV Generation suitable for stability analysis”, *IEEE trans. on energy conv*., vol.19, no.4, pp. 748-755, Dec.2004.

Sullivan, C. R. and M. J. Powers, “A high-efficiency maximum power point tracker for photovoltaic array in a solar-powered race vehicle,” *in Proc. IEEE PESC,* 1993.

Femia, N. “Optimizing Duty-cycle Perturbation of P&O MPPT Technique”, *35th Annual IEEE Power Electronics Specialists Conference.,* 2004.

Koutroulis, E., E, K. Kalaitzakis, and NC. Voulgaris, “Development of a microcontroller based photovoltaic maximum power point tracking control sytem”, *IEEE trans. on Power Electronics,* vol. 16, no. 1, pp. 46-54, 2001.

Abdulhadi Varnham, M. Abdulrahman, Al-Ibrahim, S. Gurvinder, Virk, and Djamel Azzi, “Soft computing model based controllers for increased photovoltaic plant efficiencies”, *IEEE trans. on energy conv*., vol. 22, no. 4, pp. 873-879, Dec. 2007.

Damak1, A., A. Guesmi and A. Mami, “Modeling and fuzzy control of a photovoltaic-assisted watering system,” *Journal of Engineering and Technology Research,* Vol.1, pp. 7-13, 2009.

Krishna Kumar, B., “Matlab based Modelling of Photovoltaic Panels and their Efficient, Utilization for Maximum Power Generation,” *1st National Conference on Intelligent Electrical Systems , NCIES, Salem, India ,* pp. 125- 130, 2009.

Villalva, M.G., J.R. Gazol, and E.R. Filho, “Comprehensive Approach to Modeling and Simulation of Photovoltaic

Arrays", *IEEE trans. on Power Electronics*, vol.24, no.5, pp.1198-1208, May 2009.

Patel, H. and V. Agarwal, “MATLAB based modeling to study the effects of partial shading on PV array characteristics, *IEEE trans. on energy conv*., vol. 23, no.1, pp. 302-310, Mar. 2008.

Li Wei, “Modeling control and simulation of a small Photovoltaic fuel cell hybrid generation system”, *IEEE trans. on energy conv*., Mar 2009.

Timothy, and J. Ross, “Fuzzy logic with engineering applications”, McGraw hill international editions, Electrical engineering series, New York, 1997.

Larbes, C., S.M. Ait Cheikh and T. Obeidi, “Genetic alogorithms optimized fuzzy logic control for the maximum power point tracking in photovoltaic system”, *Renewable Energy.,* vol. 34, no.10, pp. 2093-2100, Oct. 2009.

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