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Improved Solar Photovoltaic Array Model with FLC Based Maximum Power Point Tracking

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ABSTRACT

This paper presents an improved model of solar photovoltaic (PV) array along with the implementation of fuzzy logic as maximum power point tracking (MPPT). The proposed PV array behavioral model is more accurate and with reduced complexity though considered discrete components. The PV array model was well verified by considering the effect of change of environmental conditions, mainly intensity of solar irradiation (insolation) and temperature. The model was tested by feed a single phase inverter. MPPT control the operating voltage of PV arrays in order to maximize their power output as a result maximize the array efficiency and minimize the overall system cost. Using a Fuzzy logic based algorithm, the duty cycle of the converter inserted between source and load is adjusted continuously to track the MPP and compared with the conventional perturb and observed (P&O) method for changing environmental conditions. It was found that the Fuzzy logic based method can track the MPP more precisely and rapidly than the conventional one. In P&O method, if step size of input variable is very small, the accuracy in tracking MPP is sufficient but tracking speed becomes too slow. On the other hand if the step size is increased to imitate the rapidly changing weather conditions, accuracy deteriorates and unexpected results occur due to oscillation around a mean point although tracking speed increased. But in the case of proposed FLC whatever the step size of input variable it best suited to track MPP continuously and accurately. The obtained simulation results validate the competent of the solar PV array model as well as the fuzzy controller.

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1. INTRODUCTION

Energy is one of the most indispensable parts for our living being in the world. Access to energy plays a crucial role in accelerating economic growth and development activities of a country. However the existing power plants and utility grid is not able to cover the demand fully. Moreover the extreme use of fossil fuels produces harmful gases which tempted to destroy the natural ecosystem and trigger the environment pollution. Huge emission of carbon dioxide is going to destroy the ozone layer of the universe as a result global warming is threat to all. On the other hand, adequate photon energy (sunshine) which is available on the earth surface throughout the year. Solar energy in a single day is sufficient for the entire inhabitant of the earth. Photovoltaic renewable energy system may be one of the promising solutions to ease the existing energy crisis considerably in the world if it is avail in a sustainable manner. Photovoltaic power generation using solar cells that can convert solar light energy directly to DC electricity promises to be a clean, widely applicable renewable energy source. Sustainable growth of photovoltaic power generation is also reducing dependence and pressure on fossil fuel significantly. Researchers have shown great interest on photovoltaic (PV) systems and technology over the past decades. Advancement in cell efficiency and system reliability has given wide acceptance of PV technology for both standalone and grid interactive power generation. According to the renewable energy unit of European Commission [1], the capacity of installed grid connected PV grew at an average rate of 37% per year over the past decade. Figure (1) best depicted the scenario exponential escalation of worldwide PV installation.

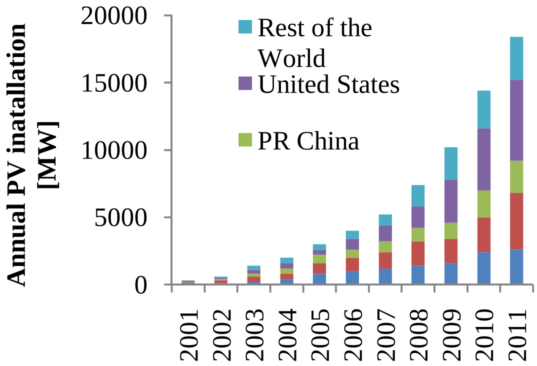

Figure 1. Grid Connected Photovoltaic Installations

At the end of 2010, the installed capacity in the USA was nearly 11,000 megawatts (MW) and the worldwide installed capacity was over 16,000 MW. Photovoltaic renewable energy is recognized worldwide as a cost-effective, environmentally friendly solution to energy shortages. The output current versus voltage curve of PV cell shows a non-linear I-V characteristic that depends on environmental conditions such as solar insolation and temperature. The presented work here is the continuation and extended version of our previous works [2]-[4]. The proposed PV array behavioral model is more accurate and with reduced complexity though considers every discrete components of a cell. In the current-voltage characteristic curve of a solar array, there is a certain operating point at which the PV array produces maximum power which is known as maximum power point (MPP). Therefore, to maximize the PV array output power at any insolation and temperature, maximum power point tracking (MPPT) is used in the PV system. Usually a DC-DC converter is used for this purpose. The maximum power theory is based on impedance matching. By adjusting the duty cycle of the converter, the equivalent load impedance as seen by the PV source is matched with its own impedance. Using an appropriate MPPT algorithm, the duty cycle of the converter is adjusted continuously to track the MPP. Several MPPT methods have been summarized in the literatures [5], [6]. The methods vary in complexity, sensors required, tracking efficiency, convergence speed, cost, range of effectiveness, implementation hardware, popularity, and in other respects. Some of the well-known techniques are perturb & observed (P&O), incremental conductance, constant current, Fuzzy based algorithms. Among them P&O algorithm is most popular and frequently used due to their fast tracking speed and ease of implementation. In this method the operating point is perturbed and then the system response is measured to determine the direction of the next perturbation. This process is repeated till the system reaches MPP. One of the drawbacks of this method is that it fails to track MPP under rapidly variation in insolation and environmental conditions [7]. This happens when the change in power due to atmospheric conditions is larger than the changes due to perturbation invoked by the algorithm [8]. In a nutshell, in fast changing environment these conventional MPPT methods face a great deal of difficulty to track the actual MPP. To overcome the difficulties of commonly used MPPT methods a unique and improved fuzzy logic control based method is proposed. The proposed controller can track the MPP not only accurately but also its dynamic response is very fast in response to the change of environmental parameters in comparison with the aforementioned conventional MPPT algorithms.

2. SOLAR PHOTOVOLTAIC CELL MODEL

The basic element of the photovoltaic module is the solar cell which usually an illuminated p-n junction diode to produce electricity by photovoltaic effect. Being exposed to the sunlight, photons with energy greater than the band-gap energy is being absorbed by the p-n junction and some electron-hole pairs are created in the vicinity of junction. Under the influence of the built-in internal electric field E of the p- n junction, the positively charged holes accelerate in the direction of the electric field and the negatively charged electrons in the direction opposite to the electric field [9]. Now if the both terminal of the cell is connected by a load the charge particles carriers are swept across the junction and create a photocurrent which is directly proportional to solar insolation. Usually available open circuit voltage and short circuit current from a single cell is 0.5V and 2.35A respectively. Due to this low voltage and current of an individual solar cell, several cells are wired series/parallel to get an appropriate current and voltage for a certain application thus making a photovoltaic module or solar panel. Modules may then be strung together into a photovoltaic array. This whole mechanism is best depicted as in Figure (2).

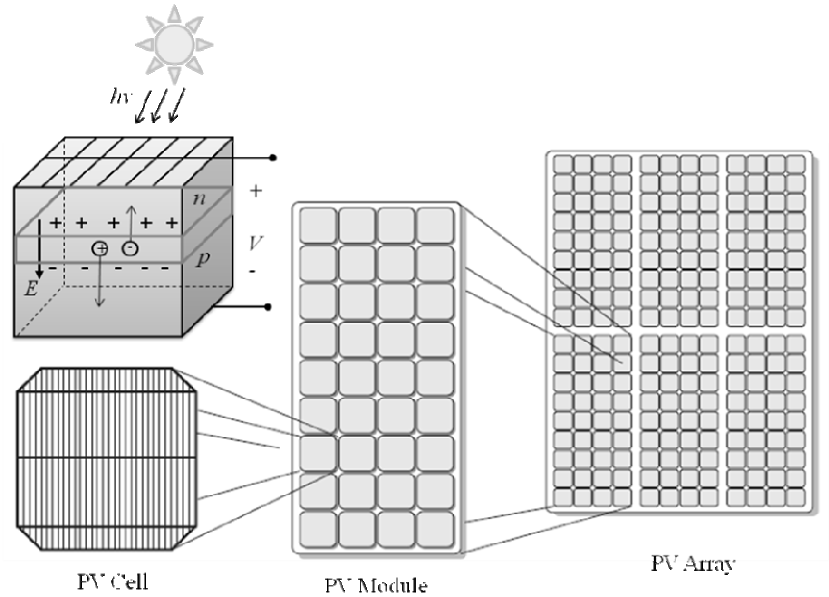

Figure 2. A typical structure of solar PV cell, module and array.

2.1. Cell characteristic equations

An ideal solar cell may be modeled by a current source connected in parallel with a diode; the current source represents the generated photocurrent when the sunlight hits on the surface of the solar panel, and the diode represents the p-n transition area of the solar cell. According to [10], no solar cell is ideal and a shunt resistance, (R_{sh}) and a series resistance, (R_s) components are added to the model according to its behavior as shown in Figure (2) of the equivalent circuit of the solar PV cell.

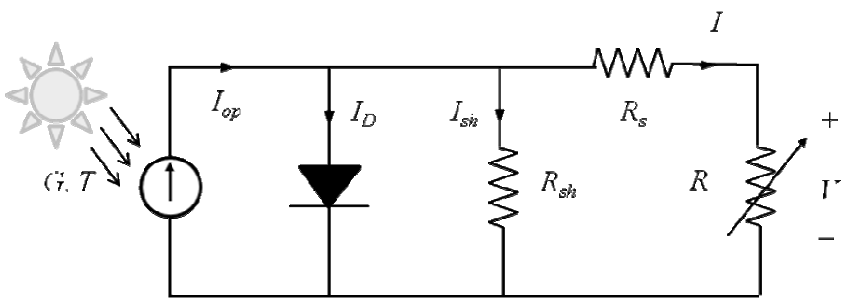

Figure 3. Equivalent circuit of a solar cell consisting of discrete electrical components.

From the above electrical equivalent circuit of the solar cell, it is evident that the, (V) is the voltage across the load resistance, (R) and the current (I) which is flowing through this load can be written as equation:

$$I = I_{op} - I_D - I_{sh} \qquad (1)$$

Where I_{op} light generated current, I_D is the diode current I_{sh} is the current which is shunted through the resistor R_{sh}.

By the Shockley diode equation [11], [12], the current diverted through the diode is given by the following equation

$$I_D = I_0\left[\exp\left(\frac{q(V + IR_s)}{nkT}\right) - 1\right] \qquad (2)$$

Here T is the absolute temperature in Kelvin. q is the charge of a electron, k is the Boltzmann's constant, n is the diode ideality factor which depends on the certain PV technology and I is the reverse saturation current in amperes. Substituting these into the equation (1), produces the characteristic equation (3), of a typical solar cell, this relates solar cell parameters to the output current and voltage.

$$I = I_{op} - I_0\left[\exp\left(\frac{q(V + IR_s)}{nkT}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \qquad (3)$$

Sometimes, to simplify the model, the effect of the R_{sh} is not considered, that is R_{sh} is infinite, so the expression of (3), simplify to as the following equation

$$I = I_{op} - I_0\left[\exp\left(\frac{q(V + IR_s)}{nkT}\right) - 1\right] \qquad (4)$$

Two important points of the current-voltage characteristic must be pointed out. First one is the open circuit voltage, (V_{oc}) and the second one is the short circuit current (I_{sc}). The other other two points such as voltage (V_{mp}) and current (I_{mp}) at maximum power point (MPP). All of these are as indicated in Fig. (4). At both points the power generated from cell is zero. V_{oc} can be approximated from equation (4) when the output terminal of the solar cell is merely open, as a result no current flow through the load. The short circuit current I_{sc} of equation (4) is the current when intuitively the terminals of the solar cell is solidly connected by a wire of zero resistance. Practically short circuit current is approximately equal to the light generated current that is

$$I_{sc} \approx I_L \,.$$

$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_{op}}{I_0} + 1\right) \qquad (5)$$

A PV array is composed of many solar cells, which are connected in series and/or parallel so the output current and voltage would be high enough for a certain application.Taking into account the simplification mentioned in above equation of (4), the output current-voltage characteristic of a PV array is expressed by equation (6), where, N_p *and* N_s are the number of solar cells in parallel and series respectively.

$$I = N_p I_{op} - N_p I_0\left[\exp\left(\frac{q(V + IR_s)}{nkTN_s}\right) - 1\right] \qquad (6)$$

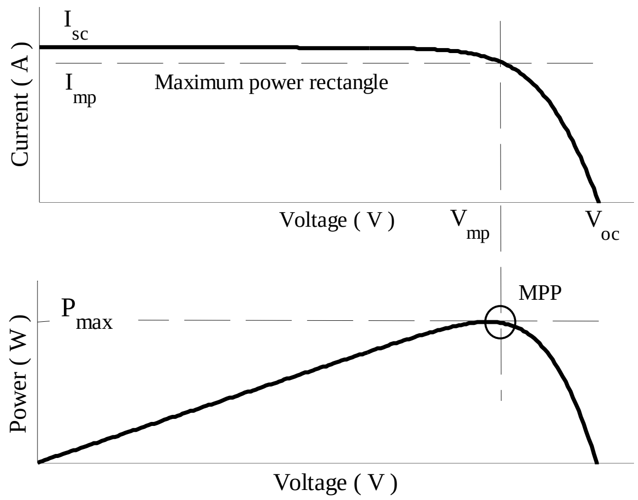

Figure 4. Typical I-V and P-V characteristic and location of V_{oc}, I_{sc}, I_{mp}, V_{mp}, P_{max} and MPP

2.2. Model validation

There are four factors that affect the characteristics of solar panel, among them the less dominant factors are the shunt resistance, (R_{sh}) and the series resistance, (R_s). The rest of the most dominant environmental factors which are the temperature and insolation are strongly affecting the electrical characteristics of solar cell. There are severals approaches to PV array model in the literatures [13]-[18]. Average circuit based model has been proposed here. Changing effect of the first two factors has ignored and the later two factors have considered in the development of PV array simulink model in Matlab/Simulink platform [19]. Electrical specification of a 100 Watt STF100P6PV module [20] has been taken. The module is available in the renewable energy laboratory of the EEE department in CUET. Electrical specifications are summarized in Table (1). The model is developed in masked subsystem form with several stages. For example the simulink masked subsystem of light generated current for a single cell is given in Figure (5). The complete PV array model consisting of 36 cells is shown in Figure (6). Both R_{sh} and R_p are calculated in the initialization option of the masked subsystem. This initialization is carried out every time at the starting of simulation.

Table 1. Electrical specifications for the test PV module

Parameters	Specification
Maximum power (Pm)	100 W
Open circuit voltage (Voc)	21.5 V
Short circuit current (Isc)	6.22 A
Voltage at maximum power (Vm)	17.30 V
Current at maximum power (Im)	5.8 A
Short-circuit current temp coefficient	6.928 mA/ ˚C
Open-circuit voltage temp coefficient	-0.068 V/ ˚C
Module size	36 Cells (4×9) each of 156 mm^2

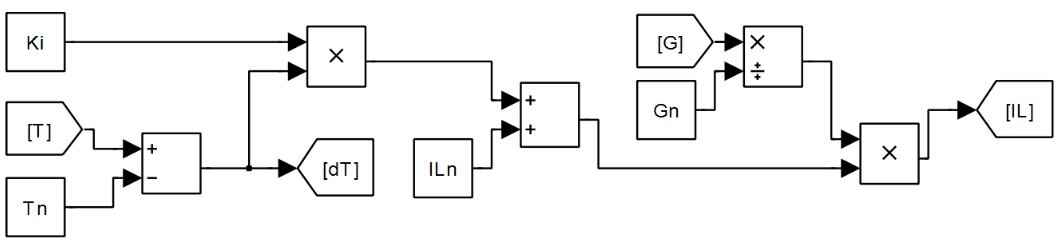

Figure 5. Masked subsystem of light generated currnt for a single cell

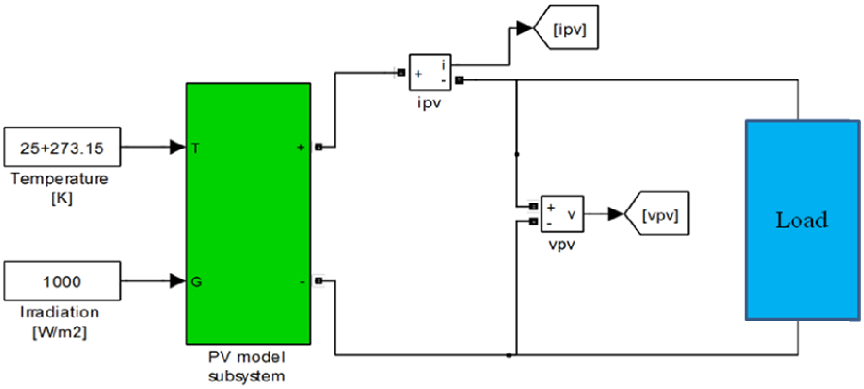

Figure 6. Simulink model of PV array

2.3. Solar insolation and temperature effects

The effect of the intensity of solar irradiance on the voltage-current (V-I) and voltage-power (V-P) characteristics of STF100P6 solar panel, under various insolations level is best depicted in Figure (7) and in Figure (8) respectively. From these figure it is clear that under higher insolation, the PV cell produces higher output currents as well as power because of the light generated current is proportionally generated by the flux of photons. The maximum power point (MPP) decreases with decreasing insolation and this is indicated on each (V-P) curve.

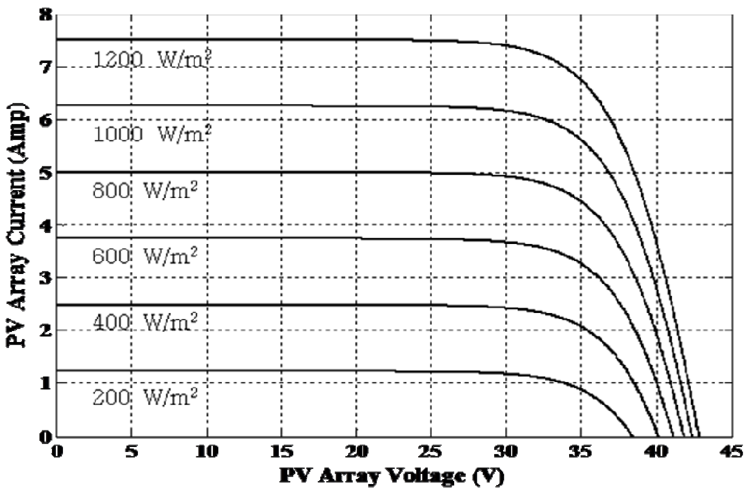

Figure 7. I-V characteristics of the solar PV array due to change in insolation at 25°C

In (I-V) characteristic curve of Figure (9) it is evident that as the cell temperature increases, the overall voltage range of the cell is decreases as a consequence the maximum power point (MPP) decreases and this is indicated on each (V-P) curve of Figure (10). Since decreasing either currents or voltages reduces output power, lower temperature and higher insolation are required to get more power under the same panel. In addition, the insolation has a much greater effects on changing the panel characteristics than does the temperature. Although both solar insolation and temperature are dominant factors but there scale of effect is different. As temperature rises rate of PV current rising is less than the voltage decreasing. As a result MPP decreases. This is due to the open-circuit voltage temperature coefficient is negative with a nominal value of 0.068 V/ ˚C. On the other hand Short-circuit current temperature coefficient is positive with a value of 6.928 mA/ ˚C. However rate of rising of MPP for increasing value of intensity of solar irradiation is less than rate of drop of the MPP for increasing the value of temperature. The voltage waveform at the ac load is also shown in Figure (11). All of these results validate the PV array simulation model to be used in further works to design a complete system of PV energy system.

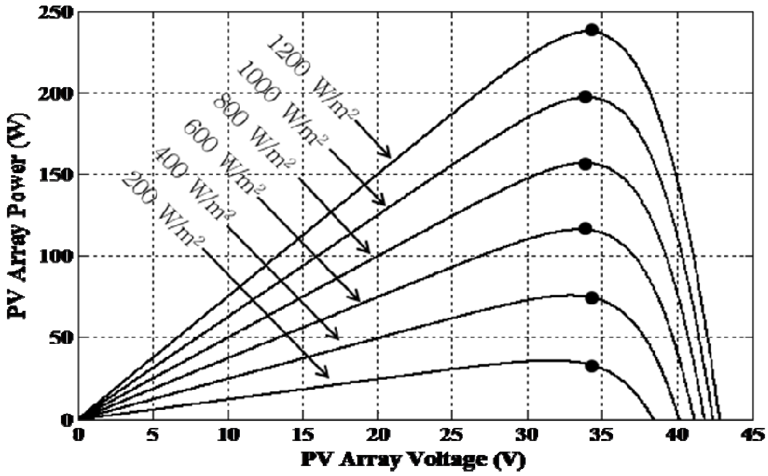

Figure 8. P-V Characteristics of the two series connected PV array due to change in insolation at 25°C

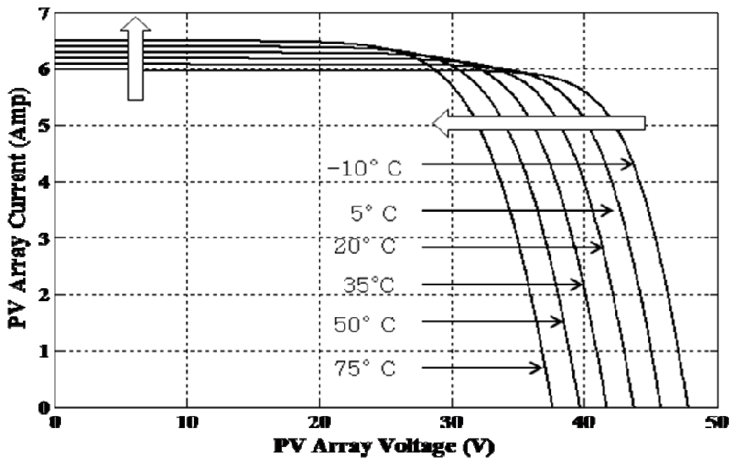

Figure 9. I-V characteristics under different temperatures at solar irradiation of 1000W/m^2

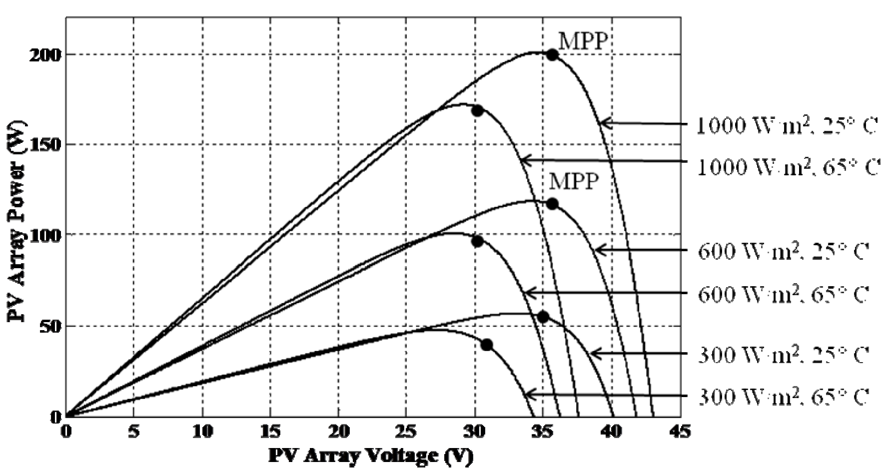

Figure 10. P-V characteristics under different insolations and temperatures

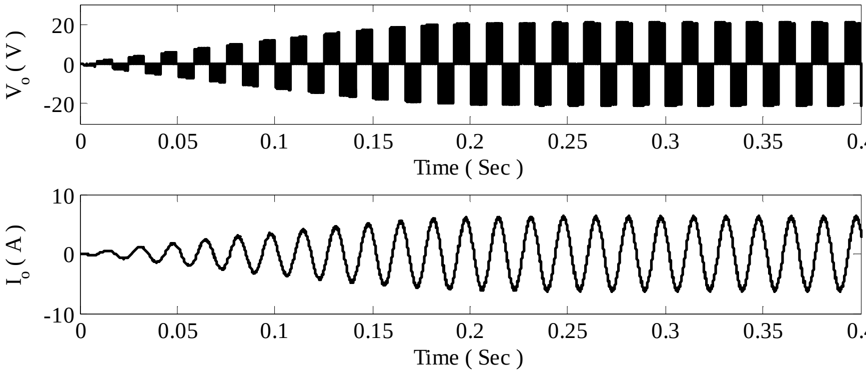

Figure 11. AC Output voltage and current waveforms of the inverter

2.4. Maximum Power Point Tracking

In MPPT by using appropriate algorithm electrical operating point (may be PV array voltage, current or duty cycle of the converter) is forced at the peak power point continuously to maximize power output. In Figure (12) of general MPPT system, during the period when open circuit voltage is sensed, S is closed and Q is opened. This will disconnect the power conditioner and load from the module. The capacitor C gets charged to a voltage that is proportional to V_{oc}. Then S is open and Q is closed for normal operation of the module and load. It is to be noted that, the duty cycle for switching S should be very small, less than 1%, so that the normal operation is not affected.

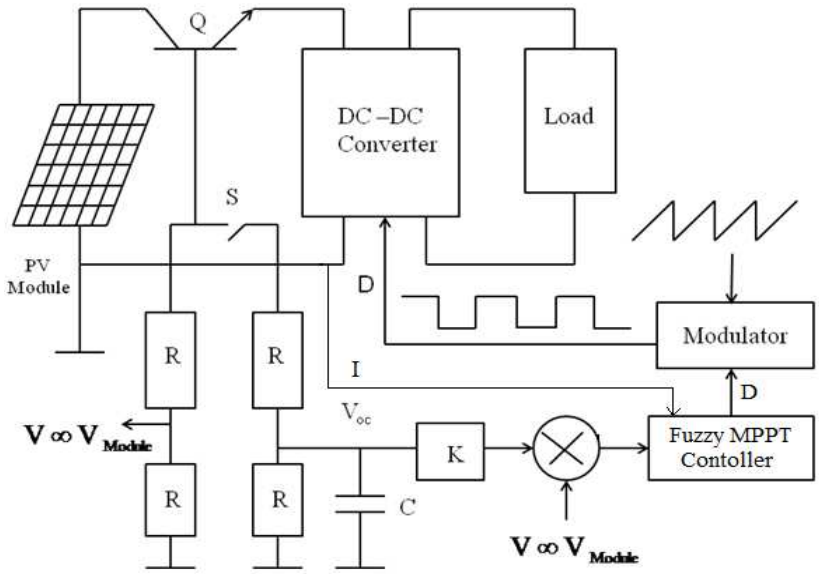

Figure 12. PV array with General MPPT system

The algorithm works as follow, since there is no reference cell and still we need to have the V_{mp} value for comparison, we need to have to measure the V_{oc} of the same cell. This is done with the help of switch S. While measuring V_{oc}, it is need to be disconnecting rest of the circuitry. This is done with active switch Q. A voltage V proportional to the module voltage is measured. This voltage is compared with a reference V_{mp}. If these two voltages match, maximum power is transferred to the load through the DC-DC converter. If these two voltages do not match, then error signal is generated. Depending on the polarity of the error signal, duty cycle is increased or decreased such that voltages match. The use of MPPT can make full use of the system capacity and thus reducing the cost of the system.

2.5. Improved Fuzzy Logic Controller for MPPT

A fuzzy control system essentially embeds the experience and intuition of a human plant operator and sometimes those of a designer and/or researcher of a plant. The design of a conventional control system is normally based on the mathematical model of a plant. If an accurate mathematical model is available with known parameters a controller can be designed for specified performance [21]. But in some cases an accurate mathematical model is not always available. Moreover, the response of a conventional controller is not always precise and fast enough if load and system parameters vary abruptly. In these situations, fuzzy logic controller (FLC) can be a very good alternative [22]. FLC can achieve robust response of a system with uncertainty and nonlinear characteristics. It has the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity. A MPP search based on fuzzy heuristic rules, which does not need any parameter information, consists of a stepwise adaptive search, leads to fast convergence and is sensorless with respect to sunlight and temperature measurements [23]. The control objective is to track and extract maximum power from the PV arrays for a given solar insolation level and cell operating temperature. The maximum power corresponding to the optimum operating point is determined for a different solar insolation level and temperature. A Functional block of FLC based MPPT system is shown in Figure (13). The fuzzy controller consists of three functional blocks as fuzzification, Fuzzy rule base and Defuzzification. These functions are described as follows:

4.1. Fuzzification

The proposed Fuzzy logic controller in this paper takes one input which is the slope $\frac{\Delta P}{\Delta V}(n)$ of the power versus voltage curve of PV array at a sampling instant of n and gives output the change in voltage $\Delta V(n)$ for the sampling instant $n+1$. The variable $\Delta P(n)$ and $\Delta V(n)$ are expressed as follows:

$$\Delta P(n) = P(n) - P(n-1)$$

$$\Delta V(n) = V(n) - V(n-1)$$

Where $P(n)$ and $V(n)$ are the power and voltage of PV array, respectively. So, $\Delta P(n)$ and $\Delta V(n)$ are zero at the maximum power point of a PV array. In Figure (13), the membership function of the input and output variables is shown which is assigned eleven fuzzy sets, including positive very big (PVB), positive big (PB), positive medium (PM), positive small (PS), positive very small (PVS), zero (ZE), negative very small (NVS), negative small (NS), negative medium (NM), negative big (NB) and negative very big (NVB). The membership functions are denser at the center in order to provide more precise output at the MPP.

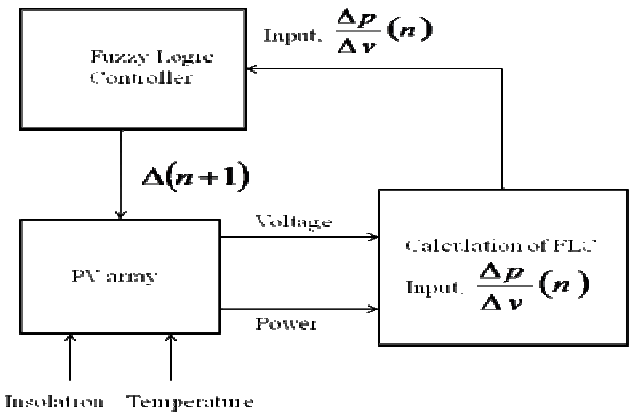

Figure 13. Functional block of FLC based MPPT system [20]

4.2. Fuzzy rule base

The fuzzy rule base should be such that it can generate an output which is changed in voltage *ΔV(n)* based on the magnitude of the input, *n+1* to operate the PV array at a voltage corresponding to MPP. At MPP, the input variable is zero. So, the output, change in voltage *ΔV*(*n*) should also be zero. But, a mean should be there to avoid the PV array voltage locking in a local maximum rather than proceed towards the actual value. The rule base, also known as rule base lookup table or fuzzy rule algorithm. Rule base table for Fuzzy logic controller is given in Table 2.

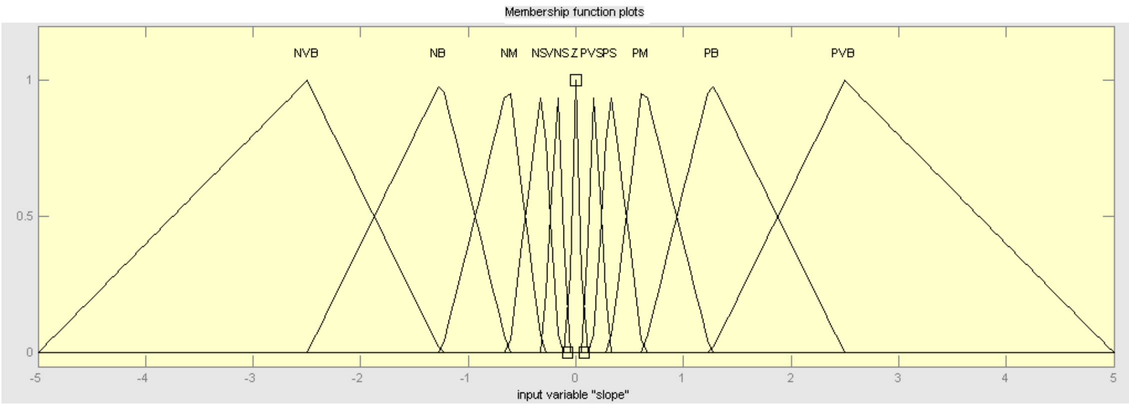

Figure 14. The membership functions of input and output variable

Table 2. Rule Base Table for Fuzzy Logic controller

Input	NVB	NB	NM	NS	NVS	ZE	PVS	PS	PM	PB	PVB
Output	NVB	NB	NM	NS	NVS	ZE	PVS	PS	PM	PB	PVB

4.3. Defuzzification

The output of the fuzzy logic converter is a change in the duty ratio of the power converter, D. The most common center of gravity method for defuzzification is used in this paper. It computes the center of gravity from the final fuzzy space, yields a result which is highly related to all of the elements in the same fuzzy set.

5. RESULTS AND DISCUSSION

As mentioned previously, the common methods to track MPP have several drawbacks. Among them, the P&O method shows slow tracking speed and oscillations about MPP. In this paper the performance of FLC is compared with that of P&O method to show FLC's superiority in tracking MPP over other conventional methods. The insolation and temperature profile are shown in Figure (15) for duration of half second. The insolation profile which has started with a value of 600 W/m^2 and continue for first 0.14 sec. Immediately after that this value rise up to 1000 W/m^2 exist for rest of the simulation period. Similarly temperature was 300K till 0.24 sec and then it change step down gradually to starting value after a sharp step up at about 0.25 sec. The voltage in the output of the converter both for FLC and conventional P&O method are shown in Figure (16) and it has been observed that the obtained output voltage level is less fluctuating with FLC than the conventional P&O controller. In this case the more ripple causes to decrease the average output voltage value and create electromagnetic interferences (EMI) and thus require additional EMI filter. Additional components increase cost and hamper overall system performances. At the same time decrease the output current as well as power. It is clear for FLC based MPPT get back its stability within a very few microsecond after some considerable change of insolation or temperature without any oscillation. Additionally FLC track accurately the maximum power point whatever the step size of voltage level. This happens because it provides the optimum duty ratio perturbation in adaptive manner.

The respective current and power levels are shown in the Figure (17) and in the Figure (18) accordingly. The variations in the current, voltage and power of the converter are almost terminated when the solar radiation is almost constant. For example this can be seen till 0.15 sec. in the time scale where in no insolation or temperature have changed. After 0.15 sec. insolation rise up to 1000 W/m^2 and as a consequence available current as well as power output dramatically improve. When temperature change step down gradually to starting value after a sharp step up at about 0.25 sec then voltage profile gradually decrease and current profile progressed step by step and power level increase steadily. FLC based MPPT only fail at the time of abrupt change of environmental condition but in steady state or gradual change of input it is best suite. On the other hand in case of P&O method, if step size of input variable is very small, the accuracy in tracking MPP is sufficient though some ripple exists but tracking speed becomes too slow. And if the step size is increased, oscillation about the mean point occurs; accuracy deteriorates even sometime unable to track MP. Both accuracy and speed of tracking cannot be achieved simultaneously. The proposed fuzzy logic based method is even better with respect to conventional fuzzy methods which can produce unexpected results when abrupt parameter changes occur in real time. The simulation results of P&O method shown here has step size relatively large to match the tracking speed of that of FLC. But in this case it shows increased oscillation.

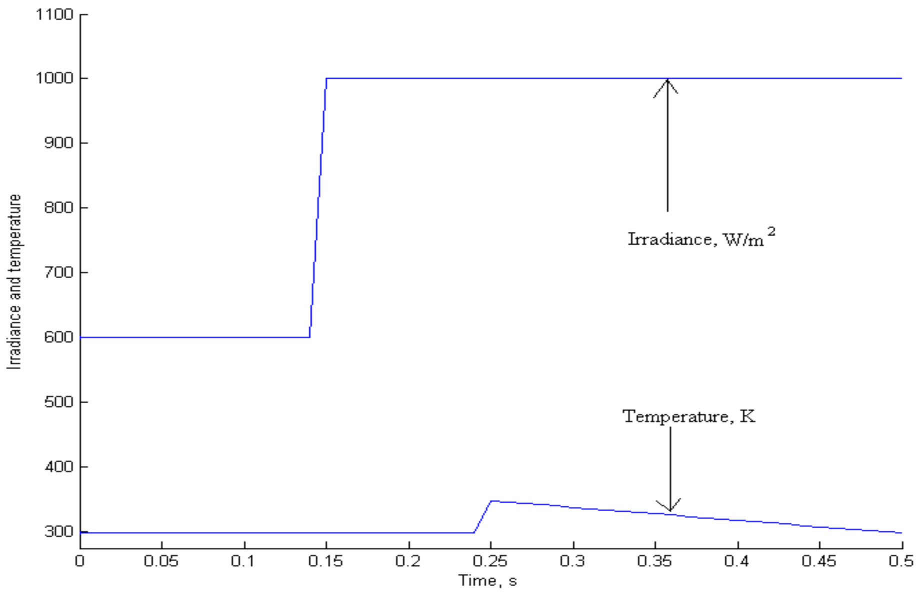

Figure 15. Step change of intensity of insolation and temperature during simulation

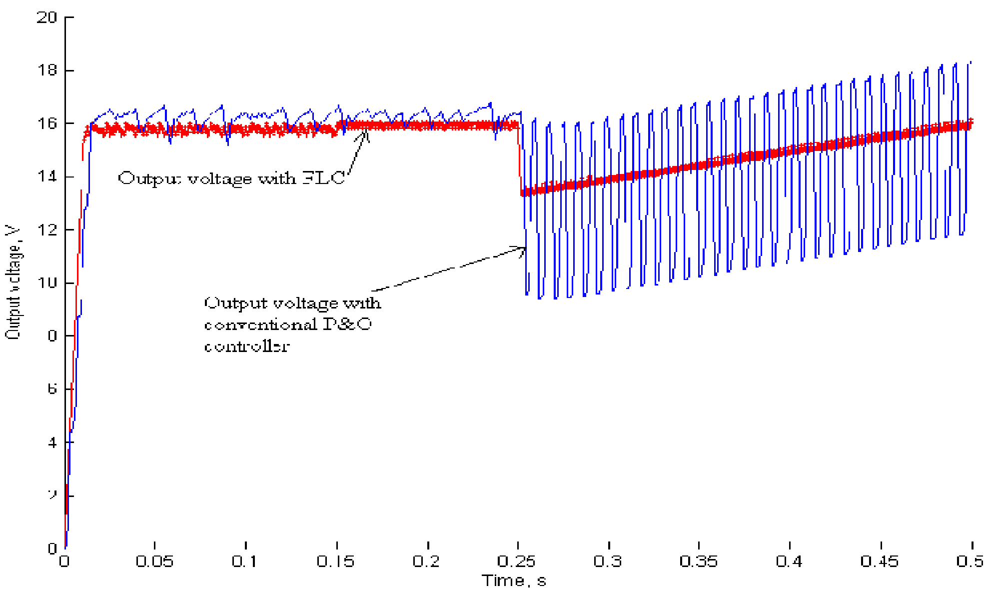

Figure 16. Output voltage with FLC and conventional P&O controller

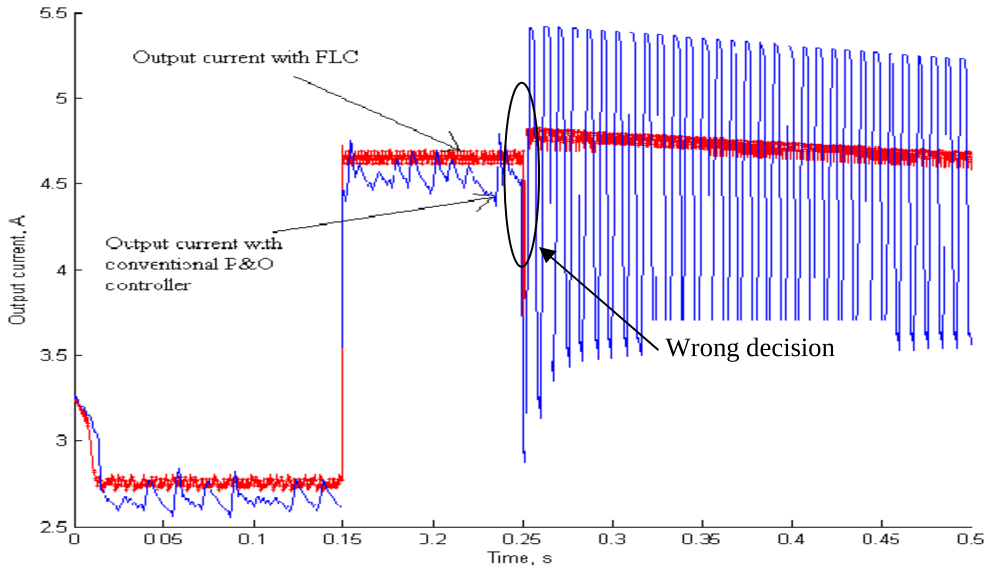

Figure 17. Output current with FLC and conventional P&O controller

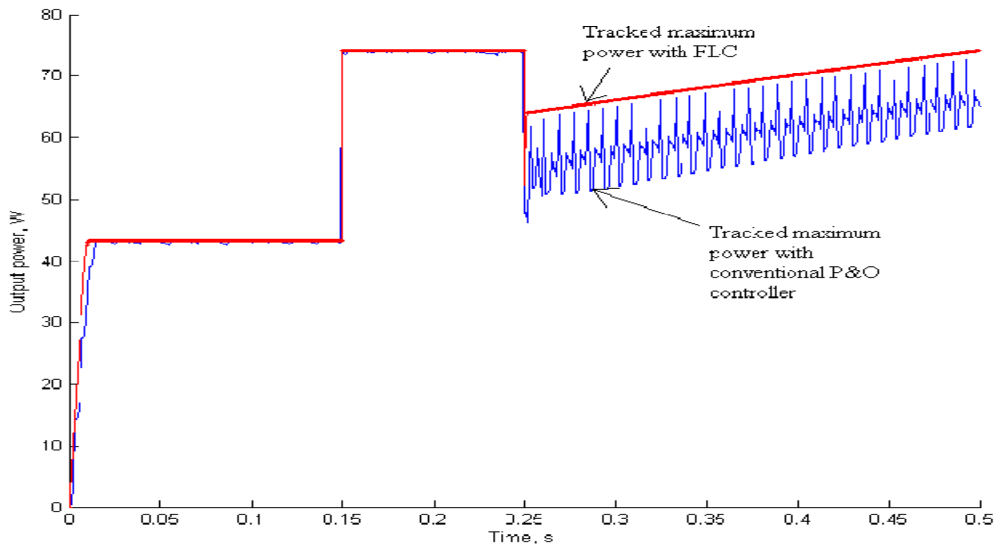

Figure 18. Output power with FLC and conventional P&O controller

6. CONCLUSION

A complete improved model of PV array along with fuzzy logic based MPPT controller was developed in this paper. The results give encouraging output on the performance of PV system and thus validate the behavior of the model. The model is simple and user friendly. This paper also presents an intelligent control strategy of MPPT for the PV system using the FLC. Simulation results show that the proposed MPPT can track the MPP faster when compared to the conventional P&O method even if the environment changes abruptly. In conclusion, the proposed MPPT using fuzzy logic can improve the performance of the system. The specialty of this FLC is that the rule base is very simple which increases the speed of computation of the processor as well.

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