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Design and Analysis of Optimal Maximum Power Point Tracking Algorithm using ANFIS Controller for PV Systems

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Abstract - **The Photovoltaic cell is considered as one of the most promising devices in photovoltaic generation. It is used to convert solar energy into electrical energy. Nowadays, Photovoltaic generation is developing more rapidly as a renewable energy source. But, the drawback is that Photovoltaic generation is discontinuous because of it depends on the weather conditions. This paper presents a high performance tracking method for maximum power generated by photovoltaic (PV) systems. Based on adaptive Neuro-Fuzzy inference systems (ANFIS), this method combines the learning abilities of artificial neural networks and the ability of fuzzy logic to handle imprecise data. It is able to handle non-linear and time varying problems hence making it suitable for accurate maximum power point tracking (MPPT) to ensure PV systems work effectively. The performance of the proposed method is compared to that of a fuzzy logic based MPPT algorithm to demonstrate its effectiveness.**
Keywords : **Maximum Power Point Tracking (MPPT), Photovoltaic (PV) Systems, Fuzzy Logic Controller (FLC), Adaptive Neuro-Fuzzy Inference Systems (ANFIS)**

I. INTRODUCTION

The fast growth of worldwide electricity consumption has raised a great demand for power generation from renewable energy sources (RESs). RESs are extremely dependent on topographical location and climate conditions, as they are vibrant in nature [1]. In our world, the sun is the largest RES. Photovoltaic (PV) cells are developed to transform sunlight directly into electricity. The characteristics of PV cells are such that for a given solar insolation, each cell has a unique operating point, in terms of the output voltage and current, that can extract the maximum power from the cell. As the solar insolation varies, a special algorithm known as the maximum power point tracking (MPPT)[2] is required to get the most power out of the cell. Since the maximum power point of a PV system leans on the temperature, irradiance, and shading or obstruction due to the clouds vastly [2], it is required that the MPPT algorithm must be adaptive and robust.

Among the various MPPT techniques of different control methods, control variables, circuitry, convergence speed, application, complexity, cost, and efficiency, etc. developed in the last few decades [3-6],the most common technique is the perturbation and observation (P&O) method[4] which has been widely employed because of its simple feedback structure and less measured parameters required. There are two types of P&O techniques; one has a perturbation occurring in the operating voltage of PV array, while the other in hill climbing on the duty cycle of the power converter, but both methods have weakness when the weather varies quickly [3].

Artificial intelligence, such as the fuzzy logic (FL), artificial neural network (ANN), and Neuro -Fuzzy, methods have had a great impact on development of new MPPT approaches [5]. While the ANN method has potent skill for plotting input and output of non-linear function though it lacks the heuristic sense, the FL method has the ability of converting linguistic and heuristic into numerical values through fuzzy membership functions and rules. These controllers can be applied for modeling, calculation, optimization and simulation of complex system to handle inaccurate inputs and have an overall rapid convergence [7].

This paper presents an adaptive Neuro-Fuzzy controller for MPPT of PV systems. In Section II modelling of the PV cell is discussed. In Section III,the proposed MPPT controller using Fuzzy logic is presented in detail. In Section IV,the proposed MPPT controller using ANFIS control is presented in detail. Section V presents the numerical simulation and results. Finally, conclusions are drawn in section VI.

II. MODELING OF PV MODULE

The schematic diagram of a three-phase grid-connected PV system which is main focus of this paper is shown in Fig. 1. The system consists of a PV array, a DC link capacitor C, a three-phase inverter, a filter inductor L and connected to the grid with line voltages. In this paper, the main aim is to control the voltage V_{dc} across the capacitor C and to make the input current in phase with grid voltage for unity power factor by means of appropriate control signals through the switches of the inverter. The mathematical model of PV system[5] is presented with a solar cell which is basically a p-n semiconductor junction. When exposed to light, a dc current is generated which varies linearly with solar irradiance. Fig. 2 shows an equivalent circuit diagram of the PV cell which consists of single diode connected in parallel with a light generated current source I_L. R_S and R_{Sh} represent the series and shunt resistance of solar cell. Usually the value of $R_{Sh}$is very large and that of R_S is very small, so this can be neglected to simplify the analysis.

1. The diode current I_{ON} can be written as:

$$I_{ON} = I_s\left[exp\left[\alpha(V_{pv} + R_s i_{pv})\right] - 1\right] \qquad (1)$$

Where, $I_s$is the saturation current, α=q T in which q is electron charge (1.6 * 10^{-19} C), K is the Boltzmann constant (1.38 * 10^{-23} JK^{-1}), T_c is the cell temperature in the standard test condition(STC), A is the ideal factor of cell dependent on PV technology whose value is in between 1 and 5,V_{PV} and I_{PV} are voltage and current generated by PV cells. The output voltage V_{PV} considered as voltage source C in this paper i.e. $V_{dc.}$

2. The output current(I_{PV}) generated by PV cell can be written as:

$$i_{pv} = I_L - I_s\left[exp\left[\alpha(V_{pv} + R_s i_{pv})\right] - 1\right] - \frac{v_{pv} + R_s i_{pv}}{R_{sh}} \qquad (2)$$

Where, I_L is light generated current that depends on solar irradiance which can be written as follows:

$$I_L = \left[I_{sc} + K_i(T_c - T_{ref})\right]\frac{G}{1000} \qquad (3)$$

Where, $I_{SC}$is cell short circuit current, K_i is short circuit current temperature coefficient, T_{ref} is the cell reference temperature,G is the solar radiation in KW/m^2.

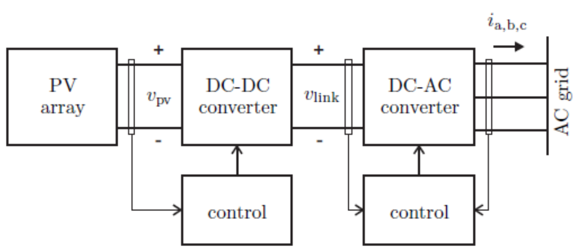

Fig. 1 Block diagram of the PV system [4]

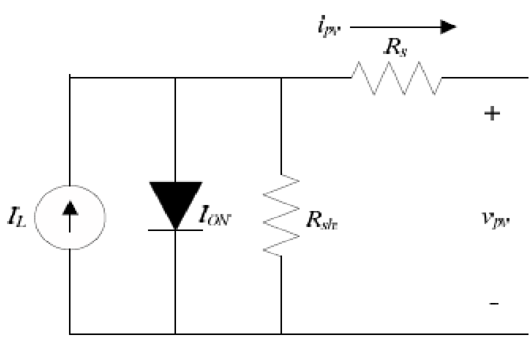

Fig. 2 Equivalent circuit diagram of PV cell [4]

3. The module saturation current I_s varies with the cell temperature according to the following equation:

$$I_s = I_{RS}\left[\frac{T_C}{T_{ref}}\right]^3 exp\left[\frac{qE_g}{Ak}\left(\frac{1}{T_{ref}} - \frac{1}{T_C}\right)\right] \qquad (4)$$

Where, I_{RS} is the reverse saturation current at a reference temperature and solar radiation, E_g is the band gap energy of the semiconductor used in the cell.

4. The output power of single solar cell is very less and it cannot be used for almost any application. So in order to increase the capability of the overall PV systems, a PV module is formed by arranging number of PV cells together and encapsulated with glass, plastic, and other transparent materials to protect from harsh environment. Then the solar cells are connected in series and parallel configuration to form solar modules and arrays.Fig.3 shows an electrical equivalent circuit diagram of a PV array.[8]

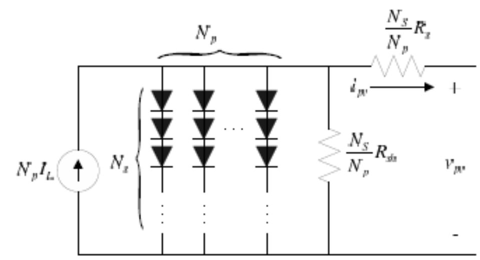

Fig. 3 Equivalent circuit diagram of PV array[4]

The output current of this PV module can be given as follows:

$$i_{pv} = N_pI_L - N_pI_s\left[exp\left[\alpha\left(\frac{v_{pv}}{N_s} - \frac{R_si_{pv}}{N_p}\right)\right] - 1\right] - \frac{N_p}{R_{sh}}\left(\frac{v_{pv}}{N_s} - \frac{R_si_{pv}}{N_p}\right) \qquad (5)$$

Where, N_s is the number of cells connected in series and N_p is the number of cells connected in parallel.

III. PROPOSED MPPT TECHNIQUE USING FUZZY LOGIC

In this paper a Fuzzy logic based MPPT technique which is described in detail in this section. The Fuzzy logic controller uses the fuzzy logics to make the decisions and to control the output of the controller. The main components in fuzzy logic based MPPT controller are fuzzification, rule-base, inference and defuzzification as shown in figure 4,[2]

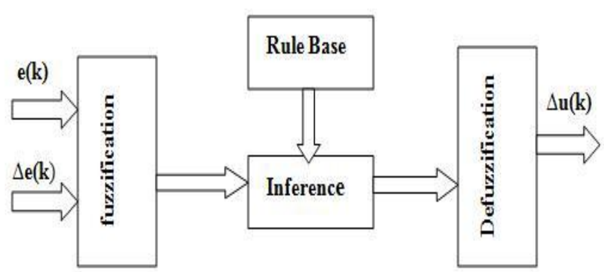

Fig. 4 Fuzzy logic block diagram

The Matlab/Simulink model Fuzzy logic based MPPT controllers as shown in the Fig. 5, [2]

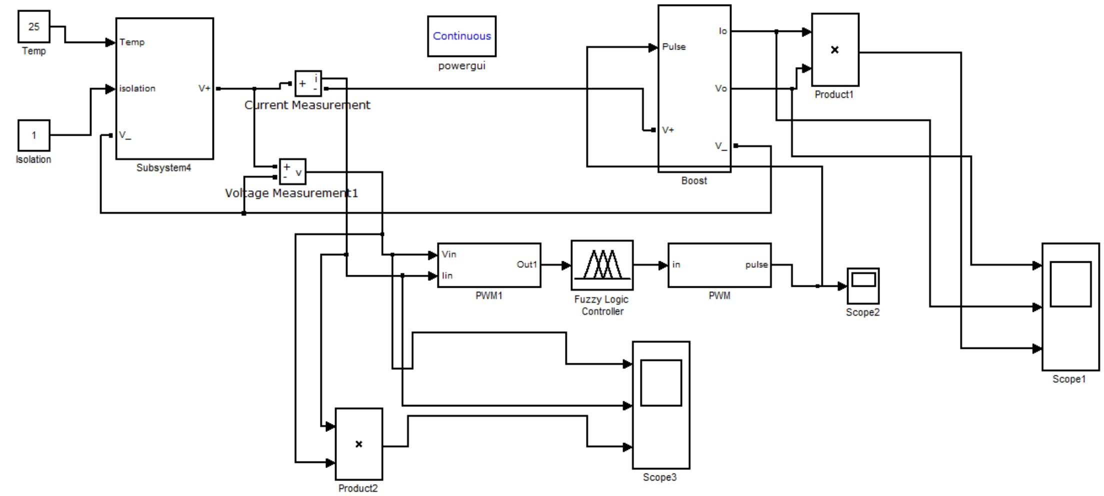

Fig. 5 Matlab/Simulink model of Fuzzy logic based MPPT controller

A. Fuzzy Inference System (FIS)

Every FIS model is composed of three stages. In fuzzification stage, FIS maps the input variables to linguistic variables by determining the membership function (MF). After that, the IF-THEN rules are p provided to set a relationship among the inputs and the output, which is called rule evaluation. Then, in defuzzification the linguistic variables are converted to a crisp value of output. The parameters are tuned according to the input-output data of model.

In general, the fuzzy logic controller (FLC) is a FIS. The first part is fuzzification, which is a procedure of converting numerical inputs into linguistic variables according to the degree of membership function. The linguistic variables are defined as Negative Large (NL) ,Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Large (PL). Each of them shows the fuzzy Large (PL). Each of them shows the fuzzy data, as can be seen in Fig.6 [2]

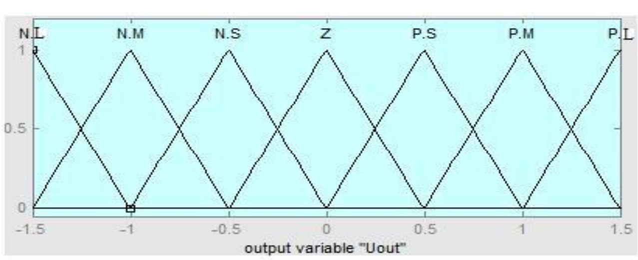

Fig. 6 Membership function for FLC

The membership functions can be an arbitrary curve whose shape can be defined as a function that suits designers in approaching of simplicity, convenience, speed, and efficiency. Membership function for ANFIS and FLC are chosen Gaussian and triangular function respectively. The Gaussian membership function has the advantage of being smooth and nonzero at all points while the triangular membership function is used because of its simplicity.

It is a general view that if the number of membership function between the defined ranges is larger, then the possible rules increases and the response will be worthy. It is desirable to increase the rules for a proper response but after increasing the rules to a certain limit (49 rules in this case) there is no need to go beyond since the response does not change appreciably. There are two common inputs for FL , error „E‟ and change in error „ΔE‟, as follows,

$$E = V_{MAX} - V_{PV} \quad (6)$$

$$\Delta E(n) = E(n) - E(n-1) \quad (7)$$

The output of FLC generally isΔD, change in duty ratio, of the power converter. Table 1 shows the second stage of FLC known as the rule based table lookup. The rules explain the relationship among E, ΔE and D represented by IF- THEN sentences. For example, if error is negative small (NS) and change of error is positive small (PS) then change of duty cycle will be zero (Z).The third level of FLC is defuzzification in which numerical variables and result will be produced to provide the analog signal that controls MPP.

TABLE I FUZZY RULES

E\ΔE	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NL	NL	NM	NS	Z	PS
NS	NL	NL	NM	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PB	PL
PL	Z	PS	PM	PL	PL	PL	PL

The input, output membership functions are shown in figures 7, 8 & 9 respectively.

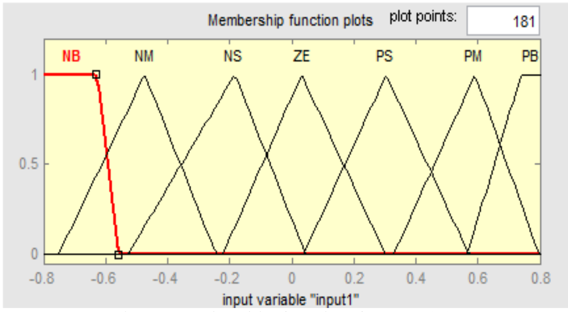

Fig. 7 Membership function for error(E)

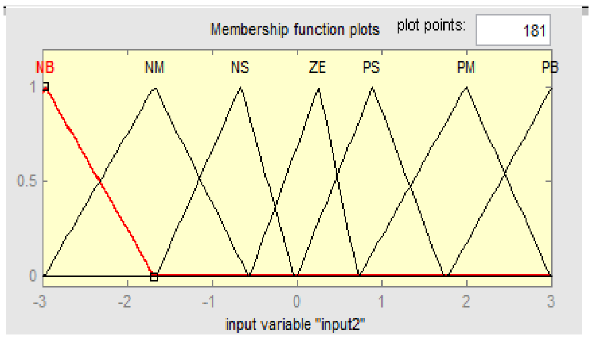

Fig. 8 Membership function for change in error(ΔE)

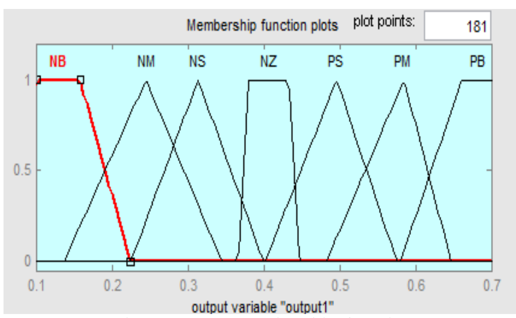

Fig. 9 Output membership function

IV. PROPOSED MPPT TECHNIQUE USING ANFIS

In this paper a new method is adapted for tracking the maximum power point i.e. using an Adaptive Neuro Fuzzy Inference system (ANFIS)[11] which is described in detail in this section. The Matlab/Simulink model of ANFIS based MPPT controllers as shown in the Fig. 10.This model requires two input training data sets which are taken as irradiance level and operating temperature of PV module. Using these data sets the ANFIS reference model gives out the crisp value of maximum available power from the PV module at a specific temperature and irradiance level. This tool enables the construction of a Fuzzy Inference System (FIS) whose membership function parameters are tuned using specific algorithm. According to figure the input data is same for both ANFIS and PV module. The actual output power of PV module is calculated using multiplication algorithm of operating voltage and current and this calculation has been done at same level of temperature and irradiance of ANFIS.The oscillations produced at the output voltage, current and power can be reduced by denoised temperature and irradiance values as inputs, which are formed by using wavelet algorithm.

The two powers from PV module and ANFIS are compared and the obtained error is given to a proportional integral(PI) controller, which will generate control signals and this signals are given to PWM generator.Then PWM signals are generated by comparing high frequency carrier signals to reference modulating (or) control signals.The frequency of carrier signal used is 50KH$_Z$.These PWM signals are given to the DC-DC converter, that is used to control the duty cycle and inorder to adjust the operation point of PV module.

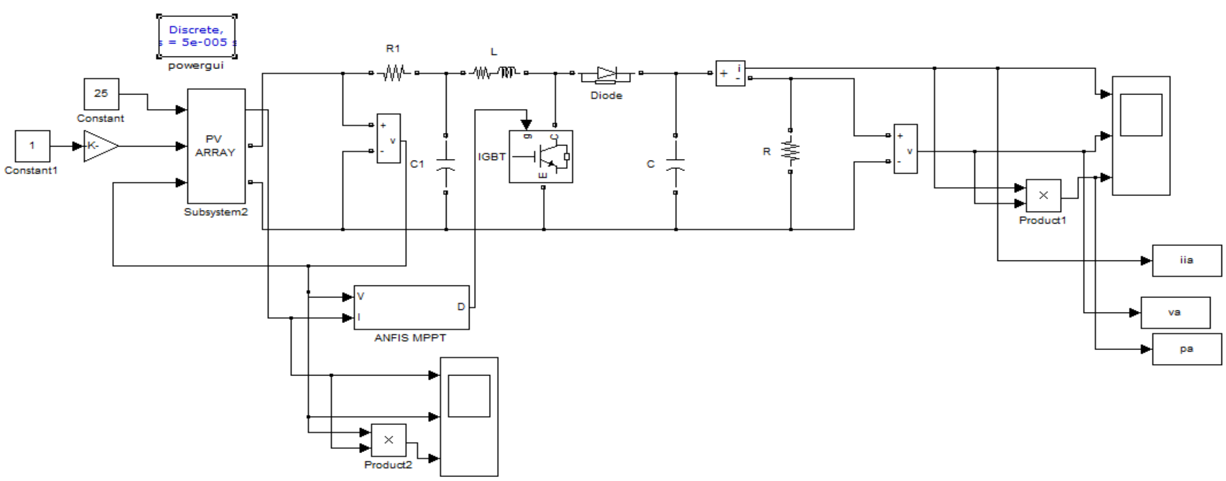

Fig. 10 Matlab/Simulink model of ANFIS based MPPT controller

Tuning of ANFIS using Matlab/Simulink can be done by tuning the parameters of a sugeno-type fuzzy inference system.The training data sets for this can be taken as,the operating temperature varied from 15^{o}C to 65^{o}C in a step of 5^{o}C and the solar irradiance level is varied from 100W/m^2 to 1000W/m^2 in a step of 50 W/m^2.From this 209 training data sets are formed and 1000 epochs are used to train the ANFIS.To form the FIS , the grid partition is selected in Matlab ANFIS block and number of inputs and outputs are chosen with the shapes of their membership function,this system consists of two inputs and one output.Then FIS is constructed by ANFIS whose membership function parameters are tuned using hybrid optimization method.This method is combination of least square type and the back propagation algorithm.

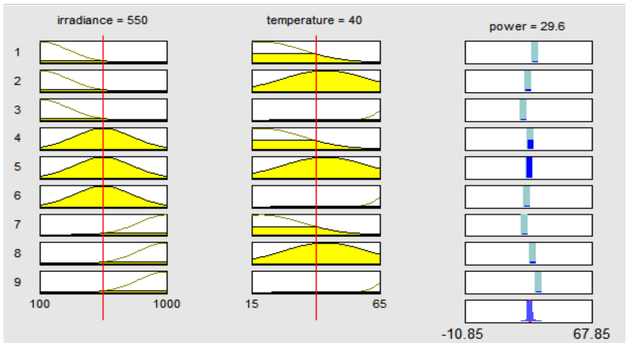

Fig. 11 Output from fuzzy rules for specific value of temperature and irradiance

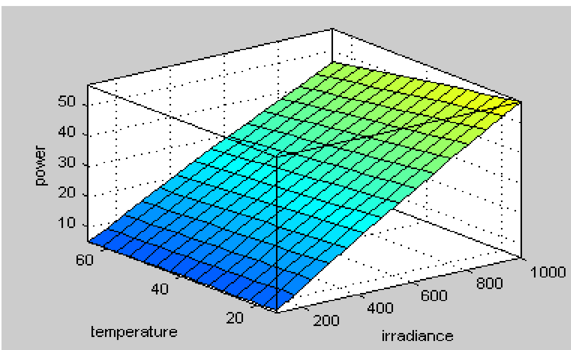

Fig. 12 Surface between two inputs (temperature and irradiance) and one output (maximum power)

FIS system consists of nine rules that are derived from six input membership function which can be formed by two inputs(operating temperature and irradiance level),one output(maximum power) and three membership function for each input.These rules are derived according to the mapping of this inputs and output,so as to produce maximum output power for a specific value of inputs, as shown in Fig. 11. The surface generated by ANFIS is a 3-dimensional plot between temperature,irradiance level and maximum power which is shown in Fig. 12.

V. SIMULATION RESULTS AND DISCUSSION

A. Operation in Standard Environmental Conditions (Constant T=25ºC & G=1000 W/m^2)

The Fig (13,14 and 15) below allow us to visualize the output of PV panel with Fuzzy Logic Control and ANFIS based MPPT Technique in standard full of atmosphere conditions[] (1000W/m^2, 25°C). At G=1000 W/m^2 and T=25^{0}C PV system Fuzzy logic based MPPT technique gives current, voltage & power 7.41 A, 47.13 V and 349.2 watt respectively. On the other hand PV system with ANFIS based MPPT technique gives current, voltage and power 8.2 A, 49.1 V and 402.6 watt respectively.

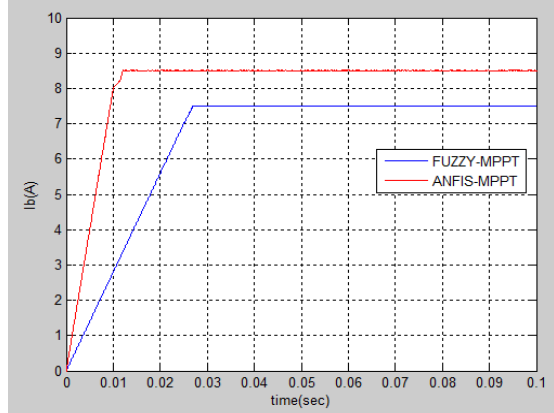

Fig. 13 Boost converter Output current

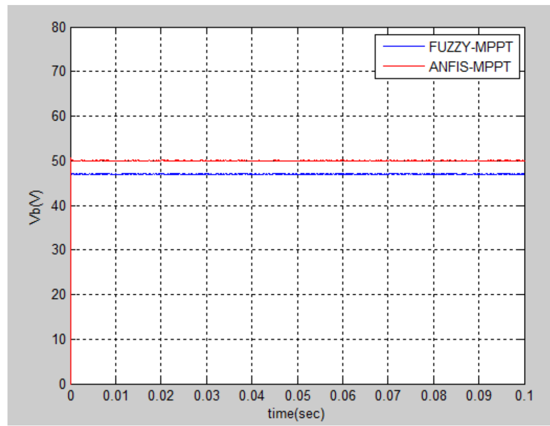

Fig. 14 Boost converter Output voltage

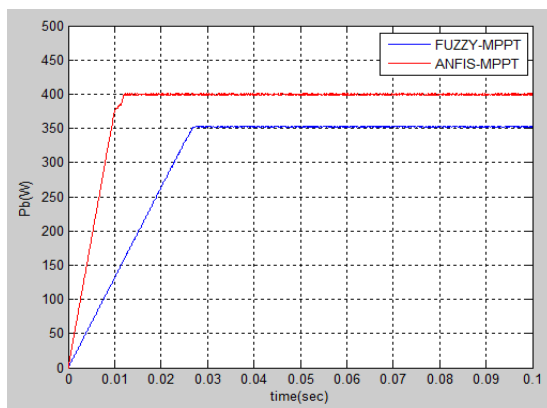

Fig. 15 Boost converter Output power

It is clear that MPPT technique increases output power. ANFIS based MPPT gives more power than that of Fuzzy logic based MPPT technique

B. Operation in Variable Solar Radiation Conditions

The Fig (16, 17 and 18) below allow us to visualize the output of PV panel with Fuzzy logic based MPPT & PV Panel with ANFIS based MPPT Technique in varying environmental conditions .For the analysis of our system in actual conditions, we vary the irradiation as the incremental step. These differences permit us to study the robustness of our system. We have tested the responses of the two controllers, for a variation in solar radiation from 250 W/m^2 to 1000 W/m^2 with a constant cell temperature T_c = 25∘C. The resulting array operating voltage and current and power are shown in Figs. 16,17 and 18.

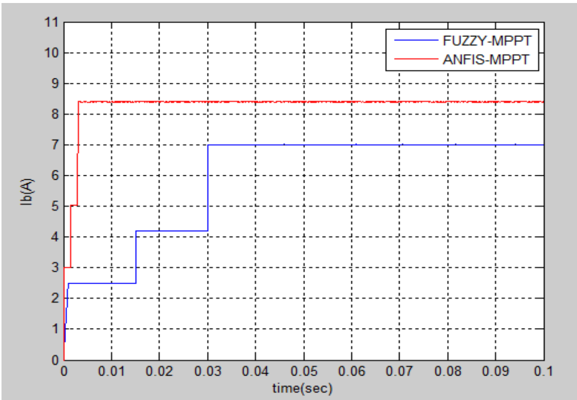

Fig.16. Boost Converter current of PV system with varying Irradiance & Temperature

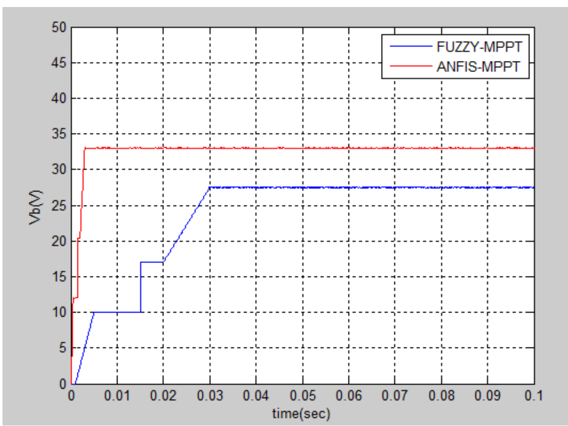

Fig.17 Boost Converter voltage of PV system with varying Irradiance & Temperature

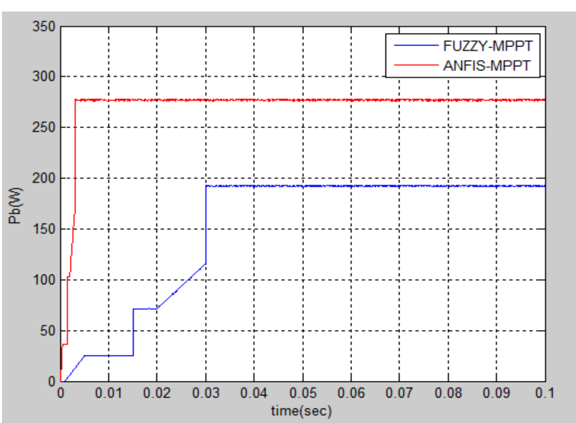

Fig.18 Boost Converter power of PV system with varying Irradiance & Temperature

It is clear that maximum power point of PV panel changes as irradiance changes, so power from PV panel increases as irradiance increases. During rapid change of irradiance from 0.015 sec. to 0.03 sec. Outputs of ANFIS based MPPT technique are smother than that of Fuzzy logic based MPPT technique and it is also clear that ANFIS logic based MPPT technique gives more power than Fuzzy logic based technique in each period.

VI. CONCLUSION

This paper has presented Fuzzy logic and ANFIS based MPPT technique for controlling PV system output voltage to operate at maximum power point although happened temperature and irradiation changes. Applications of ANFIS controller on MPPT of PV showed a good performance. The system was analyzed and designed, and performance was studied by simulation with Simulink/Matlab. PV system can operate at maximum power point although occur temperature and sun irradiation change that can shift maximum power point.

This paper deals with two control techniques namely fuzzy logic (FL) and ANFIS based MPPT technique. Both control technique applied to proposed system having a DC to DC boost converter. The results obtained are compared and shows that system performance to same environmental condition is better in case of ANFIS control than Fuzzy logic technique. The simulations results shows that the efficiency of the overall system can be improved with the help of ANFIS Controller by minimizing the power losses when the variation of irradiation is frequent rather than the Fuzzy logic based technique. The ANFIS controller shows excellent performance and decreases the time of response of the photo –voltaic system to perturbations and maintain continuity of the operation to carry on maximum power point (MPP) and also minimizes the fluctuation around operating point. The advantages mentioned above shows that proposed ANFIS controller for photo voltaic energy conversion system is very much effective as well as operate effectively under standard variable environmental operating conditions.

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