Fuzzy logic controller for the maximum power point tracking in photovoltaic system

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ABSTRACT
This paper presents afuzzy logic controller for maximum power point tracking (MPPT) in photovoltaic system.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.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. The model has been experimentally validated.

General Terms
Photovoltaic Array, DC-DC Boost converter, Fuzzy Logic

Keywords
MPPT converter, Non-linear approach, Chopper, Photovoltaic characteristics

1. 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 [1-2].The output power of a PV array varies according to the sunlight conditions such as solar irradiation, shading and temperature. To obtain maximum power from photovoltaic array, photovoltaic power system usually requires maximum power point tracking (MPPT) controller [3].

Various approaches have been reported to implement MPPT such as perturb and observe (P&O) method [4-5], the incremental conductance method, constant voltage method and short-circuit current method [6]. 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 [7-9].Among the intelligent based methods fuzzy logic 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. Therefore in the present paper, an intelligent control technique using fuzzy logic control associated with a MPPT controller are used to improve energy conversion efficiency of the photovoltaic system. The proposed intelligent fuzzy logic process comprises of expert knowledge which extracts maximum power from a PV module under varying solar irradiation, temperature and load condition. Mathematical modeling of the system and the simulation results using MATLAB / SIMULINK are presented. The fuzzy logic controller based results are compared with the conventional techniques such as P&O and PI controlling methods which validate it merits.An experimental setup of the proposed scheme has been built and the results obtained on a PV arrayof 74.8W, 21.2 V, 4.4A rating is presented.

2. MODEL OF A PV ARRAY

A PV cell can be represented by an equivalent circuit [10]as shown in Fig. 1. The characteristics of this PV cell can be obtained using standard equation (1).

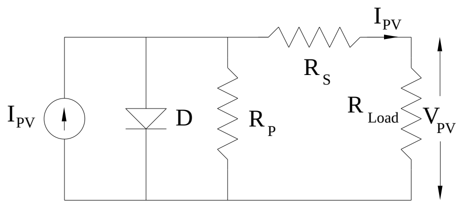


Fig 1: Equivalent circuit of PV cell

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

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. 1 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. 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 [11] given by the equation (2)

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

$I_{PV,n}$ = 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.

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

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)

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

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

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 x 10^{-8}A	K_I	2.80 mA/°C

3. 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 converteris introduced between the PV array and the inverter.The block schematic of the proposed scheme is shown in Fig.2. 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 three-phase, six-step, quasi-square-wave IGBT inverter a three-phase fixed amplitude and fixed frequency supply is obtained to feed an isolated load.

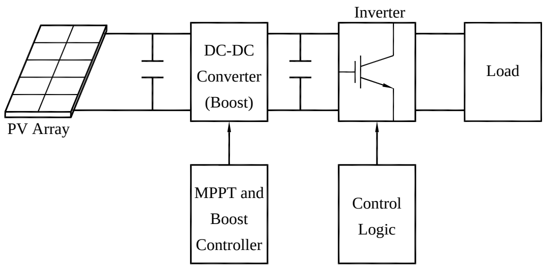


Fig 2: System configuration for PV-based system feeding power to the load

For a dc-dc boost converter, by using the averaging concept, the input–output voltage relationship for continuous conduction mode is given by

$$Vo/Vin = 1/(1 - D) \quad (5)$$

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.

4. 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.3. The two FLC input variables are the error E and change of error CE. The behavior of a FLCdepends on the shape of membership functions of the rule base.

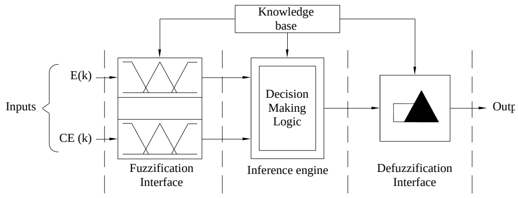


Fig 3: Block of Fuzzy controller

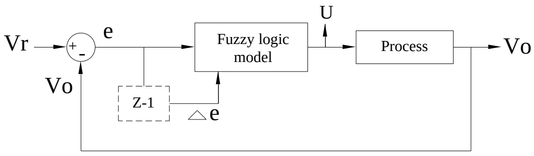


Fig 4: Fuzzy logic control scheme

In this paper a fuzzy logic control scheme (Fig.4) 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 system operation.

4.1 Fuzzification

Themembership 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 signalfor 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.

4.2 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.

4.3 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[12] is used for defuzzification in the proposed scheme.

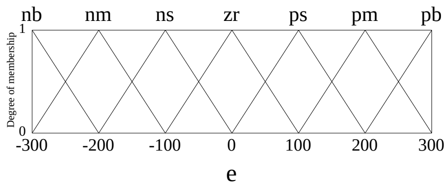


Fig 5 (a): Membership function plots for 'e'

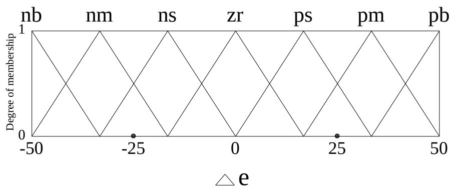


Fig 5(b): Membership function plots for 'Δe'

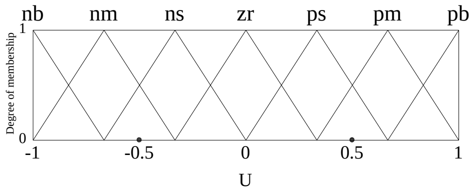


Fig 5(c): Membership function plots for 'U'

Table 2

Fuzzy associative memory for theproposed 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

The membership function of the variables error, change in error and change in reference signal for PWM generator are shown in Fig. 5a-5c respectively.

5. RESULTS AND DISCUSSION

A MATLAB based modeling and simulation scheme (**Appendix**) 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. The fuzzy logic controller based results are compared with the conventional techniques such as P&O and PI controlling methods which validate it merits.

5.1 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.

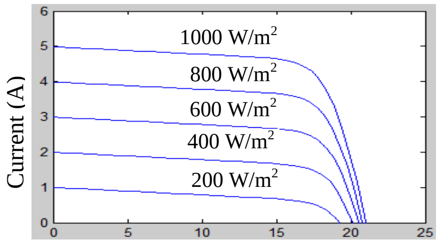


Fig 6(a): I-V Characteristics for different irradiations

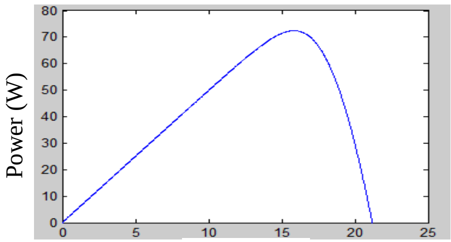


Fig 6(b): P-V Characteristics

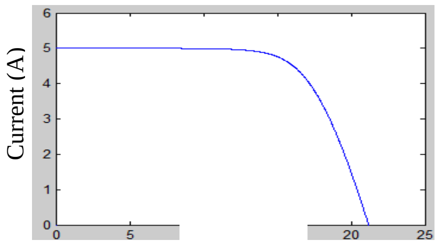


Fig 6(c): I-V Characteristics

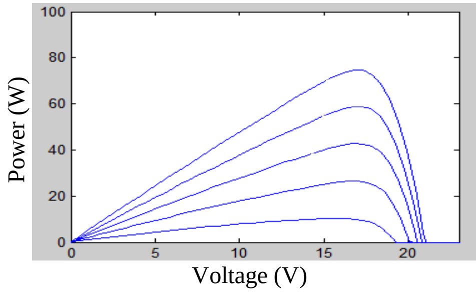


Fig 6(d): P-V Characteristics for different temperature

Fig.6(a)shows *I-V* characteristics of a PV cell. It can be observed that as the cell temperature remain constant, thePV output voltage remains nearly constant while the PV output current increases with increasing solar intensity.

Fig.6(b)& Fig.6(c) shows *P-V*&*I*-V characteristics of a PV cell respectively.

Fig.6(d) shows *P-V* curve plotted for different values of temperature.

5.2 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 [13] from 500 to 1000 W/m^{2}at fixed temperatureof 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 irradianceof 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.

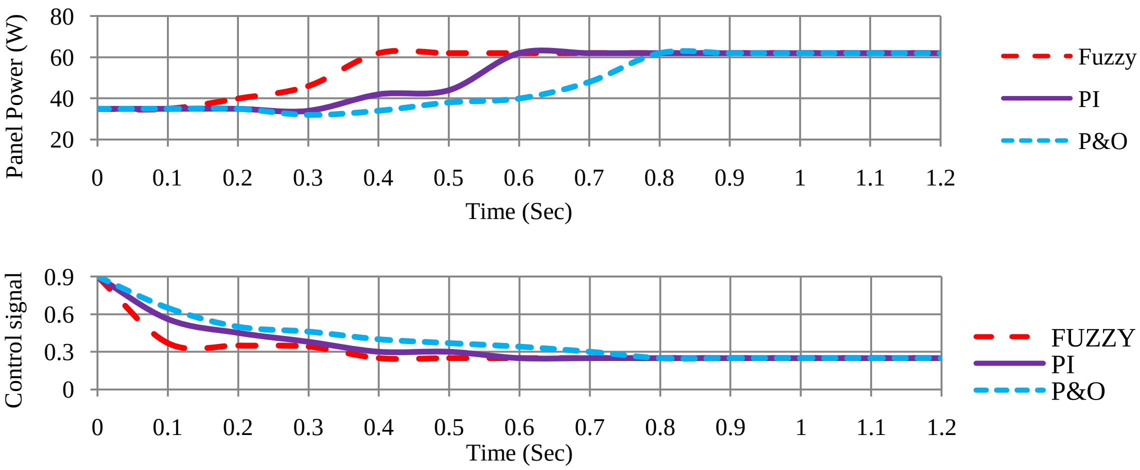


Fig 7: Response of the PV panel for a fast solar irradiance from 500 to 1000W/m^2 at 25°c

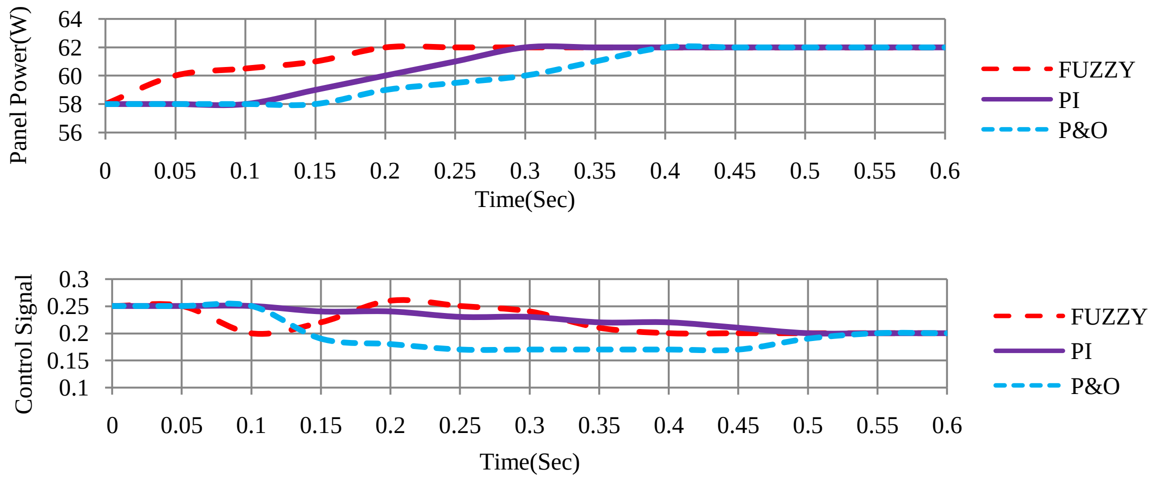


Fig 8: Response of the PV panel for a fast temperature variation from 40°c to 20°c at a solar irradiance of 1000W/m²

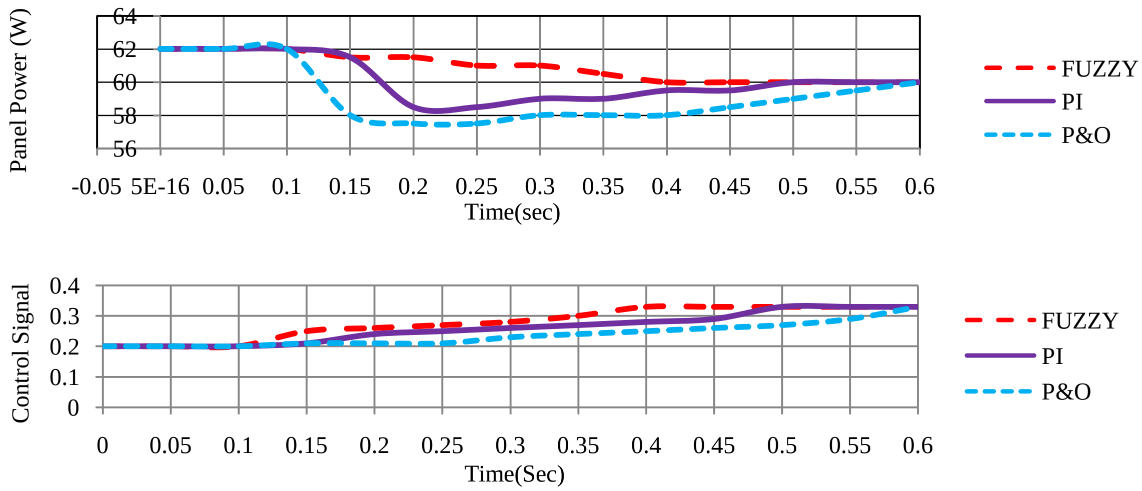


Fig 9: Response of the PV panel for a fast temperature variation from 20°c to 40°c at a solar irradiance of 1000W/m²

6. EXPERIMENTAL INVESTIGATION

The PV array in the proposed scheme shown in Fig.10(b) consist of solar PV array of 74.8W, 21.2V, 4.4A (15 panels connected in series).

A load of 80Ω per-phase was connected in star across the inverter terminals. A DC-DC converter (L=40μH, C=0.025F) was constructed with IGBT (40 A, 600 V) as a switch with a switching frequency of 2 KHz shown in Fig.10 (a). The closed loop firing scheme was employed to trigger the DC-DC converter.A 50Hz, three-phase IGBT inverter was fabricated, and a microcontroller PIC 16F877A was used to trigger the IGBT in 180 degree conduction mode. The above scheme was tested for different conditions of irradiations.

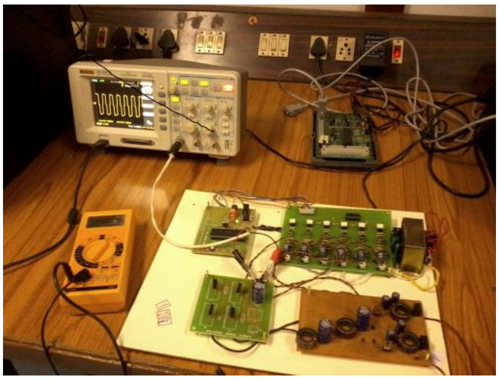


Fig 10(a): DC-DC-Converter - Inverter

Fig 10(b): Solar Panel

The simulated three phase voltage and currentwaveform at the output of the inverter shown in Fig. 11(a).
The simulated current waveform (Fig. 11(b)) shows, even though the load is applied at 0.8 seconds the voltage across the load remains constant.

Current (A)

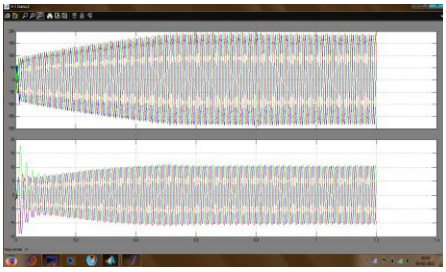
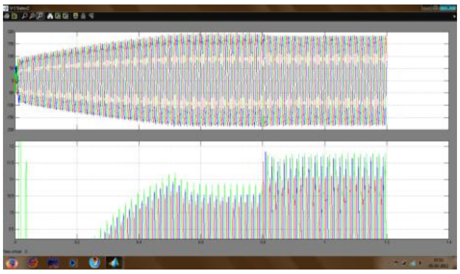


Fig 11(a): Simulated Voltage & current waveform at output of the inverter under nominal load



Time (sec)

Fig 11(b): Simulated Voltage & current waveform at output of the inverter under sudden change in load

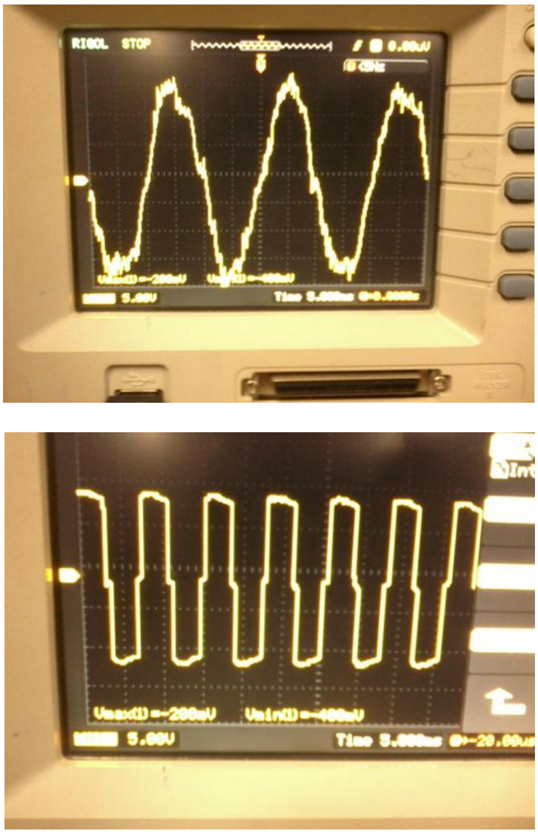


Fig 12: Voltage and current waveform (experimental) (One phase alone shown for clarity)

The experimental voltage and current waveform (one phase alone shown for clarity) at the output of the inverter is shown in Fig. 12. Some harmonics have been introduced in the proposed scheme found in the waveforms it can be eliminated by introducing necessary filters.

7. 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 results obtained from the experimental investigation and simulation studies of the proposed scheme are compared and it has been found that the simulation results closely agree with the experimentally obtained results, thus validating the experimental 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.

8. ACKNOWLEDGEMENT

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APPENDIX

A MATLAB based modeling and simulation scheme along with MPPT and fuzzy logic controller is proposed (Fig. 13) which are suitable for studying the *I-V* and *P-V* characteristics of a PV array under a non-uniform irradiation and different temperature. The configuration of the proposed scheme is simulated under different condition of irradiations (0.4 kW/m^2 to1kW/m^2) in the power system block set platform of the MATLAB. The simulated current waveform (Fig.11(b)) shows, even though sudden change in load is applied at 0.8 seconds the voltage across the load remains constant. In order to achieve the load voltage constant the actual voltage fed to the inverter is compared with the reference maximum voltage that can be obtained at the load for a given V_{oc} and I_{sc}.The error is calculated and accordingly the reference signal to the PWM generator is changed in order to maintain the load voltage constant.

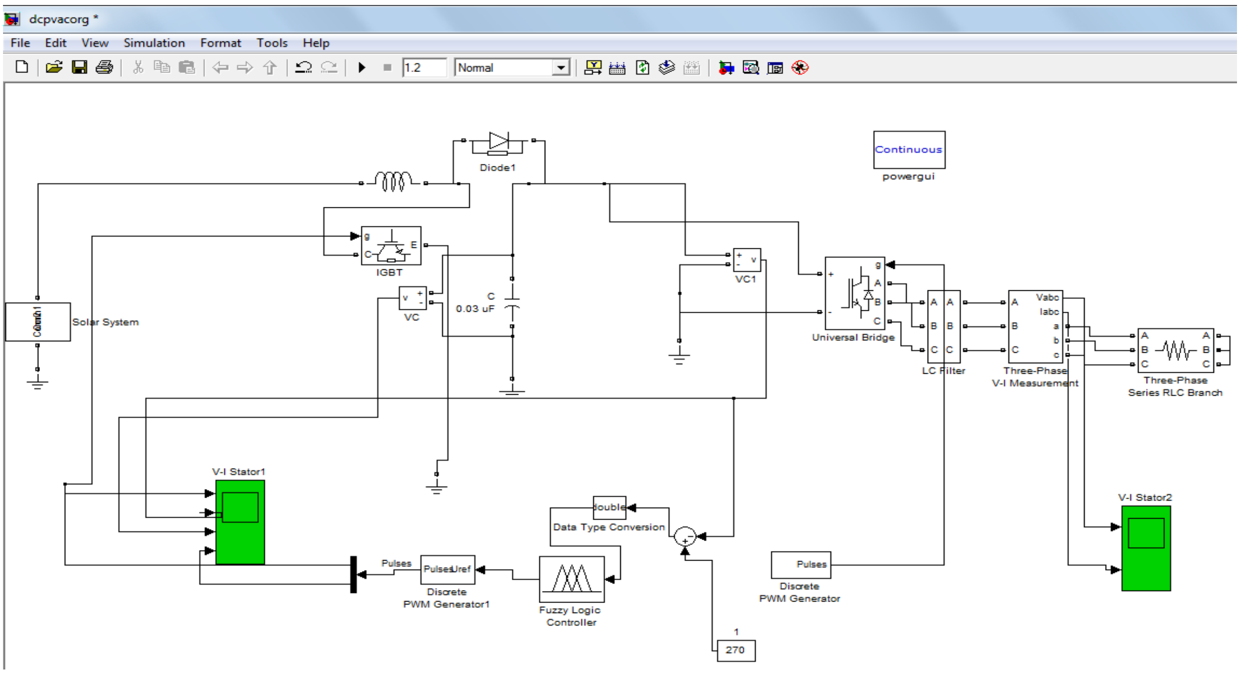

Fig 13: Photovoltaic and MPPT Fuzzy controller implemented in SIMULINK