Analysis of High Performance MPPT Controllers for Solar Photovoltaic System

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Abstract--- *In photovoltaic (PV) power generation, rapidly changing atmospheric condition is an unavoidable complication that significantly reduces the performance of the system. MPPT is broadly used to extract maximum power under changing atmospheric condition. Various conventional, soft computing and meta-heuristic MPPT techniques are compared and implemented to determine its performance under various atmospheric condition. The MPPT algorithms used in this work are Particle swarm optimization (PSO), Adaptive Neuro fuzzy inference system (ANFIS), Artificial neural network (ANN), Fuzzy logic control (FLC), Incremental conductance (IC), Perturb and observe (P&O), and newly suggested technique for MPPT using the Whale optimization algorithm (WOA). The novelty of this work is the Whale optimization algorithm (WOA) proposed for MPPT. The parameters considered in determining the performance of MPPT in this work are response time, tracking efficiency, oscillations around maximum power point (MPP), verve condensed to reach stable state and hardware implementation complexity. The simulation was done in MATLAB/Simulink. The outcome of this analysis is expected to be useful for the investigators functioning in the section of MPPT techniques. This paper likewise fills in as a legitimate reference for future clients in choosing proper MPPT calculations.*

Keywords--- *Power Conversion Harmonics, DC-DC Power Converters, DC-AC Power Converters, Solar Panels, Maximum Power Point Trackers.*

I. INTRODUCTION

Non-conventional energy sources like biomass, wind, geothermal and hydropower, solar energy are carbon neutral and they do not produce greenhouse gas to pollute air, land and water. Solar energy is available abundant in nature. The solar PV generation technology used to convert the sun's power into electricity. Unfortunately, this system has two major drawbacks such as the efficiency of electric power generation is low during conversion, the measure of electric force created by sunlight based board changes quickly with fluctuating climatic conditions. Thus, MPPT is essential to reduce the difference between the MPP and load of the PV module. In the recent past, to track the MPP many MPPT methods have been proposed. The most popular MPPT techniques based on this approach are P&O and IC. These approaches are applied extensively to MPPT controllers due to its less complexity in implementation and simplicity. Soft computing techniques like FLC, ANFIS and ANN are more efficient, they have fast response, but they are more complex compared to the conventional techniques. During the recent past, these soft

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computing techniques are applied in the field of design, modeling, predicting, optimizing (PSO and WOA) and forecasting data analysis in solving various problems in renewable energy systems. Performance assessment has been done on MPPT techniques used in the converter to justify the output power [1].

II. DESIGN OF BOOST CONVERTER

The step up converter as shown in fig. 1. is responsible for extracting power existing at the PV. To meet the load requirements with the help of MPPT techniques it gets reference input from PV source. Reference parameters like voltage, current, irradiation, and temperature are sensed to generate a gate pulse and deliver to switch. The MPPT techniques with the help of PWM generators generate gate pulses/duty cycle to the switch in boost converter to extract maximum output power [2-17]. Tab. 1 shows the parameters used in the converter. In step up converter, the load voltage is connected to the source voltage by the relation shown in equation (1).

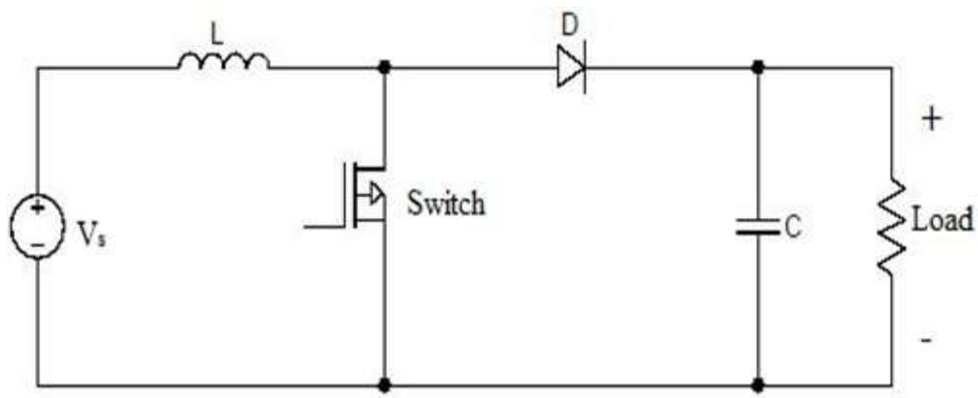

Fig. 1: Boost Converter

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \tag{1}$$

The duty cycle produced by MPPT techniques to the switch in step up is given by

$$D = 1 - \frac{V_{in}}{V_{out}} \tag{2}$$

The inductor in DC-DC converter is given by,

$$L_{\min} = \frac{(1-D)^2 * D * R_{load}}{2f} \tag{3}$$

The capacitor in DC-DC boost converter is given by,

$$C_{\min} = \frac{V_{out} * D}{R_{load} * f * \Delta V_r} \tag{4}$$

where V_{out} is the voltage output from the converter, V_{in} is the converter input, duty cycle is given by D, the value of the inductor is given by L_{min}, the value of the capacitor is given by C_{min}, R_{load} is the resistive load in converter, f is the frequency for switching and ΔV_r is the ripple voltage.

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Table I: Boost Converter Parameters

Parameters	*Value*
DC link capacitor	100 µF
Inductor (L_{min})	0.5 mH
Capacitor (C_{min})	300 µF
Switching frequency (f_s)	20 kHz

III. MAXIMUM POWER POINT TRACKING TECHNIQUES

MPPT techniques are aimed to derive utmost power available from the modules of PV in any atmospheric condition. The general block representation of MPPT techniques applied to proposed configuration is represented in fig.2. PV modules are synchronized to the load to ensure maximum generation of power. MPPT techniques, get the reference input of PV parameters like voltage, current, irradiation, temperature to generate a gate pulse to step up converter switch. The implementing strategy of MPPT techniques are as follows:

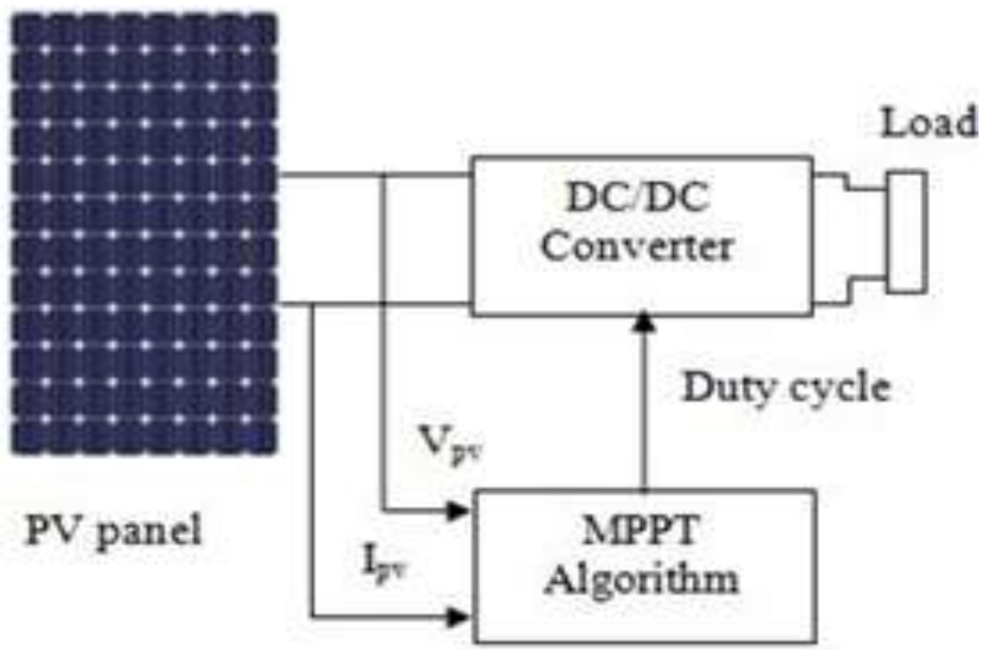

Fig. 2: Block Diagram used to Implement MPPT Algorithms

Perturb and Observe

P&O is the most normally utilized ordinary technique to follow the MPP from the PV. As the P&O name infers that it depends on the annoyance of the framework by venturing up or down the Vref or by coordinating straightforwardly on the obligation pattern of the lift converter and seeing the effect on the yield intensity of the board as appeared in fig. 3.

P&O is simple and easy to apply, but the major drawback in P&O is its oscillation around MPP which results in loss of energy and leads to reduced efficiency. For P&O MPPT technique voltage and current from the PV string are taken as a feedback to produce duty cycle and fed through a PWM generator to trigger the converter switch [18].

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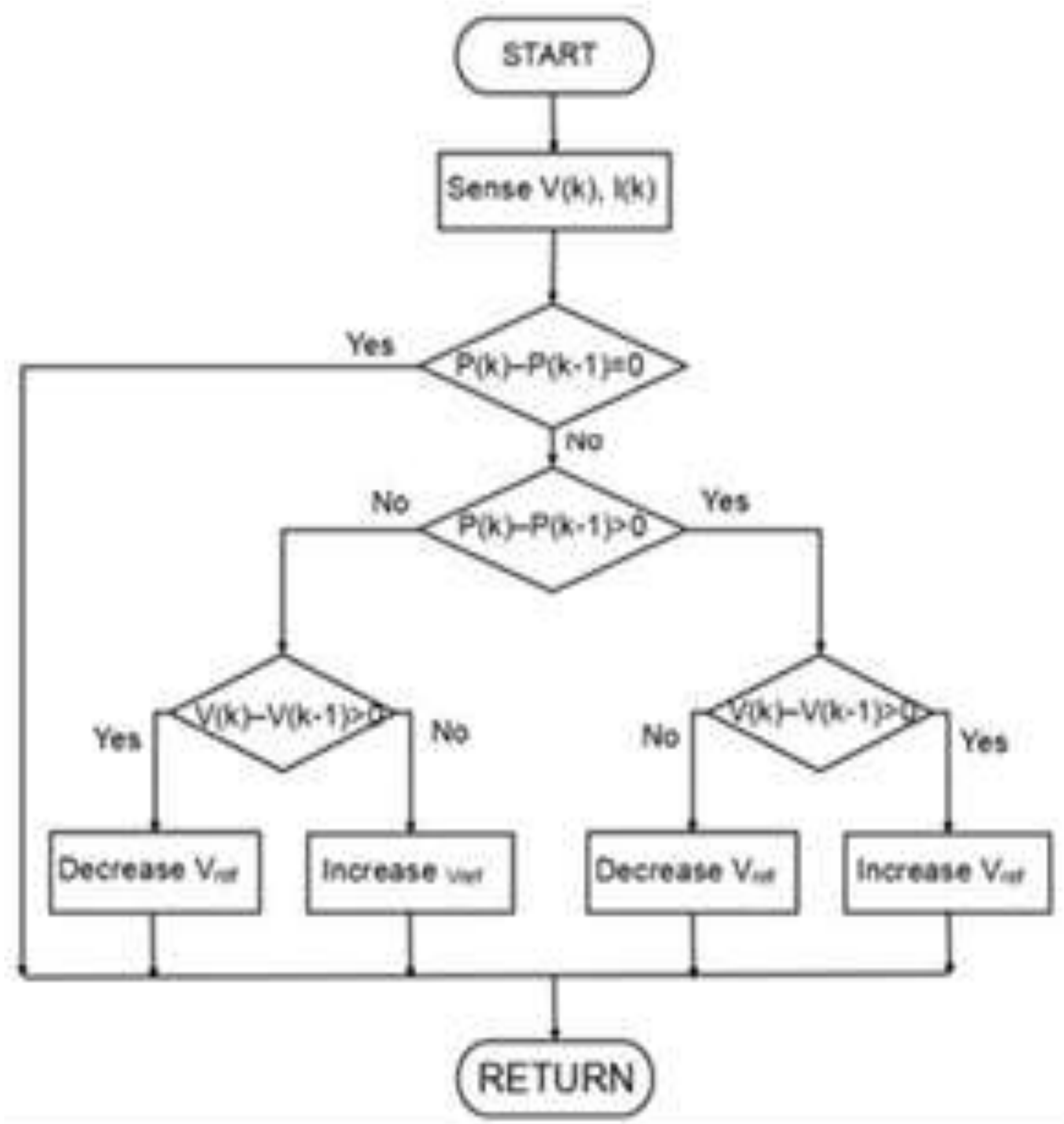

Fig. 3: Flowchart of P&O Method

The basic action of P&O for creating a reference voltage and the obligation cycle is showed up in Tab. 2. In the PV board, if the present force regard P(k) is higher than its past force regard P(k-1) by then we keep a comparable after course of following, if not switch the MPP following to the past cycle.

Incremental Conductance

IC looks at the gradual conductance ($\Delta I/\Delta V$) to the momentary conductance (I/V) in a PV framework. Contingent upon the outcome, it increments or diminishes the voltage until the greatest force point (MPP) is come to as appeared in fig.4. Not at all like with the P&O calculation, the voltage stays steady once MPP is come to right now.

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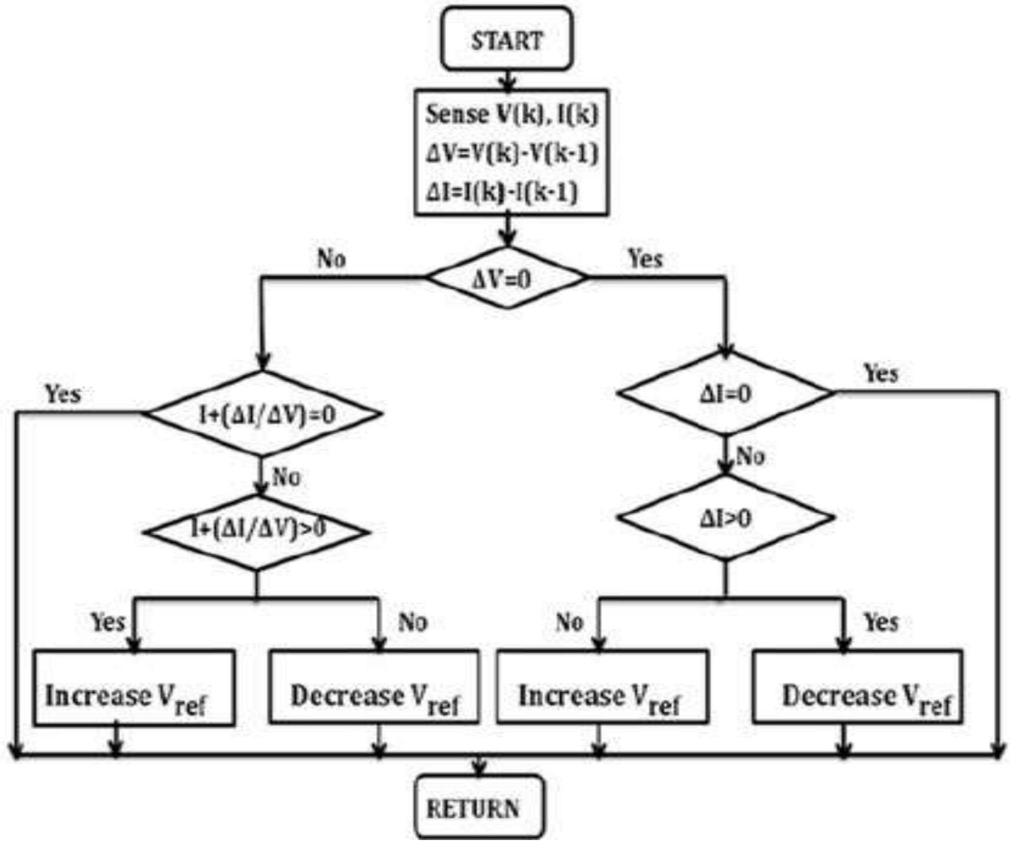

Fig. 4: Flowchart of IC method

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\,\frac{dI}{dV} \cong I + V\,\frac{\Delta I}{\Delta V} \tag{5}$$

In IC the oscillations are fewer compared to P&O due to the fact that it tracks the MPP and stays in MPP for some period of time, but the major drawback is it loses its track of MPP when the irradiation changed very rapidly [19]. For IC MPPT technique voltage and current from the PV string are taken as a feedback to produce a reference voltage and fed through a PWM generator to produce duty cycle to the converter switch.

Fuzzy Logic Control

Due to the dynamic atmospheric conditions and non-linear complexities in PV, it is good to use soft computing MPPT techniques which can handle nonlinear problems effectively in a fully digital controlled environment. In FLC the non-linear problems can be handled effectively with un-molded basic quantities and unpredictable changes in MPP operating point. The major drawback of the FLC is the rule table need to be frequently updated during the tracking mode of MPP which is practically impossible [20-23]. For FLC MPPT technique the inputs of FLC are E (K) and dE (K), the power change ΔPpv and change in voltage ΔVpv from the PV strings at sample time K are taken as a feedback to generate duty cycle to the converter switch as shown in fig.5. The rule viewer for the simulated model using FLC MPPT is shown in fig.6.

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$$E(K) = \frac{Ppv(k) - Ppv(k-1)}{Vpv(k) - Vpv(k-1)} \quad (6)$$

$$dE(k) = E(k) - E(k-1) \quad (7)$$

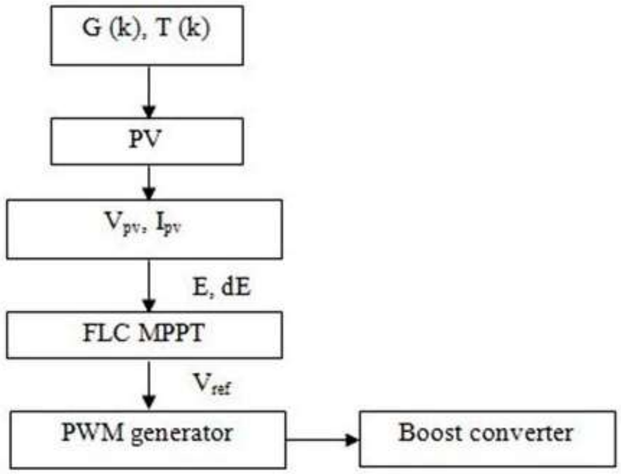

Fig. 5: FLC MPPT Control System

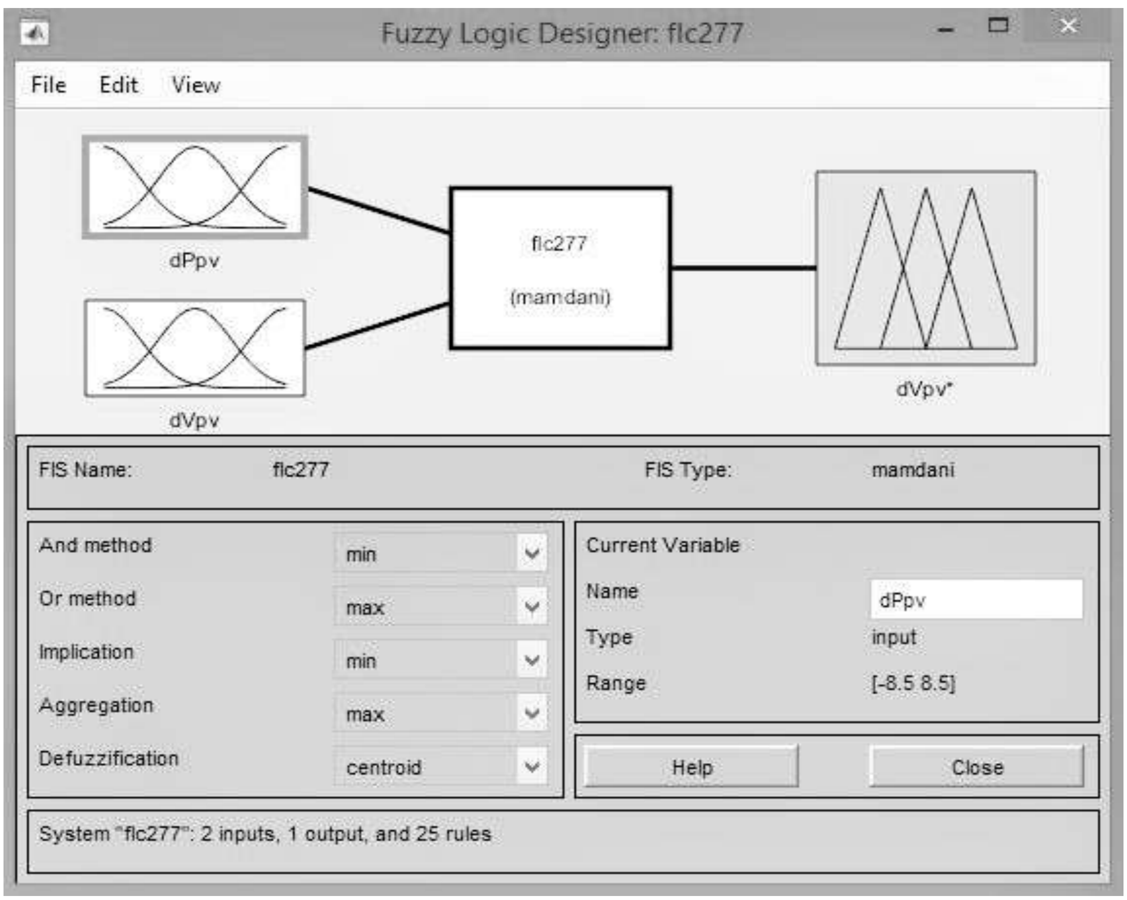

Fig. 6: Rule Viewer

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Where, the error at sample time k is E (k), the change in error is dE (k), Ppv(k) is the power extracted from panel during kth iteration. Ppv(k-1) is the power extracted from the solar panel during (k-1)th iteration. Vpv(k) is the panel voltage during k^{th} iteration, Vpv(k-1) is the voltage extracted from the panel during (k-1)th iteration. Error input E(k) is occurring during the k^{th} iteration, error input during (k-1)th iteration is E(k-1).

Adaptive Neuro Fuzzy Inference System

The drawbacks occur in FLC can be eliminated by coupling it with another controller like ANN by re-tuning its membership functions repeatedly [24]. Voltage and current inputs from PV strings are used as a training data set for ANFIS. Overall, 202 training data sets and 2000 epochs are utilized for training in ANFIS [25]. Trained data are compared with PV string data sensed in real time. Trained and sensed data are compared and the error is given to a repeating sequence block at a specific switching frequency to generate a control signal to PWM generator. PWM signal controls the gate pulse of the step up converter to regulate the PV string operating point as shown in fig.7. Maximum available power is calculated and recorded in ANFIS. The error occurs during training the ANFIS are shown in fig.8 using hybrid optimization technique. The control viewer of ANFIS system can be represented as in fig.9.

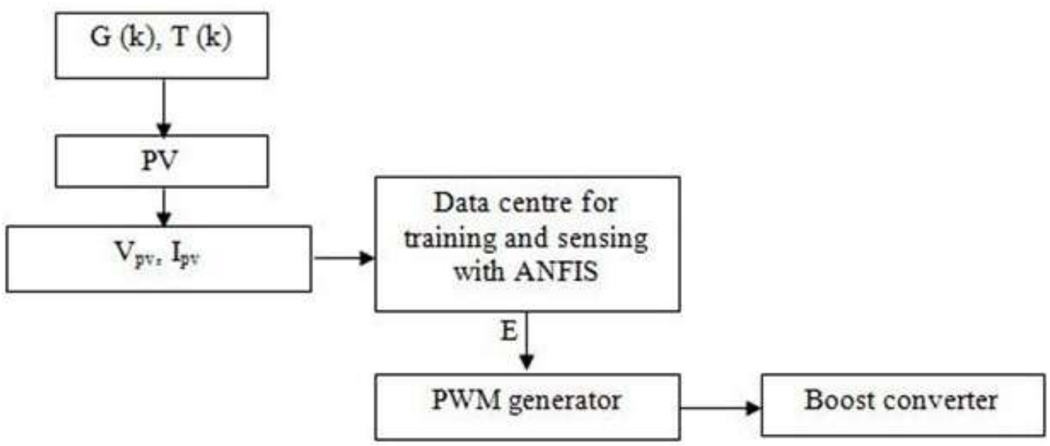

Fig. 7: ANFIS MPPT Control System

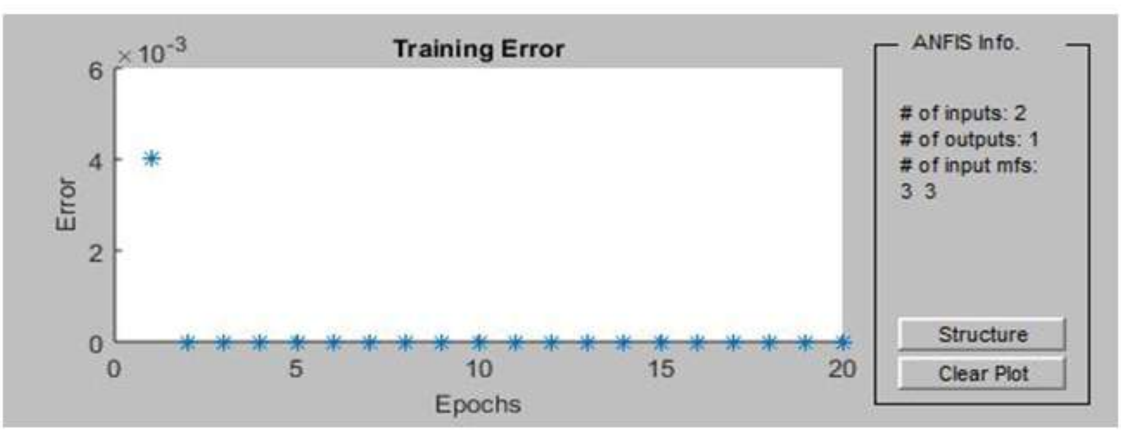

Fig. 8: Training Evolution of Error

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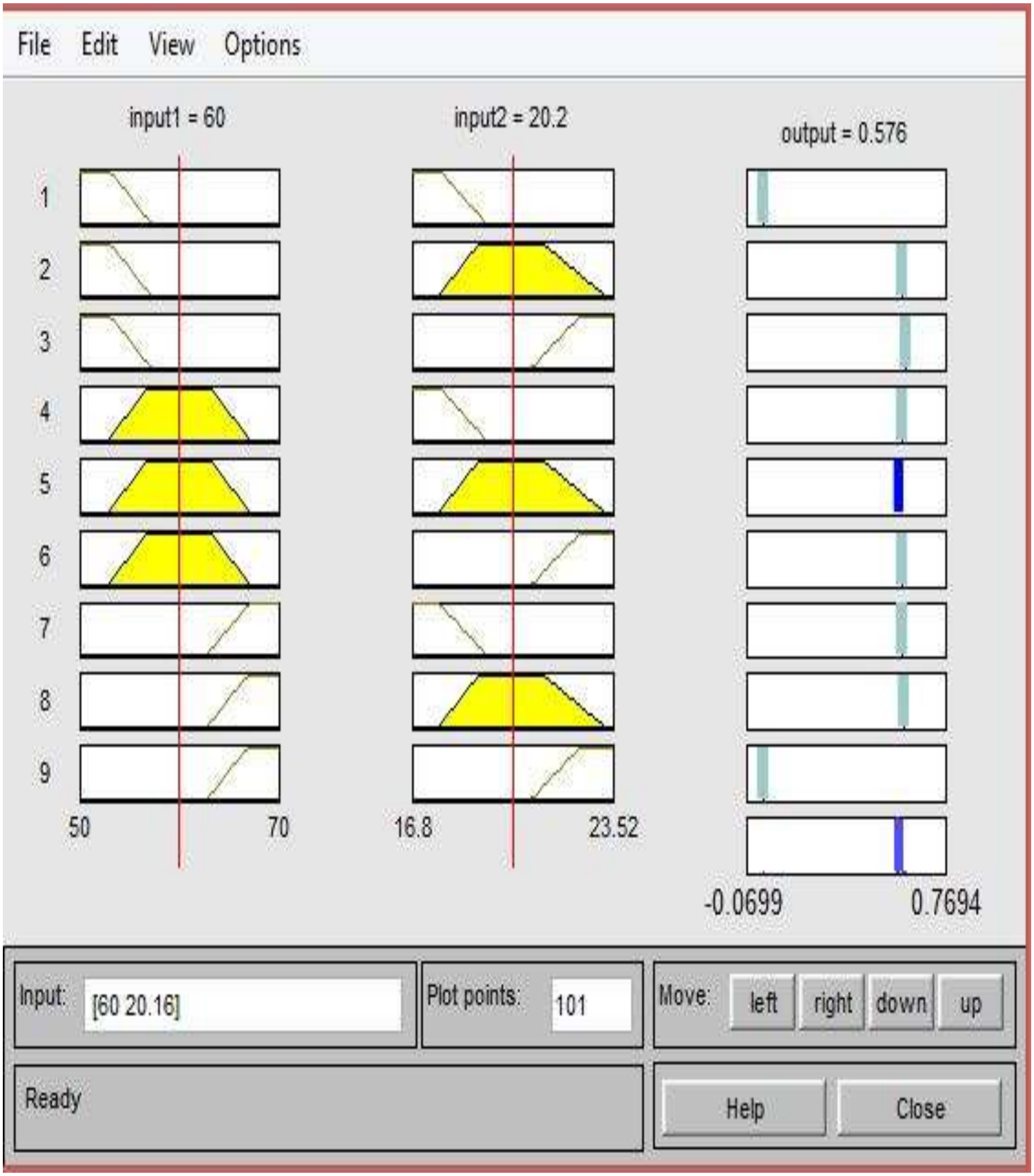

Fig. 9: ANFIS MPPT Control Viewer

Artificial Neural Network

The 3 common layers of ANN are the input, hidden, and output layers. The number of nodes in each layer varies and is user-dependent [26]. The control viewer of the ANN system can be represented as in fig.10. The variables at the input of the neural network are the PV voltage and current at various atmospheric conditions as shown in fig.11.

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During the training process, the weights are attuned after loading the training data in the tool [27]. Over a longer period of time to execute the training data, the data from the output and input are recorded by neural network. Evolutions of the ANN error during the training time are shown in fig.12. After training the predicted datas of the duty cycle for the corresponding voltage and current from the strings are shown in fig.13.

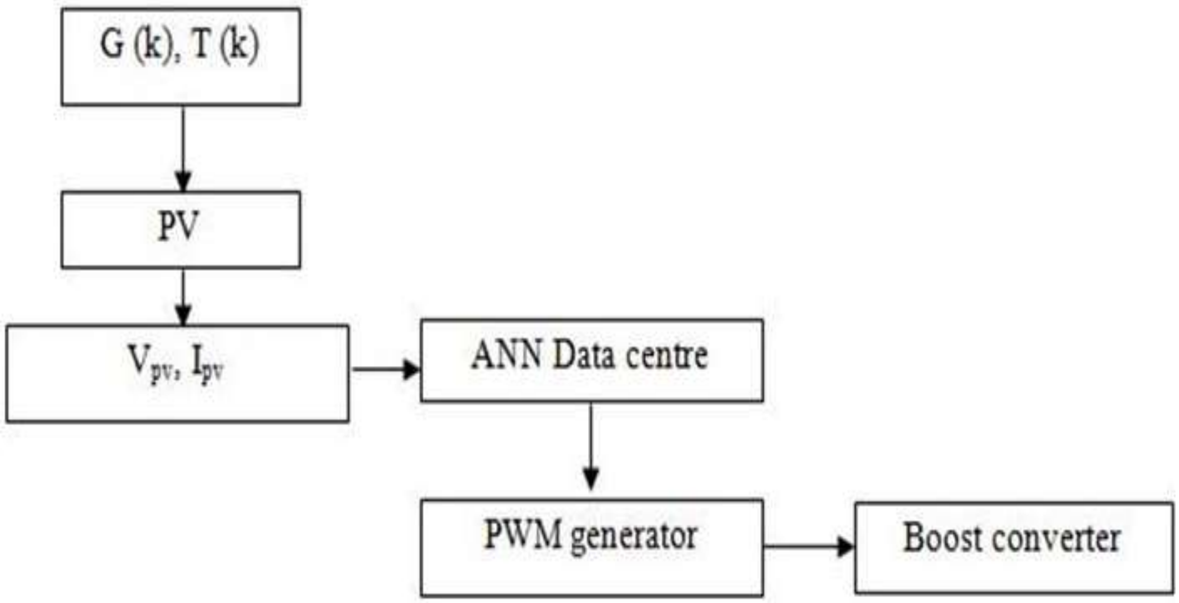

Fig. 10: ANN MPPT Control System

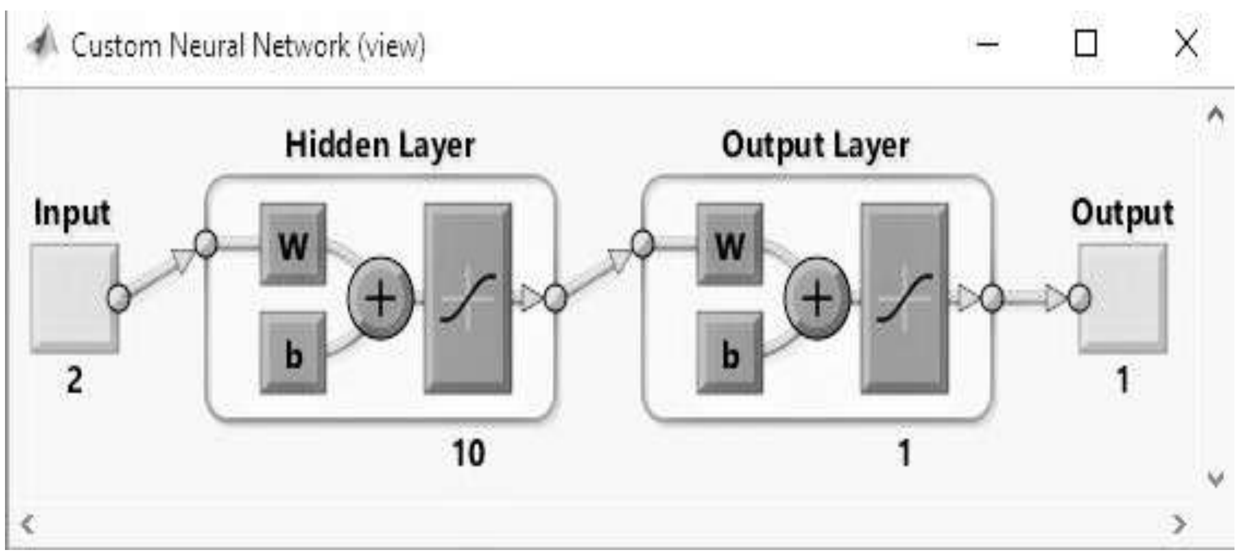

Fig. 11: Feed Forward Neural Network Approximation

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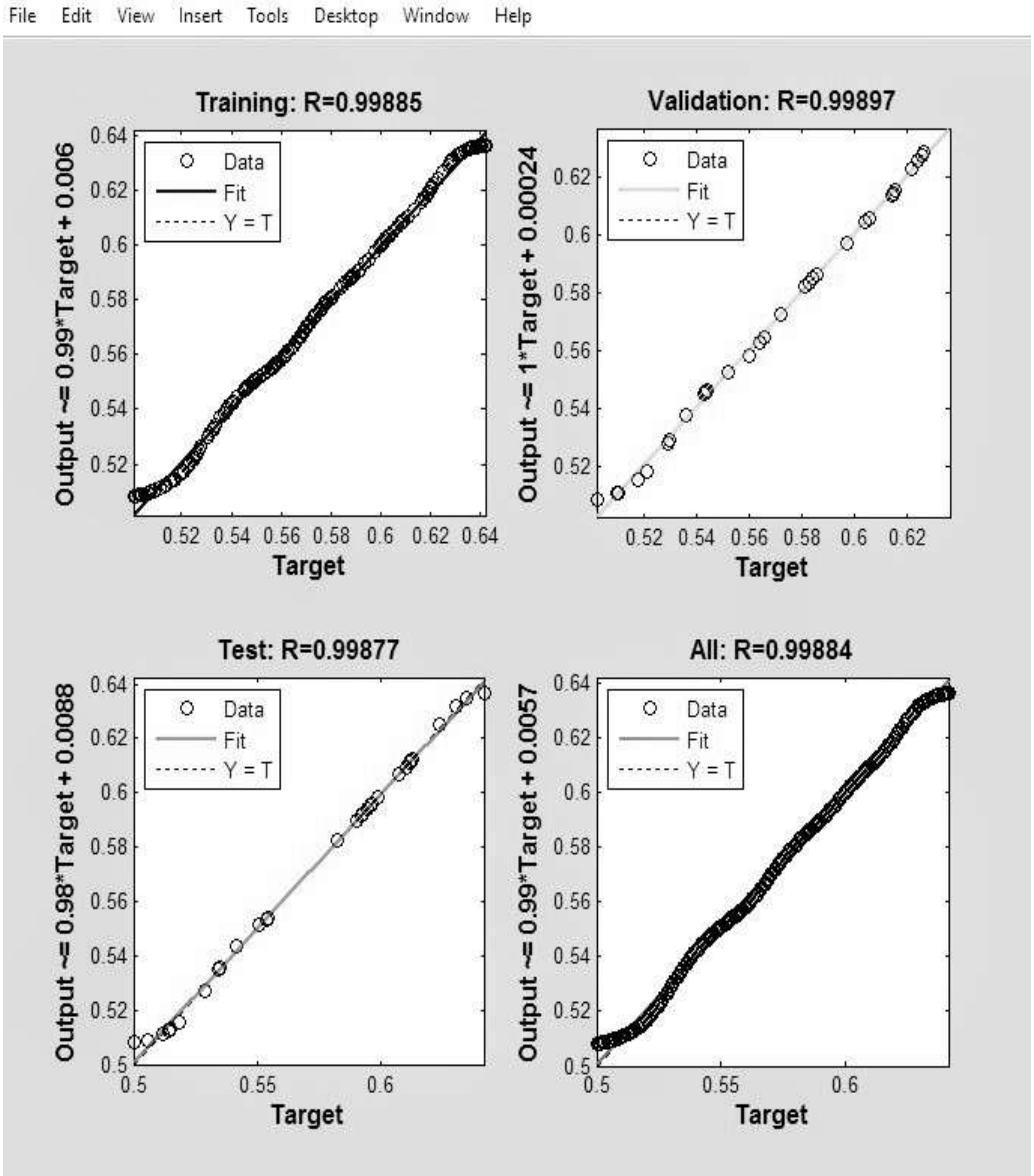

Fig. 12: ANN Training Evolution Error

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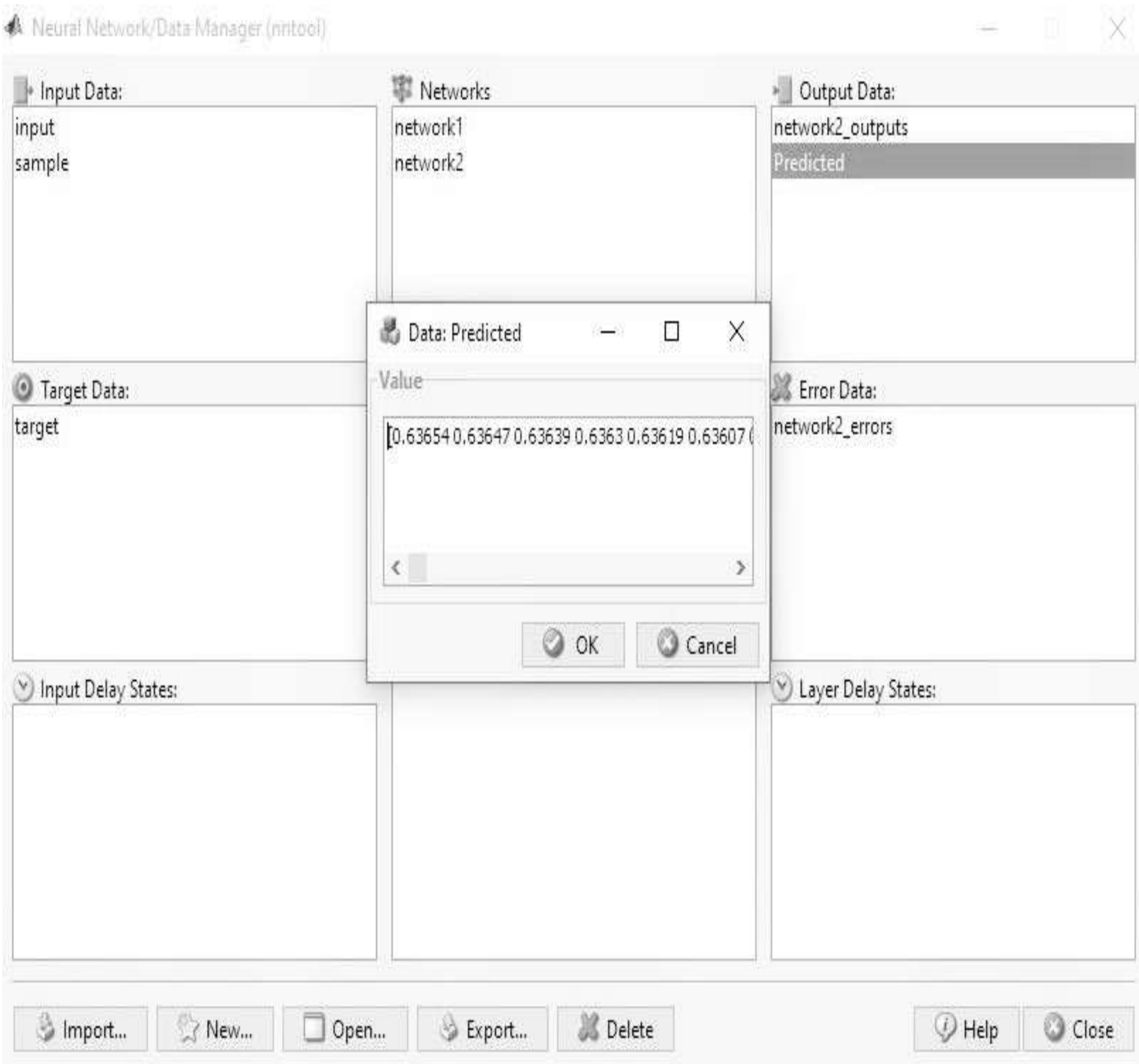

Fig. 13: ANN predicted datas after training

Particle Swarm Optimization

A PSO MPPT approach by one technique instead of two is shown here, the information about voltage on the boost converter is updated continuously [28][29]. In this work, the PSO MPPT algorithm is implemented for two boost converters to update the gate signals to the switches of the converter so that the global maxima can be attained. The initialization of the agents is shown in Tab. 3. The C++ language is used to write the algorithm and simulated in Matlab/Simulink. During each iteration, after the re-organization, each particles in the swarm is given by the following equation.

The position vector of the agents are grouped by the Duty cycles as

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$d_{i,k}$=[d1 d2 d3 …..dn] i=1,2,3,….m

The subscript i,k in the above condition demonstrates the obligation patterns of ith specialist at kth emphasis, dn is the obligation patterns of the nth converter for operator i, and the all out number of specialists is indicated by m.

$$d_{i,k+1} = d_{i,k} + W_1 * (d_{i,k} - d_{i,k-1}) + W_2 * r_1 * (d_{i,best} - d_{i,k}) + W_3 * r_2 * (d_{g\_best} - d_{i,k}) \quad (8)$$

Where, the position vector di, best relating to the most extreme force accomplished by the operator i and the position vector dg-best comparing to the greatest force accomplished by any specialists.

Whale Optimization Algorithm

WOA is the multi-objective algorithm proposed for the optimization and non-linearity problems [30]. It is a population based method. They are generally used for power system applications to solve economic dispatch problem. WOA concept was developed based on humpback whales special hunting technique. Their foraging behavior is called bubble net feeding method. They prefer to hunt small fishes close to the surface. The whales cordially dive down and then create bubbles in a circular shape around the prey and swim up the surface. In this work the circular bubble net feeding is mathematically modeled to perform optimization. The basic concepts of the WOA involve, encircling prey, bubble-net fishing and search of prey.

Table II: Initial Duty Cycle of Different Agents

Agents	*DC-DC converter1*	*DC-DC converter2*
1	0.3	0.4
2	0.4	0.6
3	0.5	0.3
4	0.7	0.4
5	0.5	0.6

Tab. 2 represents the initial duty cycle of different agents in the algorithm.

The whales with humpback know the area of prey and circle them. They consider the present best competitor arrangement is best acquired arrangement and close to the ideal arrangement. In the wake of allotting the best up-and-comer arrangement, different operators attempt to refresh their situations towards the best pursuit specialist as appeared in the accompanying condition

$$E = \left| D.y^*(t) - y(t) \right| \quad (9)$$

$$y(t+1) = y^*(t) - B.E \quad (10)$$

where, t is the present cycle, B and D are coefficient vectors, y* is the position vector of the best arrangement and y demonstrates the position vector of a solution,‖ is the total worth. The vectors B and D are determined as follows.

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$$B = 2b.s.b \qquad (11)$$

$$D = 2.s \qquad (12)$$

Where segments of 'b' directly diminished from 2 to 0 through the span of cycles and s is an arbitrary vector in [0;1]. The humpback whales assault the prey with bubble net instrument. This component is scientifically detailed as follows. In winding enclosing system, the estimation of A will be an arbitrary incentive in interim [-b, b] and the estimation of 'b' is diminished from 2 to 0 throughout cycles as appeared in condition 13. In winding refreshing system position component, the separation between the whale area and the prey area is determined then the helix molded development of humpback is made as appeared in the accompanying condition.

$$y(t+1) = \vec{E}.e^{bi}.\cos(2.\prod.l) + \vec{y}^*(t) \qquad (13)$$

Where,

$$\vec{E} = \left| y^*(t) - y(t) \right| \qquad (14)$$

Condition 15 is the separation between the prey (best arrangement) and the ith whale, b is a steady, l is the arbitrary number in [-1;1]. The humpback whales utilized the referenced two systems when they swim around the prey. Set the scientific model of these two components, expect that there is a likelihood of half to pick between these two instruments to refresh the situation of whales as follow

$$y(t+1) = \begin{cases} y^*(t) - B.D & \text{if } P<0.5 \\ \vec{D}.e^{bi}.\cos(2\Pi l) + y^*(t) & \text{if } P>0.5 \end{cases} \qquad (15)$$

Where p is an arbitrary number in [0;1]. In the investigation stage, the humpback whales (search specialists) scan for prey (best arrangement) arbitrarily and change their situation of different whales. So as to drive the hunt specialist to move far away from reference whale, we utilize the B with values >1 or <1. The mathematical model of the exploration phase is as follows.

$$E = \left| D.y_{rand} - y \right| \qquad (16)$$

$$y(t+1) = y_{rand} - B.E \qquad (17)$$

Where yrand is a random position vector chosen from the current population. This procedure is done till the optimum value is approached. The purpose of the MPPT is to extract the maximum power by tracking the peak point. This WOA concept is similar to tracking MPP where the WOA search for fish in a sea is a search space. The WOA is applied to find the MPP by minimizing the objective function of the PV system where the voltage and current are taking the positions of the whale and prey, the search space is the varying atmospheric condition, the lower and upper bound values of the voltage and current are taken as per the data sheet provided by the panel manufacturers. The duty cycle is generated by the algorithm based on the optimal value.

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IV. RESULTS AND DISCUSSION

The simulation constraint of the proposed system is as pursuing: PV strings modeled for rating up to 3 kW, each PV string connects to boost converters with an inductor and capacitor parameters of 0.507 mH and 307 μF operating with switching frequency 20 kHz. In order to attain the MPP of the PV strings, P&O, IC, FLC, ANFIS, ANN, PSO and WOA MPPT tracking systems [31] are developed in MATLAB/Simulink. The results are presented for the following configurations.

- Standard test condition (STC) of PV module.
- Dynamic variation in irradiation.

During STC, the solar irradiation pattern are shown as in Tab. 3. The PV strings are connected to the resistive load of 33Ω interconnected by boost converter at the frequency of 20 kHz. The solar irradiation is held constant from 0s to 0.3s. The simulation results are shown in Tab. 4. Soft computing techniques show better tracking efficiency compared to conventional systems by solving non-linear characteristics in PV. But, the major drawback in this is the real-time implementation complexity, Large memory space is needed to upload the data. In conventional MPPT IC MPPT extracts the MPP with the efficiency range of 80.3% with better tracking speed and thin oscillations when compared to other techniques.

All MPPT techniques are able to extract MPP at the specified conditions during analysis. It can be noted that the tracking speed of soft computing techniques is fast compared to other techniques. But, the drawback is during dynamic atmospheric condition the oscillations produced by soft computing techniques are high compared to other techniques. Due to this, the tracking efficiency has huge deviation. In conventional model IC MPPT produces the better deviation in tracking efficiency (less than 20%) whereas the rest of the MPPT techniques has high deviations in tracking efficiency (greater than 20%).

Table III: STATIC response of irradiation pattern

PV strings Pattern	String 1 and string 2 pattern	
	Irradiation G (W/m2) (From t=0s to t=0. 3s)	Cell temperature T(°C)
SR1	1000	25

Tab. 3 represents the static response irradiation pattern.

During change in irradiation, the solar irradiations at dynamic test conditions are shown as in Tab. 5. The solar irradiation is held constant from 0s to 0.1s at 1000W/m2 then reduced to 200W/m2 from 0.1s to 0.2s and gradually increase to 600W/m2 from 0.2s to 0.3s as shown in fig. 14. The simulation results are shown in Tab. 6. The response time or tracking speed of MPPT techniques should be very less to perform better by extracting maximum power in real time. ANFIS MPPT technique shows better performance with tracking speed of 0.016s when compared to IC whereas WOA shows better tracking speed of 0.03s. The implementation complexity of ANFIS and WOA MPPT technique in real time is difficult, so the next best performing MPPT technique like IC is used due to better tracking speed of 0.037s. Tab. 4 represents the static response of MPPT at STC.

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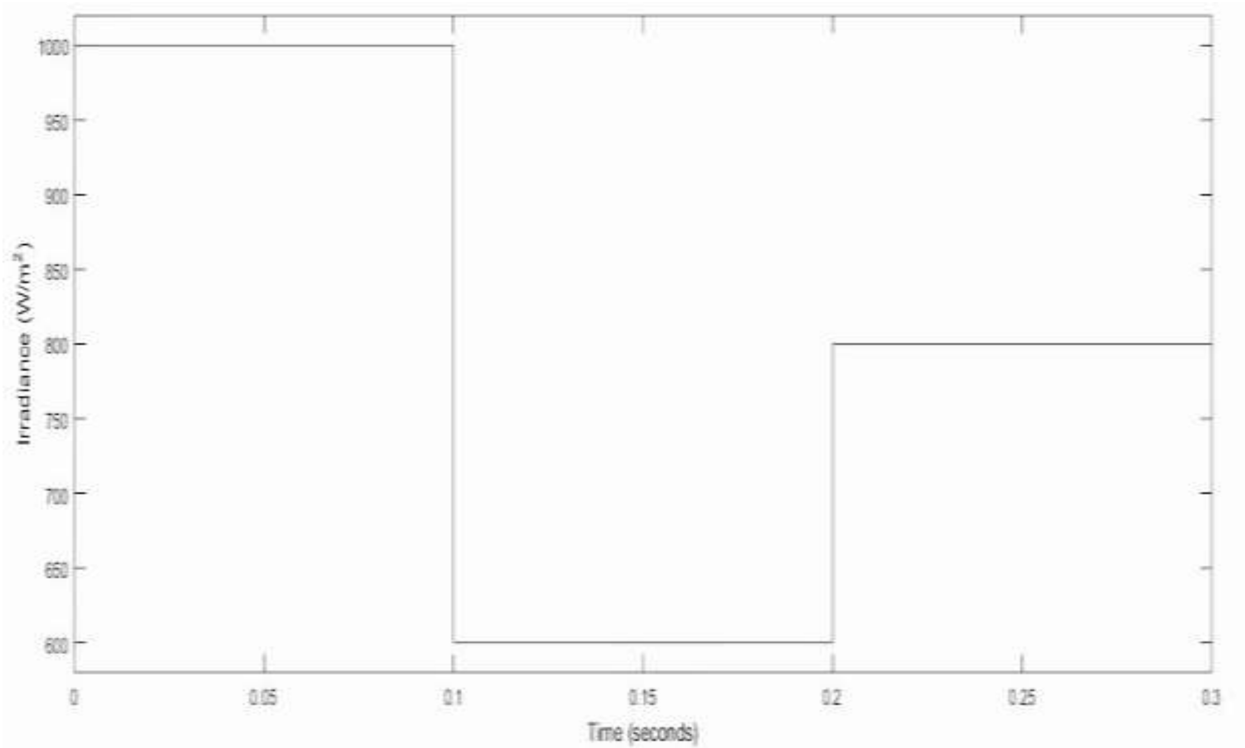

Fig. 14: Pattern of Dynamic Behavior

Overall performance can be determined by comparing best MPPT techniques from these three categories. In conventional MPPT IC performs well. In soft computing based MPPT ANFIS performs well. In optimization based MPPT WOA performs well. The comparisons of these three categories of MPPT techniques based on power extraction, oscillations and tracking speed are shown in fig.15.

Tab. 5 represents the dynamic response irradiation pattern. Tab. 6 represents the response of MPPT during dynamic irradiation pattern.

Table IV: Static Response of MPPT Techniques at STC

MPPT	*Pattern*	*Simulation time From t=0s to t=0.3s*				
		Vdc (V)	*Pdc (W)*	*Tracking speed (s)*	*Tracking Efficiency (%)*	*H/W*
P&O	SR1	206.8	2138	0.0236	71.2	Easy
IC	SR1	219.1	2401	0.037	80.3	Easy
FLC	SR1	205.5	2112	0.019	70.4	Med
ANFIS	SR1	203.8	2186	0.016	72.86	Hard
ANN	SR1	210.7	2220	0.0175	74	Hard
PSO	SR1	190	1805	0.025	60.1	Med
WOA	SR1	217.3	2361	0.03	78.7	Med

Table V: Dynamic Response of Shaded Irradiation Pattern

PV string Pattern	*String 1 and string 2 pattern*	
	Irradiation G1 (W/m2) (From t=0s to t=0. 3s)	*Irradiation G2 (W/m2) (From t=0s to t=0.3s)*
SR2	1000	800
SR3	600	1000
SR4	800	600

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Table VI: Dynamic Response of Irradiation Configuration

MPPT	*Pattern*	*Simulation time From t=0s to t=0. 3s*				
		Vdc (V)	*Pdc (W)*	*Tracking speed (s)*	*Tracking Efficiency (%)*	*H/W*
P&O	SR2	206.8	2138	0.0236	71.2	Easy
	SR3	179.7	1614	0.0236	53.8	
	SR4	179.4	1608	0.0236	53.6	
IC	SR2	219.1	2401	0.037	80.3	Easy
	SR3	190.4	1813	0.037	60.4	
	SR4	190.1	1807	0.037	60.2	
FLC	SR2	205.5	2112	0.019	70.4	Medium
	SR3	154.9	1200	0.019	40	
	SR4	150.9	1168	0.019	38.9	
ANFIS	SR2	203.8	2186	0.016	72.86	Hard
	SR3	170.7	1537	0.016	51.2	
	SR4	170.6	1532	0.016	51	
ANN	SR2	210.7	2220	0.0175	74	Hard
	SR3	167	1394	0.0175	46.4	
	SR4	165.9	1364	0.0175	45.4	
PSO	SR2	190	1805	0.025	60.1	Medium
	SR3	170	1343	0.025	44.7	
	SR4	153.2	1172	0.025	39	
WOA	SR2	217.3	2361	0.03	78.7	Medium
	SR3	188.9	1784	0.045	59.4	
	SR4	188.6	1778	0.047	59.2	

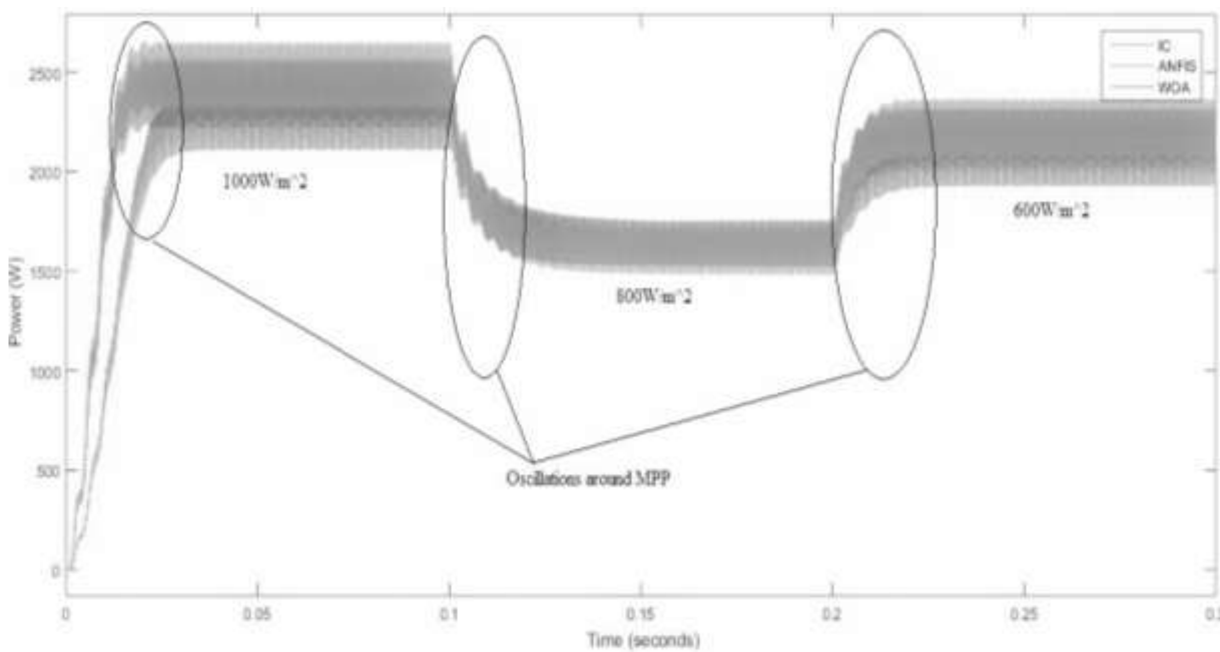

Fig. 15: Oscillations and tracking speed of MPPT techniques at different atmospheric

V. CONCLUSION

This paper elaborated the performance of MPPT techniques for a PV system. The configuration of the system is modelled and simulated using MATLAB/Simulink. The acceptable outcomes are summarized as follows. The PV

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system shows a better static and dynamic performance using MPPT algorithms to track the MPP at any environment condition. The DC-DC boost converter with proposed WOA MPPT algorithm shows good tracking efficiency (78.7%). But, the implementation complexity in real time is difficult. IC MPPT is chosen because it has high tracking efficiency (80.3%). It can provide output with less oscillations and better tracking efficiency than other MPPT techniques. The results thus obtained shows that the IC MPPT technique can be incorporated for applications in grid connected/standalone PV system.

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