Adaptive MPPT Algorithm for stand-alone PV System Under Partial Shading Condition

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Abstract: Partial Shading in Photovoltaic (PV) is a situation which has negative effect on the PV array output. It results in multiple peaks in non-linear Power Voltage (P-V) characteristic with only one peak having the maximum power i.e. Global Maximum Power Point (GMPP). Thus, an efficient controller needs to be implemented with fast tracking efficiency to track GMPP. In the present paper, Adaptive Neuro-Fuzzy Inference System (ANFIS) is designed, developed and validated for a solar PV system to detect maximum power under standard test condition (STC) and partial shading condition (PSC). Comparative analysis of ANFIS and Perturb & Observe (P&O) maximum power tracking algorithm is presented to establish the superiority of the ANFIS algorithm.

***IndexTerms* - Photovoltaic system, Adaptive Neuro Fuzzy Inference System, DC-DC Boost Converter, Maximum Power Point Tracking.**

I. INTRODUCTION

Due to fast exhaustion of conventional energy resources and their harmful effect on living beings, the energy demands may be fulfilled by the existing power generation system. This results in increased use of renewable energy resource for electrical power generation. Among various renewable energy resources solar photovoltaic is most widely used [1,2]. The solar energy is clean, carbon free, abundant and freely available. Also, the price of PV panels is declining, making it more economical. The PV panel gives maximum output at rated STC condition, but the environmental conditions kept on changing resulting in the reduced PV output [3]. Partial shading is the condition in which the whole PV array is not uniformly irradiated. It can be caused because of dense moving clouds, big nearby building, large trees, ageing or cracking in PV panels. The partial shading leads to multiple peaks in PV characteristics, having single GMPP and many LMPP [4]. In this case, the conventional MPPT algorithm may not be able to track GMPP and lurch's around LMPP, power is wasted.

Researchers have implemented several conventional MPPT techniques viz. perturb & observation (P&O), incremental conductance (INC), fractional open circuit voltage (FCOV) etc. have been reviewed and addressed in [5,6]. Among all these conventional methods, P&O is most widely used because of its ease of implementation and simplicity. But its reliability is low in PSC. This challenge can be met by reducing the step size of perturbation, but small perturbation size delays the MPP tracking [6,7]. The INC algorithm has been offered with improved tracking accuracy under steady state and variable environmental conditions [8,9]. The INC algorithm is founded on the fact that the rise of the PV module power curve is zero at the MPP, positive on the left side and negative on the right position of the MPP. It uses the derivative algorithm to find the MPP. This method takes more computation in the controller because the differentiation process involves a relatively complex decision-making procedure [10-13]. So, implementing INC algorithm increases the cost and complexity of the system and it may give unsatisfactory results at low insolation level. Ahteshamul Haque [14-15] developed and implemented a control circuit for MPPT. PSIM simulation software is used for simulation study. A prototype setup was tested under different irradiation levels provided through artificial light setup.

FLC do not necessitate knowledge of exact model but it is costlier at the time implementation. [16-19]. In [20] authors have compared P&O and intelligent FLC algorithm under partially shading condition for stand-alone PV system and simulation results shows that FLC can track maximum power with better tracking efficiency.

In the present study, authors have optimized the membership function by heuristic approach for ANFIS algorithm. ANFIS algorithm has been implemented as it is simple and easy and does not involve complex mathematical equations and calculations for their implementation. The simulation results of the proposed adaptive algorithm demonstrated their ability to track GMPP, with less fluctuation around MPP and minimum settling time.

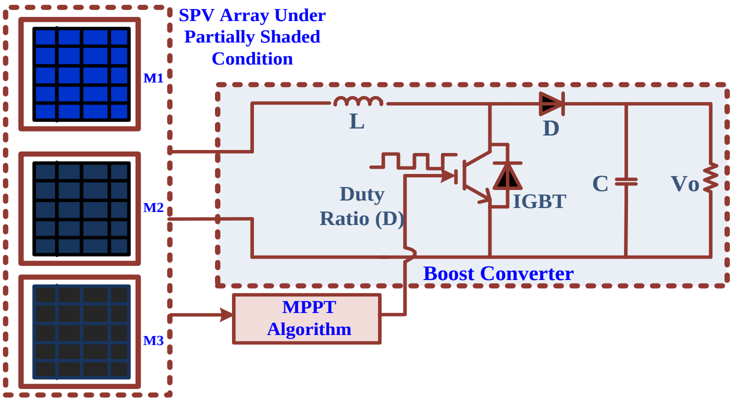


Fig.1 Block Diagram of Stand-alone SPV System under Partially Shaded Condition

Fig.1 presents the SPV system under PSC consists of a PV array source, MPPT algorithm and DC-DC converter (boost). The ANFIS algorithm which is combination of neural network and fuzzy inference system is designed, developed and validated to track the global peak from multiple peaks of P-V curve depicted under partially shaded condition which may not be tracked by conventional MPPT.

II. Organization Of Paper

Equivalent circuit of SPV module has been discussed and its characteristics has been determined in section II. Design of DC-DC Boost converter, which is a power interfacing device between source and the load, is discussed in section III. MPPT algorithms for PV module are explained in section IV. In sections V and VI the results and conclusions respectively of the proposed research work has been discussed.

III. Equivalent Circuit of SPV Module

Solar cell works on the principle of Photovoltaic effect. It is an active transducer which converts energy from sunlight (photons) into electricity (current). Voltage produced by solar cell is very small (0.5 to 0.8 V), to get appreciable power from solar PV cell they need to be connected in series [21]. The ideal equivalent circuit of solar cell incorporates light generated current source with single anti-parallel diode. Fig. 2 presents the equivalent circuit of single diode model used in the proposed system.

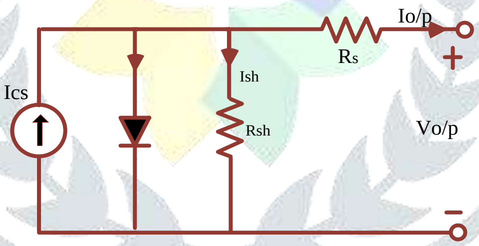


Fig.2 Equivalent circuit of PV cell

The output current $I_{o/p}$ of PV cell is given as

$$I_{o/p} = I_{cs} - I_{sat} * \left[exp\left(\frac{q(V_{o/p} + I_{o/p} * R_s)}{N_s AkT_{ac}} \right) - 1 \right] \quad (1)$$

where, $I_{o/p}$ is the output current, I_{cs} is the photon current, I_{sat} is the diode saturation current, q is the elementary charge (1.602*10^{-19} C), $V_{o/p}$ is the output voltage, R_s is the series resistance (Ω), N_s is the number of series cell, A is the ideal factor of the cell dependent on PV technology, K is the Boltzmann constant (1.38*10^{-23} J), T_{ac} is the actual operating temperature.

In the present work, Sun Power Solar panel X22-360 PV modules is used. Table 1 shows the sun power solar panel specifications used in simulation and modeling of PV array. An array of (3X1) PV modules each of 360W simulated in MATLAB/Simulink. The maximum power obtained by the array is (360*3) 1.08kW.

Table 1 Specification of Sun Power PV Module

SPR-X22-360	
Power Nominal (Max), P_{nom}	360W
Rated Voltage, V_m	60.6V
Rated Current, I_m	5.94A
Open-Circuit Voltage, V_{oc}	69.5V
Short-Circuit Current, I_{scc}	6.48A
Total No. of Cell in Series, N_s	96

IV. DC-DC CONVERTER

In the proposed system, the boost converter is used as a dc-dc converter (fig.1). The main components of boost converter along with IGBT switch are the series inductor and shunt capacitor, which are passive components. The expression of inductor, capacitor, duty ratio and resistive load to obtain the dc bus voltage are expressed as:

$$L = \frac{V_{o/p}\,\alpha}{(\Delta I f_{sw})} \quad (2)$$

$$\alpha = 1 - \left(\frac{V_a}{V_{o/p}}\right) \quad (3)$$

$$C = \frac{I_a\,\alpha}{(\Delta V f_{sw})} \quad (4)$$

V. MAXIMUM POWER POINT TRACKING ALGORITHM

As the environmental conditions are ambiguous, so input voltage to the DC-DC converter by PV array varies and maximum power operating point changes. In order to ensure that during PSC the power tracked by the MPPT is GMPP not LMPP, adaptive MPPT algorithm is employed that can take into account the fluctuations around MPP and long settling time. MPPT finds the MPP and operates at optimal point by regulating the duty ratio of dc-dc converter. The adaptive MPPT algorithms are presented below.

5.1 Perturb and Observe (P&O)

The Perturb and Observe Maximum Power Point Algorithm is based on the criterion that on the right of the MPP, if voltage increases, power decreases then in this condition perturbation is made on the opposite direction whereas towards the left of MPP, if increasing the voltage, power also increases then perturbation should be made in same direction.

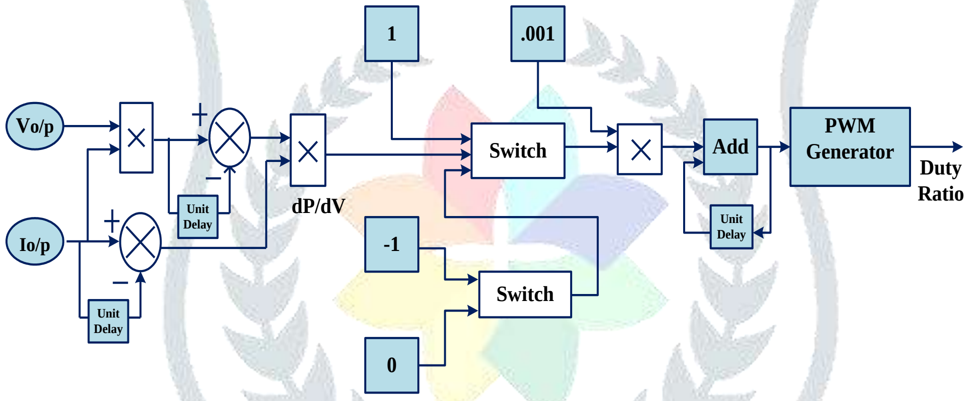


Fig.3 Block Diagram of P&O Algorithm

Table 2 The Operation of P&O Algorithm

S.No.	ΔP_{pv}	ΔV_{pv}	V_{pv}(ref.)	Duty Ratio
1.	>0	>0	↑	↓
2.	>0	<0	↓	↑
3.	<0	>0	↓	↑
4.	<0	<0	↑	↓

The main drawback of conventional MPPT algorithms is that they may not track GMPP and has larger settling time. The main drawback of the P&O algorithm is its lack of ability to track maximum power point due to the oscillations near MPP region under varying environmental conditions. To overcome these disadvantages, the membership functions are fine tuned to obtain greater sensitivity in the MPP region utilizing ANFIS algorithm [22,23].

5.2 Adaptive Neuro-Fuzzy Inference System (ANFIS)

Adaptive neuro fuzzy inference system (ANFIS) uses both FL and ANN in its process of mapping input and output. ANFIS uses neural network to adjust membership function, its distribution and making fuzzy rules as all these parameters are obtained by heuristic approach. The block diagram of ANFIS MPP tracker for solar PV system is shown fig.4.

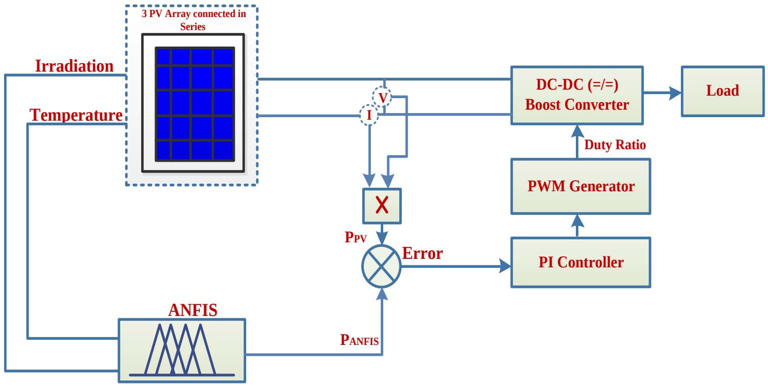


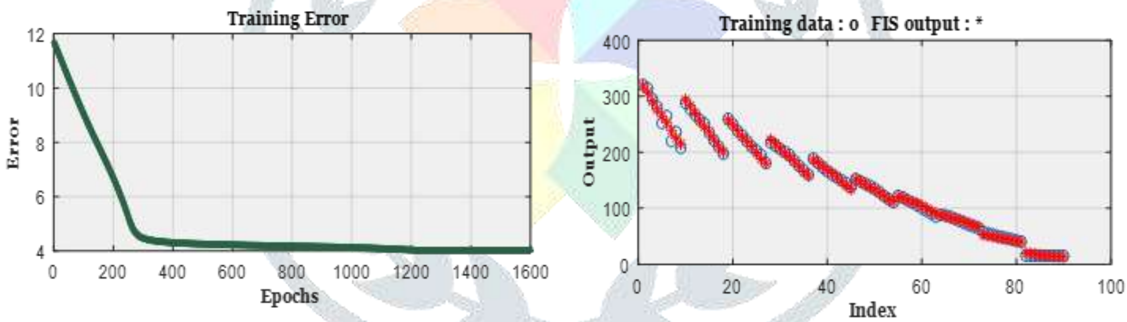
Fig.4 Block Diagram representation of ANFIS MPPT for SPV system under steady state and dynamic condition

Solar irradiation and temperature are used to generate the training data set for the ANFIS tracker. The training data set is taken under different environmental condition by changing irradiation as well as temperature. The two inputs are irradiation and temperature and one output power. The actual power and power from trained data set are compared and error is given to the PI controller. The output generated from PI controller is compared with modulating signal having frequency 10 kHz [24]. The output from PI controller is given to the PWM generator where the duty ratio of the converter is adjusted according to the environmental condition.

ANFIS Tuning

To tune the ANFIS, firstly the training data set is required. To get this training data the MATLAB/Simulink of PV module is operated for solar irradiation variation from 0.1kW/m^2 to 1kW/m^2 at fixed step of 0.05 kW/m^2 and similarly temperature is varied from 20^{o}C to 60^{o}C at a step of 5°C. The retrieved training data is saved in workspace of MATLAB. The ANFIS generates fuzzy inference system (FIS) by using loading training input and output data set. The ANFIS uses hybrid optimization technique for training, which is combination of least square type method and back propagation algorithm [25].

Fig.5 (a) shows training error v/s epoch waveform which has been reduced to approximately 4%. Fig.5 (b) shows the training data and ANFIS output, it can be seen trained data that ANFIS data matches closely to actual data of PV module.



(a) (b)

Fig.5 (a) Training error Vs Epoch waveform for ANFIS (b) Training Data and ANFIS output

Fig.6 shows the surface view generated by ANFIS. Fig.7 represents the structure of ANFIS. Input to ANFIS are irradiation and temperature and output is power. Inputmf, outputmf represents membership function of input and output. In the present study, the membership function for both inputs learned by ANFIS is shown in fig.8. Nine fuzzy rules have been derived from two inputs each having three membership functions. The developed fuzzy rules derived according to input and output mapping.

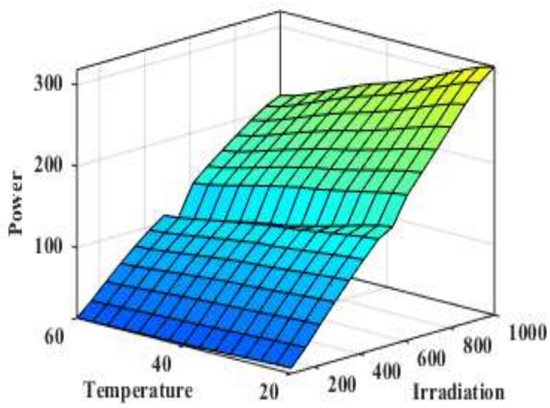


Fig.6 3-D surface view representation between two inputs (irradiation and temperature) and one output (Power) generated by ANFIS of proposed SPV system.

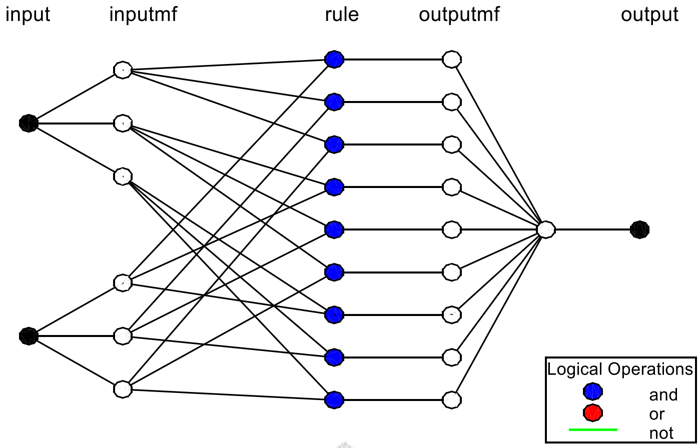


Fig.7 Structure of ANFIS

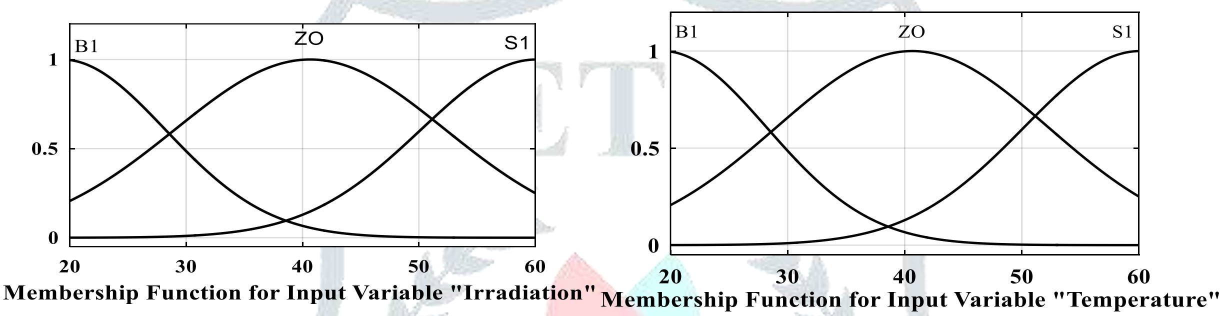


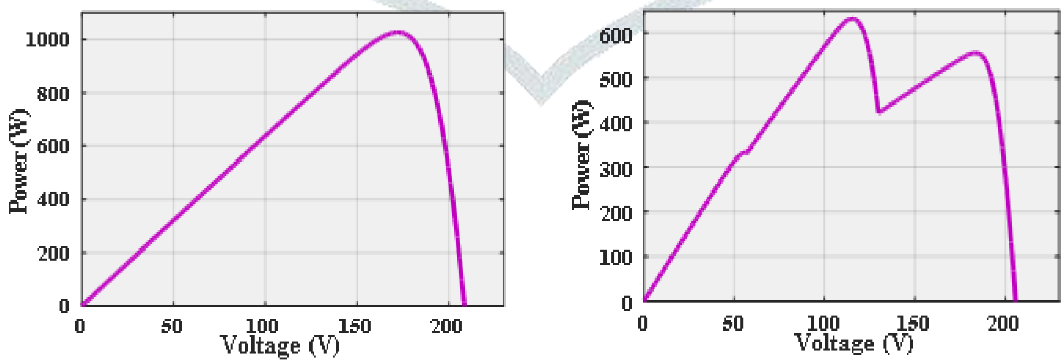
Fig.8 Membership functions for input variables 'Irradiation' and 'Temperature' after learning in ANFIS

VI. SIMULATION RESULTS

The MATLAB/Simulink is used to develop SPV system. In the proposed SPV system, ANFIS algorithm has been implemented to trace maximum available power under varying environmental conditions.

The MATLAB/Simulink model for ANFIS algorithm and P&O has been designed, developed and validated under various conditions i.e. (i) STC (ii) PSC (iii) Dynamic condition.

In fig.9 (a) P-V characteristic achieved is at STC i.e. at insolation 1kW/m^2 and temperature 25°C. In fig. 9 (b) P-V characteristic is obtained when module M1 given insolation 1kW/m^2, M2 0.9kW/m^2 and M3 0.5kW/m^2 and temperature 25°C.



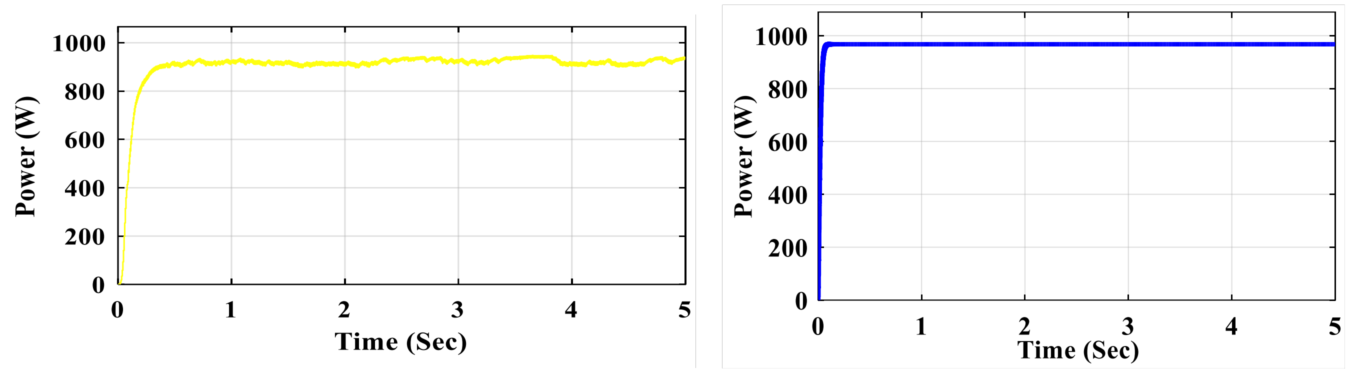
(a) (b)

Fig.9 (a) PV characteristic achieved at STC (b) PV characteristic at PSC

As seen from fig.9 (b) P-V curve has multiple peaks depicted under partial shading condition, in which 2 lower peaks are LMPP and maximum peak is GMPP. In the present study, adaptive MPPT algorithm have been designed to track GMPP which may not be tracked by conventional MPPT algorithms. Results under STC, steady state condition as well as dynamic condition for both the algorithms i.e. P&O and ANFIS has been presented.

(i) Performance of P&O and ANFIS under STC

Fig.10 shows the power v/s time plot of PV module under uniform shading condition at STC. The power drawn by P&O and ANFIS is 920W and 967.5W with settling time 0.35s and 0.09s respectively.

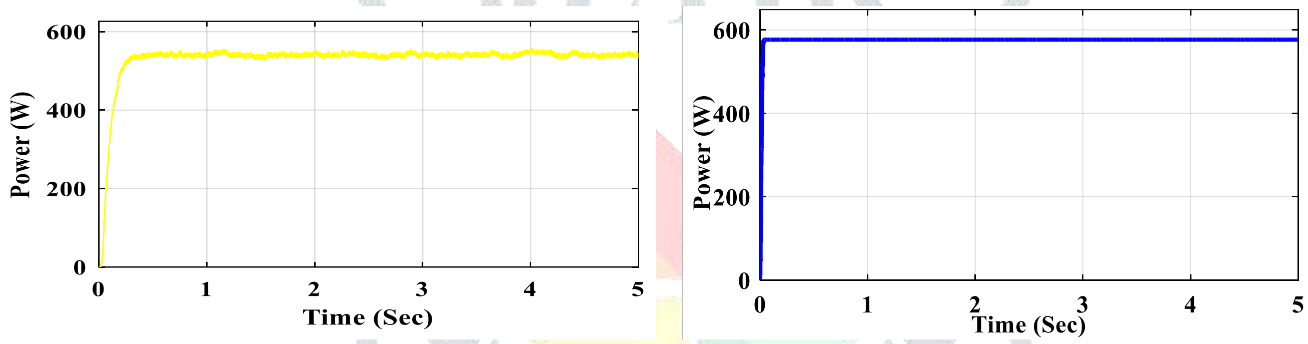


(a) (b)

Fig.10 Power v/s Time plot of (a) P&O and (b) ANFIS algorithm at STC

(ii) Performance of P&O and ANFIS under PSC

Fig.11 shows the power v/s time plot of PV module under partial shading condition. The PV modules have insolation levels as M1:1kW/m^2, M2:0.9kW/m^2 and M3:0.5kW/m^2 and temperature 25°C. In this condition the power drawn by P&O and ANFIS is 542 W and 576.6W with settling time 0.4s and 0.02s respectively.



(a) (b)

Fig.11 Power v/s Time plot of (a) P&O and (b) ANFIS algorithm at PSC

(iii) Performance of P&O and ANFIS under Dynamic condition

Dynamic performances of both the MPPT algorithms are tested for rapidly changing irradiation level. Table.3 refers the shading pattern for each module under dynamic condition.

Table 3 Shading Pattern on PV array

Pattern No.	Irradiation Level in (W/m^2)	Time (Sec)
SP1	[M1:900, M2:700, M3:500]	0-2
SP2	[M1:700, M2:500, M3:600]	2-4
SP3	[M1:400, M2:300, M3:200]	4-5

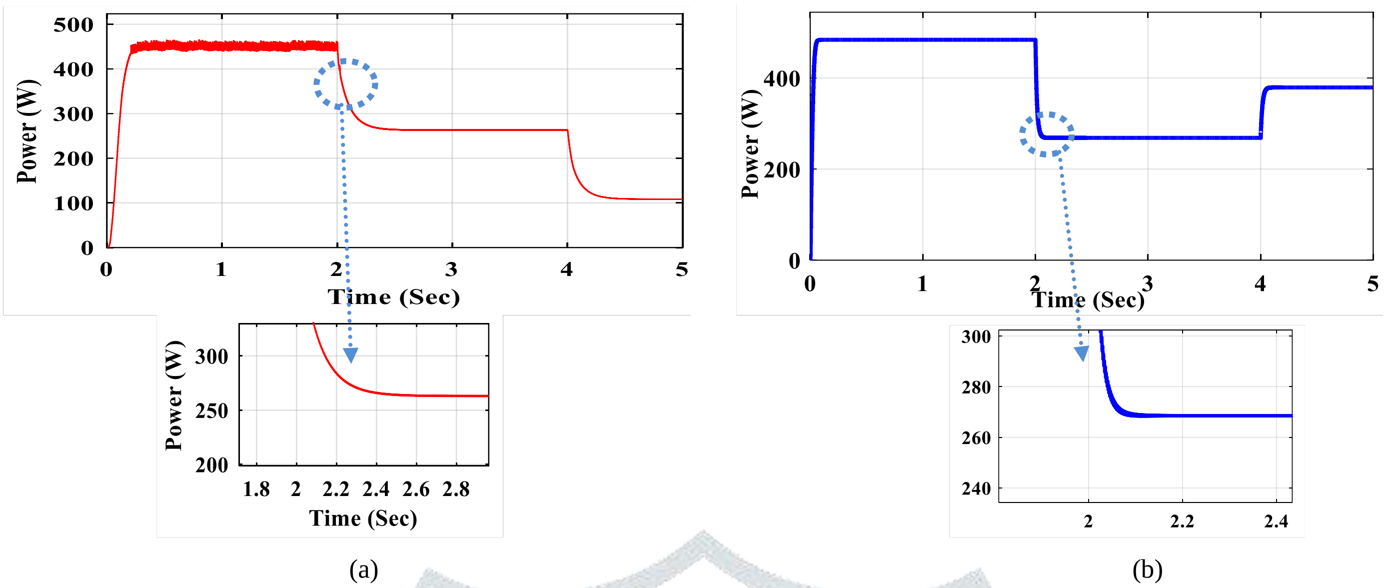


Fig.12 Dynamic performance of (a) P&O (b) ANFIS algorithms during changing irradiation level and enlarged transient response

It can be seen from fig.12 the performance of ANFIS is superior to P&O in terms of power tracking and settling time. Table 4 gives the comparative analysis of P&O and ANFIS algorithm under dynamic condition.

Table 4 Comparison of P&O and ANFIS algorithms under dynamic condition

Pattern No.	ANFIS		P&O	
	Power	Settling Time	Power	Settling Time
SP1	484W	0.07 Sec	450W	0.25 Sec
SP2	268W	2.08 Sec	263W	2.4 Sec
SP3	379 W	4.06 Sec	108 W	4.35Sec

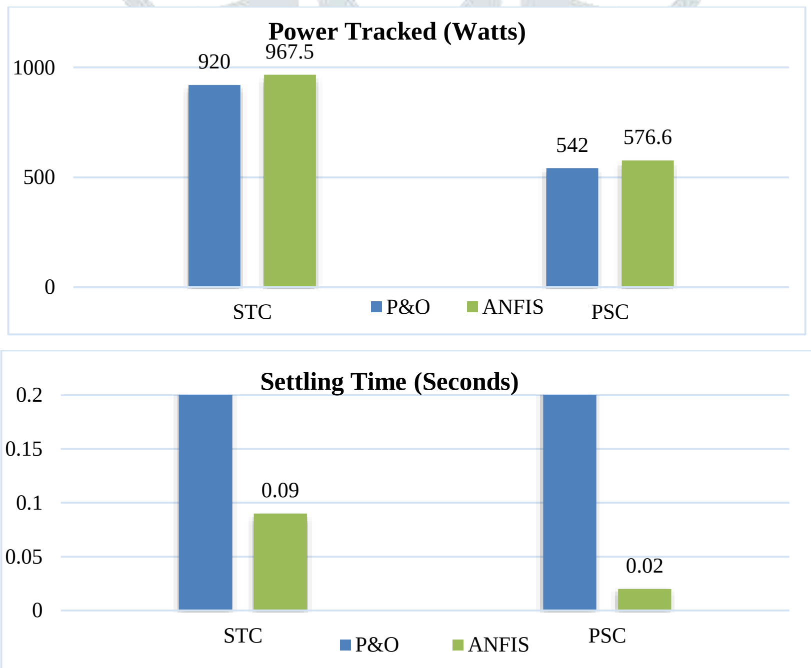


Fig.13 Comparison of power tracked and Settling Time of P&O and ANFIS under (a) STC (b) PSC

From fig.13 it can be concluded that ANFIS has better power tracking capability under the conditions of STC and PSC.

VII. Conclusion

In the present work, Adaptive neuro fuzzy inference system based maximum power point trackers for PV system under PSC has been presented. The presented algorithm is simple and gives remunerative solution under varying environmental condition in residential applications. The proposed algorithm has been designed, developed and validated to track the maximum power under various shading scenarios viz standard test condition, partially shaded condition as well as dynamic condition. Simulation results demonstrated that ANFIS can track maximum power having lower settling time under different shading scenarios. Comparative analysis of ANFIS and P&O has established the superiority of the ANFIS algorithm as an efficient tool to track maximum power under steady state and transient condition for SPV system which makes it more suitable for residential applications.

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