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Performance Evaluation of Maximum Power Point Tracking Approaches for PV Array under PSC with Differential Converters

K. Mounika, M. Sunil Kumar, J. Ayyappa

Abstract: ***One of the most important issue in the operation of a photovoltaic (PV) system is extracting maximum power from the PV array, especially in the partial shading condition(PSC).In this paper a PV array mathematical model with different MPPT techniques in a standalone model is validated. The characteristics of PV array are highly non-linear as they depend on temperature and irradiation. Therefore it is important to extract the optimum possible power from PV panels with control algorithms. The reduction of total efficiency of PV generation conversion is due to partial shading. PV array along with boost converter and MPPT controller are simulated in MATLAB/Simulink environment. When there are changes in climatic conditions, the parameters of capacitance and inductance of the DC-DC converter will change to attain optimal efficiency. This paper presents different MPPT techniques like Perturb & observe, Incremental conductance, fuzzy logic methods to extract the optimum power from the PV panel. This paper proposes a differential power converter to overcome the PV partial shading problem along with INC control algorithm and fuzzy logic controller.***

Index Terms: ***Maximum Power Point Tracking (MPPT), Perturb & Observe (P&O), Incremental Conductance (INC), Fuzzy Logic Controller, Partial Shading, Differential Power Converter.***

Nomenclature:
Iph, I =photo voltaic & output current,
I0, I0ref = saturation & nominal saturation current,
Vt = thermal voltage,
a = emissivity factor,
Rs = series resistance,
Rsh = shunt resistance,
G,Gref = irradiance & nominal irradiance,
T,Tref = actual and nominal temperature of the cell,
q = change of electron,
k = Boltzmann's constant,
Eg = Energy Band Gap,
Id,Ish = Diode current & current in the shunt resistance

I. INTRODUCTION

In recent years there has been increasing interest in a renewable energy source spatially in photovoltaic (PV) systems. PV Systems can be operated as grid-connected or stand-alone structures. PV array is the main element in a PV system and it is a set of PV modules connected in series and parallel. In a PV array, voltage and current have a nonlinear relation, maximum power is generated only in one operating Voltage. Therefore, our main target is to extracting maximum power from a PV system in all operating conditions. Some of the numerous maximum power point tracking (MPPT) techniques has been presented and implemented. In that, some of the important ones are perturbe and observe (P&O), incremental conductance (IC), and short-circuit current, and open-circuit voltage. Some techniques are also presented based on artificial intelligence, such as fuzzy logic and neural network, but have more computation load [1].

Partial shading condition (PSC) occurs in which the entire modules of an array do not receive the same solar irradiance. PSCs occur especially in solar systems installed in urban areas and in areas where low moving clouds are common [2]. Solar PV systems need to produce reliable, affordable and sustainable energy over the life of the system when it reaches to grid parity [4]. To control the energy obtained from a PV panel power electronic equipment is used which increases the balance of system costs]. The utilization of solar photovoltaic system as residential and Street lighting, electric vehicles, water pumping, military and space applications, refrigeration etc. all in either stand-alone (or) grid-connected configurations. A PV array has a nonlinear power voltage characteristics and VI characteristic under uniform irradiance condition like shown in figure 1(a). The characteristics and efficiencies depend on insulation levels, temperature and load conditions. To eliminate these unfavorable conditions we have an MPP on the solar characteristic curves. Shading occurs when PV panels are connected in series. The total efficiency of PV generation conversion ratio is reduced due to partial shading. This kind of energy waste could bring very serious economic problems considering the high cost of PV investment.

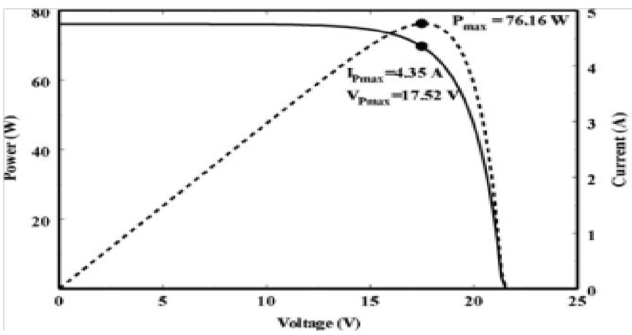

Fig 1 (a): PV Array I-V and P-V Characteristics

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The difference between MPPT system and a mechanical tracking system is that when the panel is placed squarely at the sun then mechanical system is physically oriented, while the MPPT system electronically control the system so it can change the electrical output of the panel in accordance with changes in irradiation or temperature, so that the solar panel is able to get the maximum available power.

When the load resistance (RL) is directly connected to a PV module, at different values of RL, the operating point is varying from A to B as shown in figure 1(b), and there is only one maximum power point(MPP) in that range. This occurs when the load resistance is equal to the optimal value (load resistance at MPP: RL = Ropt).

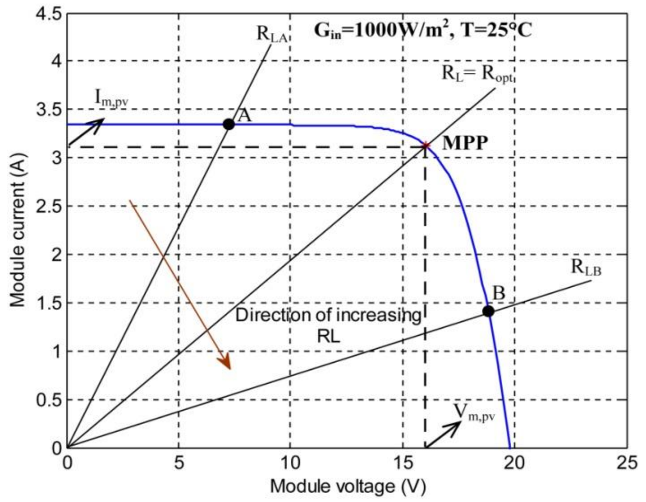

Fig 1(b): Operating Point of a PV Module with Different Resistive Loads

In the source side, we are using a boost converter connected to a solar panel in order to enhance the output voltage. By changing the duty cycle of the buck converter appropriately we can match the source impedance with that of the load impedance. In the literature, many maximum power point tracking systems have been proposed and implemented.

To maintain the operating point of the PV array at MPP, we need a maximum power point tracker (MPPT). The controlling of MPPT is done by different search algorithms depends on the voltage and current of the PV array. Nowadays, the research and development are done in the operations of MPPT techniques in terms of convergent speed, complexity, the effectiveness of the system, Sensors required for measurement and implementation hardware.

The Different MPPT techniques include lookup table methods, P&O methods [3] – [5] and computational methods [6]. This thesis presents a comparison of MPPT techniques like P&O, INC, Constant voltage, Constant current and Fuzzy Logic Control method with boost converter. The proposed differential converter improves the output of the PV panel under Partial shading conditions.

II. SIMULATION OF THE PV SYSTEM

The operation of a solar panel or solar cell is explained by the process of the photovoltaic effect. The theoretical studies give the guidance on losses and solar cell efficiency [8]. In practice, there is no ideal solar cell, so a series and shunt resistance are added to that model. The equivalent circuit is given by,

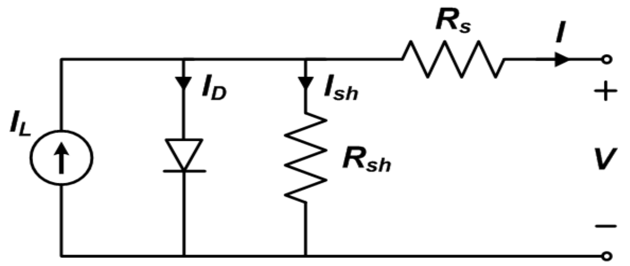

Fig 2: Equivalent Circuit of PV Cell

From the Equivalent circuit, the characteristic equation of the PV cell is

$$I = I_{ph} - I_d - I_{sh} \quad \rightarrow \quad (2.1)$$

By placing all the values of currents, we calculate the current obtained from a PV cell.

Diode current

$$I_d = I_0 * \left(\exp\left(\frac{q*(V_{PV}+I_{PV}*R_S)}{Akt} - 1\right)\right) \quad \rightarrow (2.2)$$

The reverse saturation current, I0 is varied with temperature and expressed by the following equation

$$I_0 = I_{0ref}\left({}^{T}/_{T_{ref}}\right)^3 * \left(\exp\left(\frac{qe_g}{k_\gamma}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right)\right) \rightarrow (2.3)$$

$$I_{0ref} = \frac{I_{SC}}{\exp\left({}^{V_{OC}}/_{a}\right) - 1} \quad \rightarrow (2.4)$$

The photocurrent, Iph depends on the solar radiation (G) and temperature (T)

The equation can be expressed as

$$I_{ph} = \frac{G}{G_{ref}}\left(I_{ref} + \mu(T - T_{ref})\right) \quad \rightarrow (2.5)$$

The current flowing in the shunt resistance is

$$I_{sh} = \frac{V+I*R_s}{R_{sh}} \quad \rightarrow \quad (2.6)$$

By placing the equations 2.2, 2.5 and 2.6 in equation 2.1 we get

$$I = I_{ph} - I_0 * \left(\exp\left(\frac{q*(V_{PV}+I_{PV}*R_s)}{Akt} - 1\right) - \left(\frac{V+I*R_s}{R_{sh}}\right)\right) \quad \rightarrow \quad (2.7)$$

To simulate the PV array from the above equation, the mathematical model contains and Np cells in parallel and Ns cells in series.

Assuming that the solar array has Np equal to 1,

Then the equation is

$$I = I_{ph} - I_0 * \left(\exp\left(\frac{q*(V_{PV}+I_{PV}*R_s)}{AktN_s} - 1\right) - \left(\frac{V+I*R_s}{R_{sh}}\right)\right) \quad \rightarrow (2.8)$$

The power of the PV array is calculated as follows

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$$P = V * I \quad \rightarrow \quad (2.9)$$

The specifications are shown in table 1

Table 1: Specifications of the PV Array

AT TEMPERATURE=25°C		
Open Circuit Voltage	V_{OC}	21.0V
Short Circuit Current	I_{SC}	3.74A
Voltage At Maximum Power	V_m	17.1V
Current At Max Power	I_m	3.5A
Maximum Power	P_m	60W

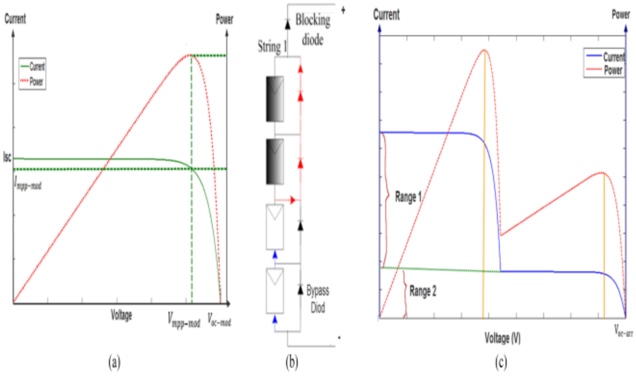

Fig:2(a) P–V and I–V characteristics of a typical PV module. (b) Structure of a sample shaded string. (c) P–V and I–V characteristics of the shaded string.

A. Partially Shaded Condition

For simplicity, it is initially supposed that the array under PSC is subjected to two different irradiance levels. Modules that receive high irradiance level (*HS*) are called isolated modules and those which receive lower irradiance level (*LS*) are named shaded modules.

The isolated modules of a string drive the string current. Therefore, a portion of the string current that is greater than the generated current of shaded modules passes through a parallel resistance of the shaded modules and generates a negative voltage across them. Thus, the shaded modules consume power instead of generating it. In this condition, not only the overall efficiency drops but also the shaded modules may be damaged due to hot spots. To prevent this condition, a bypass diode is connected in parallel to each module, to let the extra current of the string pass through it. Consequently, the voltage across that module will be about −0.7 V and the efficiency of the string will improve. The structure of a sample shaded array is shown in Fig. 2(b).Further details about the modeling of the array in PSC are given in[3]–[24].

III. BOOST CONVERTER

MPPT has basically a load matching problem. In order to change the input resistance of the panel to match the load resistance (by varying the duty cycle), a DC to DC converter is required [9]. The converter can operate in two distinct modes of operation, the continuous conduction operation (CCO) or the discontinuous conduction operation (DCO). The CCO occurs when the inductance current is always greater than zero and is preferred for high efficiency.

The DCO is not preferred since the dynamic order of the converter is reduced [9-10]. The design optimization is based on two principles:

1) For a steady-state operation in a continuous conduction mode, the inductance value for all choppers must be greater than the maximum value of boundary inductance.

2) In order to limit the output voltage ripple of DC-DC converter below the desired value, the filter capacitance must be larger than the maximum value of boundary capacitance

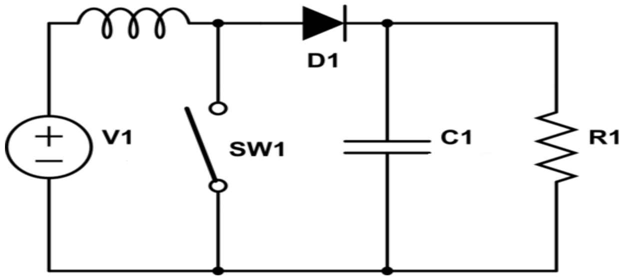

Fig 3: Boost Converter

Table 2: Characteristic Parameters of Boost Converter

Parameters	Boost converter
A_V	$^{1}/_{1-\alpha}$
A_i	$1-\alpha$
R_{in}	$(1-\alpha)^2 R_l$
L_{bo}	$(1-\alpha)^2 \alpha R_l / 2f$
C_{bo}	$^{\alpha V_o}/_{\Delta V_o R_l f}$

IV. MPPT TECHNIQUES

A. MPPT by P&O Method:

Perturb and observe method is one of the hill climbing method based on the voltage power characteristics of the PV array. This algorithm is mostly used for PV systems because of its low complicatedness and easy to implement.

The power drawn from the PV array is examined by changing the direction of operating voltage. If it increases then the module voltage is further increased in the same direction, if it decreases the direction of voltage module perturbation is reversed. The flowchart of the P&O method is shown in figure 3(a)

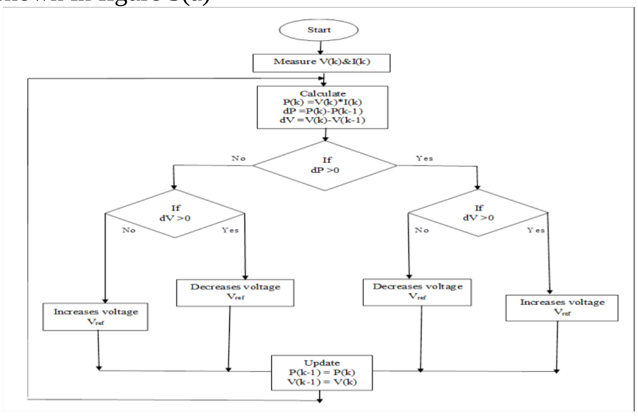

Fig 3(a): Flow Chart of P&O Algorithm

The main disadvantages of this algorithm are oscillations occurred around MPP under steady-state conditions and poor tracking capacity under swiftly changing irradiations.

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B. MPPT by Incremental Conductance Algorithm:

Incremental conductance algorithm is also a hill climbing method similar to that of a P&O algorithm. This method is more efficient than the P&O algorithm in terms of tracking the maximum power point of the PV array correctly.

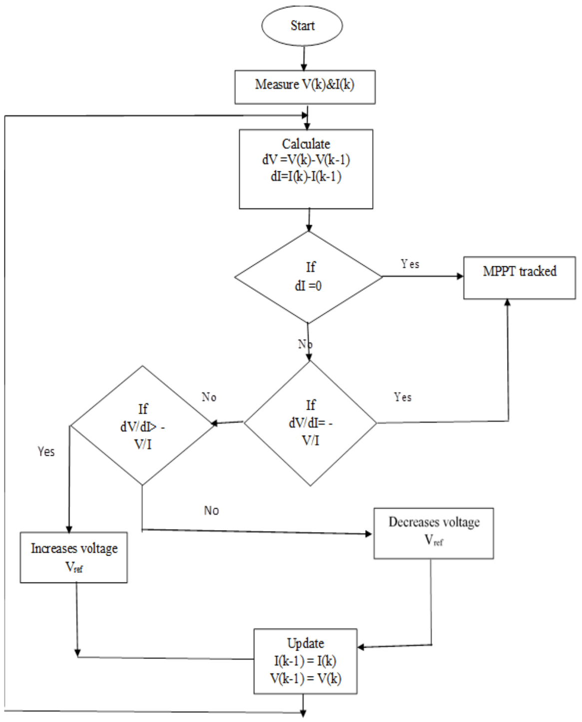
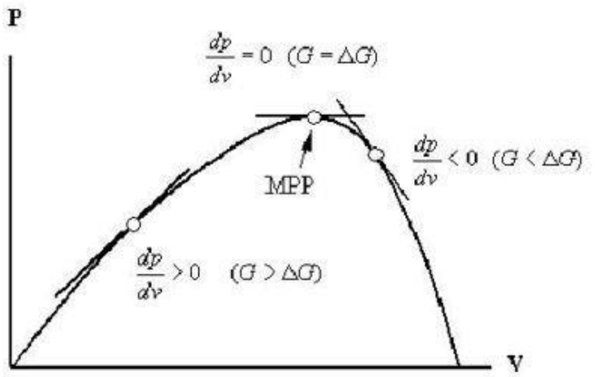


Fig 3(b): Flow Chart of Incremental Conductance Algorithm

This algorithm has a concession between maximum efficiency and reliability of tracking MPP. The flowchart for INC is shown in figure 3(b).

This method uses conductance for searching the maximum power point (MPP). The output voltage and current from the PV array are sensed and the MPPT controller leans to calculate the conductance and incremental conductance. By comparing both, make its decision to increase (or) decrease the module voltage.



The slope of the power vs voltage (current) characteristics of the PV module is zero at MPP, negative (+ve) on the right of it, and positive (-ve) on the left of it as shown in the above figure.

The incremental conductance method is processed by using MATLAB simulation. The oscillations around the MPP are eliminated by this method.

C. MPPT by Fuzzy Logic Controller:

The fuzzy logic controller does not require the knowledge of the exact model. It is robust and relatively simple [12]. The proposed MPPT fuzzy logic controller is shown in figure 3(c) with 2 inputs and 1 output.

The input variables are defined by

$$E = \frac{P(K) - P(K-1)}{I(K) - I(K-1)}$$

$$CE = V(K) - V(K-1)$$

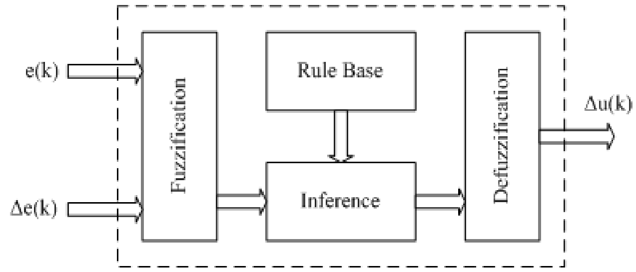


Fig 3(C): General Diagram of Fuzzy Controller

The membership function of inputs is shown in figure 3(D) and figure 3(E).

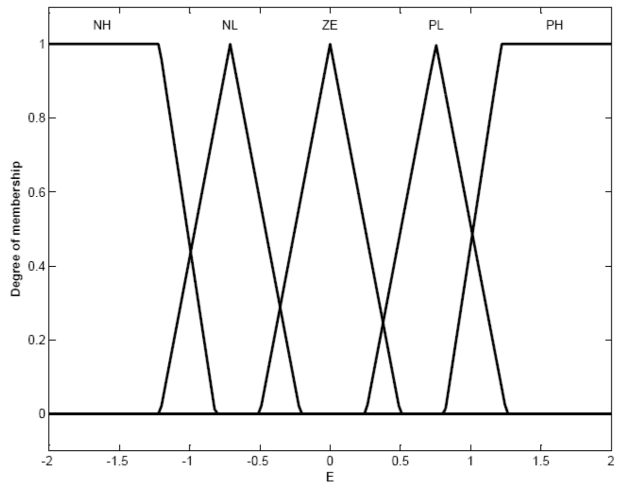


Fig3 (D): Membership Function of An Error

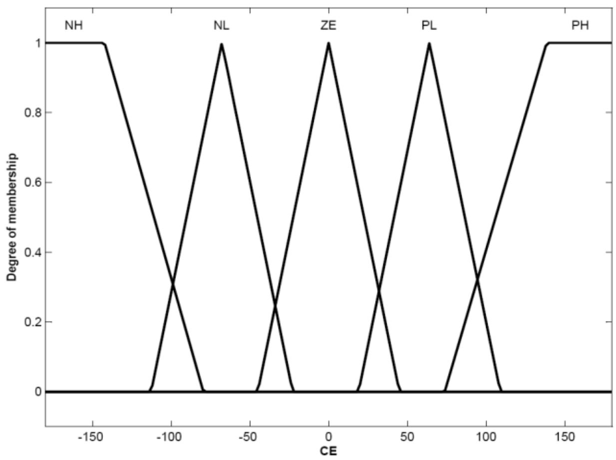


Fig 3(E): Membership Function of Change in Error

The duty cycle is calculated from the change in duty cycle from the equation:

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Duty cycle D = dD + dD (k-1)

Where dD is the change in duty cycle. Fig 3(a) illustrates the fuzzy set of change in duty cycle output which contains triangular membership functions.

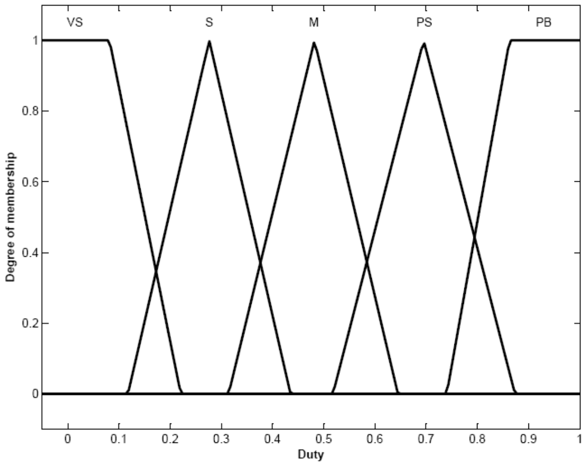

Fig 3 (F): Membership Function of the Change in Duty Cycle

Table 3: Rules for the Proposed FLC

E \ CE	NH	NL	ZE	PL	PH
NH	PS	PB	PB	PS	M
NL	S	PS	PB	PB	PB
ZE	PB	M	M	M	S
PL	VS	S	S	PB	PB
PH	VS	VS	PB	PB	PB

V.OPEN-LOOP CONTROL OF BOOST CONVERTER IN THE PV SYSTEM

The main role of dc/dc boost converter is to absorb power from the PV array by controlling its voltage. Boost converter has two control approaches for regulation of a PV array; i.e., close-loop and open loop controls. It shows that in a PV array Connected to the boost converter, the worst case from stability and dynamic response points of view occurs when the array operates in the constant current region and low irradiance level, negative value occurs when the dynamic resistance of the array.. Due to dependency of the system dynamic response to the operating point and environmental conditions, it is not possible to control the array voltage in closed-loop fashion using a single-loop PI voltage controller properly, and another inner control loop is required (boost converter inductor current loop)to reach desired dynamic response of the system (high-speed,low-transient, and zero steady-state error). This two-loop control method needs two PI controllers and an expensive current sensor. In contrast, in open-loop control, which is a common method for boost converters control, there is no feedback, and the appropriate input voltage is generated considering the relation between the input voltage (v_{in}) and output voltage (v_o) of the converter as in (4)

$$\mathbf{vin = vpv = (1 - D)vo}$$

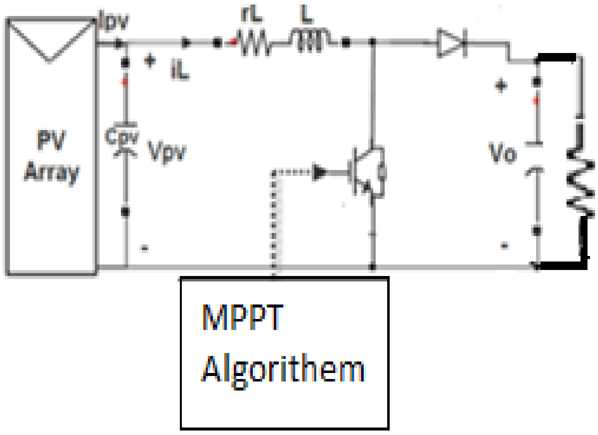

Fig 4: Overview PV System Structure

VI. SIMULINK REPRESENTATION AND RESULTS

In order to access the implementation of all algorithms, a PV module with a maximum output power 60W, short circuit current 3.74AMP and open circuit voltage 21.1V under standard temperature and irradiance conditions was simulated using MATLAB. The basic representation of a simulation diagram is shown in figure 5.

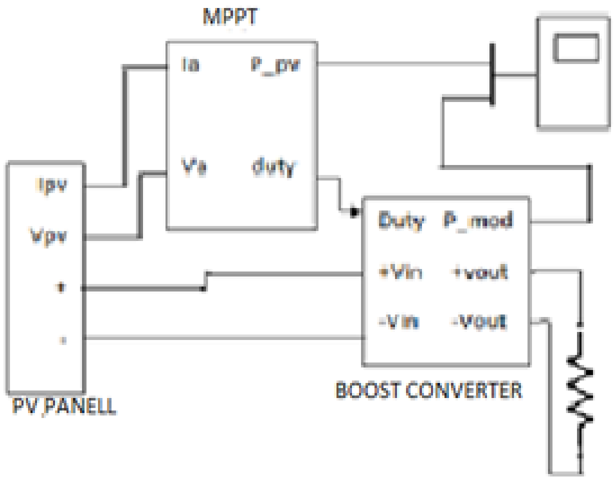

Fig 5: Basic Simulink Representation

Table 4: Pmax at Constant Irradiation for Different MPPT Techniques

AT irradiation=1000W/m^2		
MPPT technique	**Maximum power obtained**	**Settling time**
P&O algorithm	**65**	**0.5**
INC algorithm	**78**	**0.4**
Fuzzy logic controller	**81**	**0.35**

At constant temperature and constant irradiation, the maximum power obtained for different MPPT techniques is shown in table 3. Figures 5(a), 5(b),5(c) shows the PV array output power, output voltage& output current with respect to change in irradiations.

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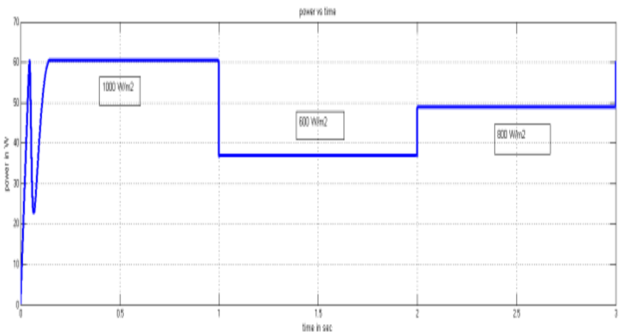


Fig 5 (a): PV Panel Output Power at Various Irradiations

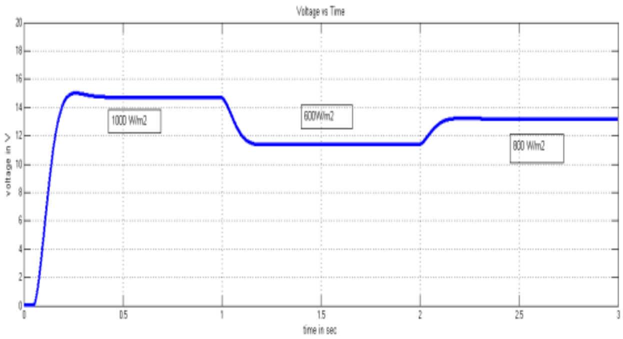


Fig 5(b): PV Panel Output Voltage at Various Irradiations

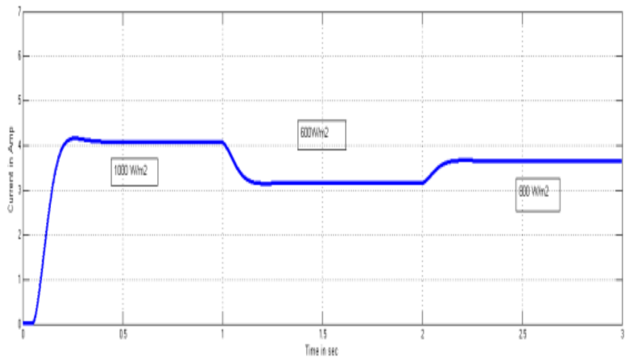


Fig 5(c) PV Panel Output Current at Various Irradiations

Figure:6 shows the comparison of converter output power with various MPPT techniques at various irradiations.

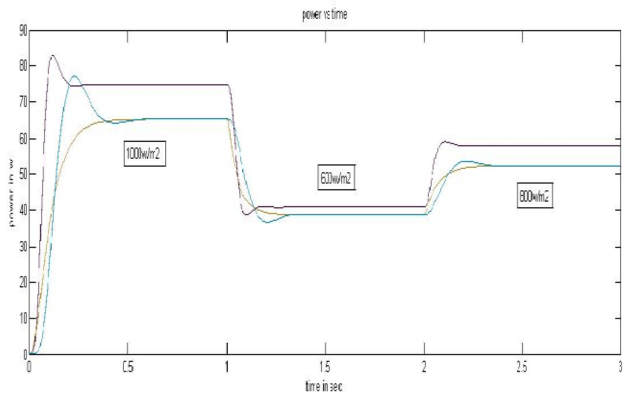
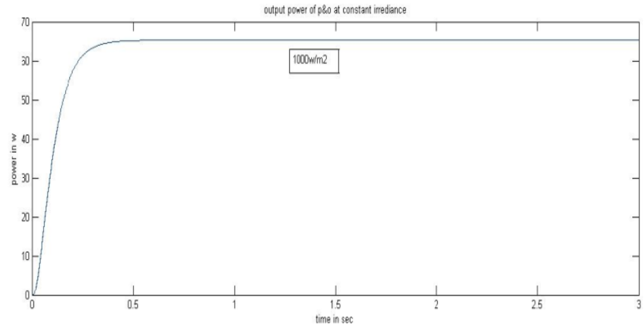
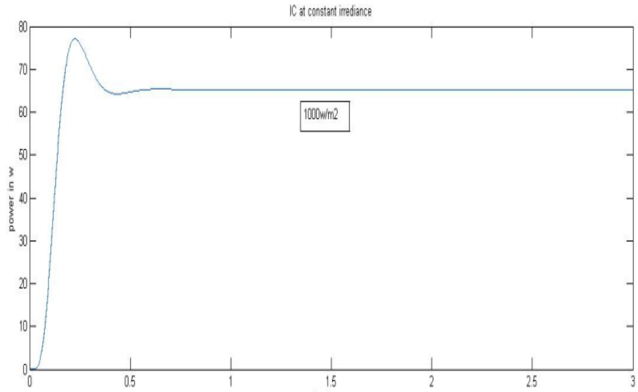


Fig 6: Converter Output Power with Different MPPT Techniques at Various Irradiations

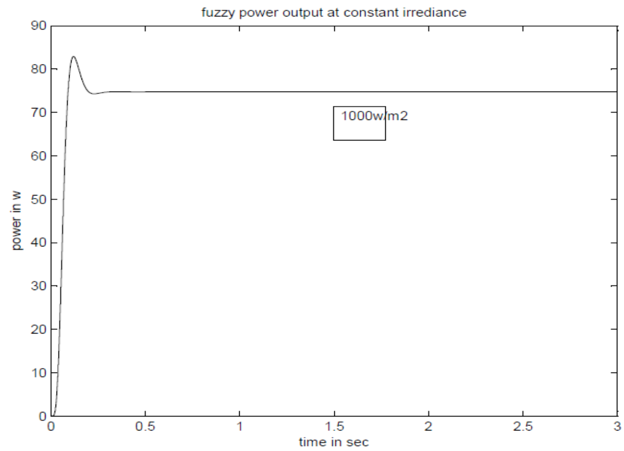
Fig 7(a),7(b)and7(c) shows the power output's of P&O,IC and FUZZY at constant irradiations



7 (a). P&O at Constant Irradiation

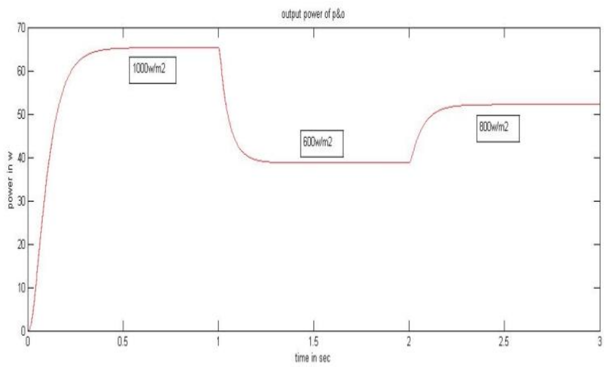


7 (b). IC at Constant Irradiation

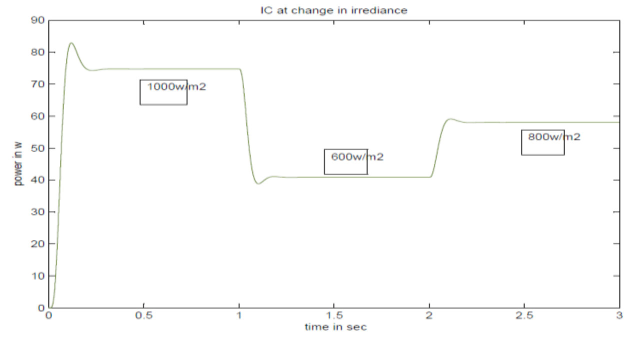


7 (c). FUZZY at the Constant Irradiation

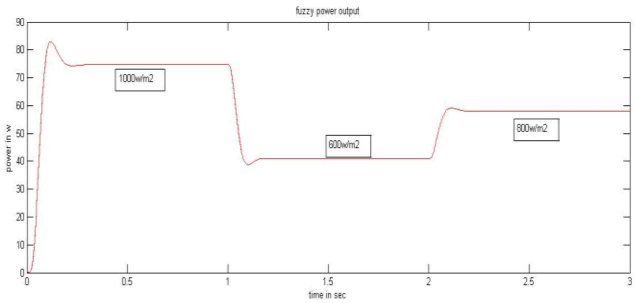
Fig 8(a),8(b)and8(c) shows the power output's of P&O, IC, and FUZZY at various irradiations



8 (a). P&O Output Power at Various Irradiations



8 (b). IC Output Power at Various Irradiations



8 (c). Fuzzy Output Power at Various Irradiations

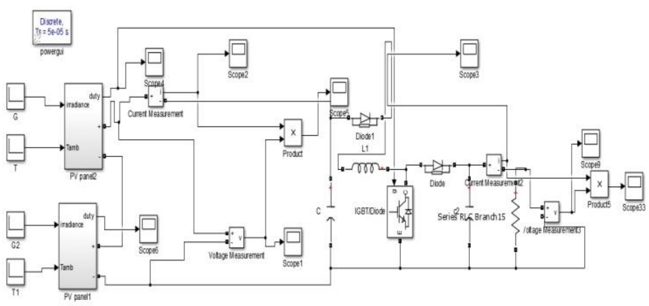
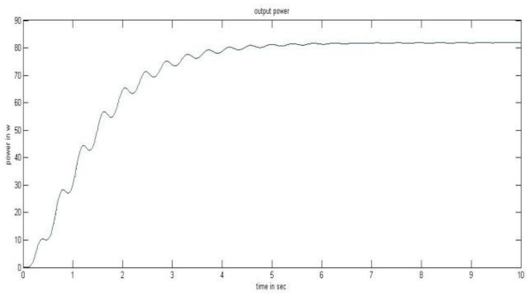
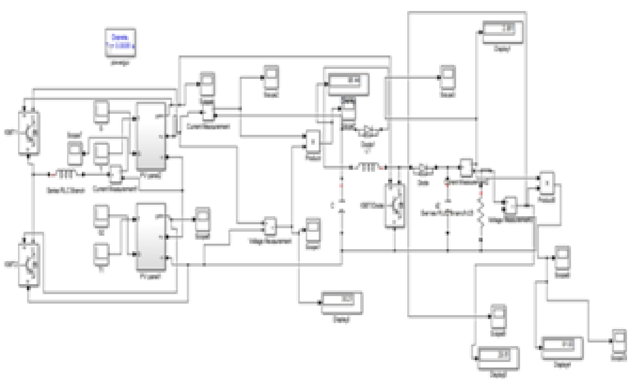


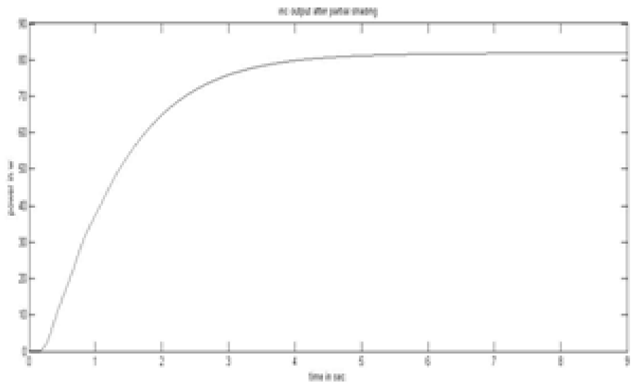
Fig 9(a): Simulation Diagram of Series PV Modules Under Partial Shading



9 (b). Output Power of series PV Panels Using Fuzzy Logic Controller under Partial Shading



10(a). Simulation Diagram of series PV Modules with Differential Converters under Partial Shading



10(b). Output Power of series PV Panels with Differential Converters under Partial Shading

VII. CONCLUSION

This paper authorized the simulation model of the Maximum Power Point of photovoltaic array based on MATLAB/Simulink for different MPPT techniques with different light intensities and comparisons are given. From the results pertain to power efficiency; INC and fuzzy method could accommodate a better tracking of MPP with high speed of convergence than other techniques. It produces fewer oscillations around the MPP and reduces power loss. The differential power converter with the INC method and FUZZY gives the best solution for partial shading problem. Tracking step value has a considerable effect on the effectiveness of MPPT algorithms. So in the future research, the self-adaptive step size needs to be further optimized in order to reduce the oscillation amplitude of output current and output voltage.

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