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RESEARCH ARTICLE

DEVELOPMENT of an ANFIS BASED CONTROL ALGORITHM for MAXIMUM POWER POINT TRACKING in ON-GRID DOUBLE STAGE SINGLE PHASE PV INVERTER

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ABSTRACT

In recent years, interest in solar energy has increased due to the increase in power consumption, the inadequacy of fossil resources and the damage it causes to the environment, as it is a natural energy source and is sustainable. Electricity is generated from solar energy using photovoltaic (PV) panel systems, and PV systems can be easily installed anywhere. In the PV panel systems, the power obtained at the panel output decreases and the efficiency decreases due to geographical conditions, environmental factors and system design. Maximum Power Point (MPP) tracking algorithm is used to obtain maximum output power from the PV panel system and to increase system efficiency. In this study, an Adaptive Network Based Fuzzy Inference System (ANFIS) based MPP tracking algorithm has been developed to obtain maximum power continuously from on-grid double stage 2 kW single phase PV inverter. The ANFIS algorithm uses an adaptive neural network to optimize the parameters of the membership function, and is a combination of artificial intelligence and fuzzy logic. In the algorithm, Direct Quadrant (dq) synchronous reference frame transform is used to generate PWM signals of active switches in on-grid single phase PV inverter. In this algorithm, dq control is performed by converting the grid current and its component obtained by 90° time delay from the stationary axis to the synchronous rotating axis. The algorithm developed based on dq and ANFIS provides the power demanded by the AC grid in a stable and continuous, while following the MPP, increasing the power obtained from the PV panel and inverter, providing maximum efficiency. The validity of the developed algorithm was tested using the Matlab/Simulink simulation program. The comparison simulation results with the PandO algorithm confirm the superiority of the developed ANFIS algorithm.

Keywords: *Adaptive Neuro-Fuzzy Inference System Controller ANFIS, Maximum Power Point Tracking, DC/DC Boost Converter, On-Grid Single Phase PV Inverter*

1. INTRODUCTION

With the depletion of fossil fuels from conventional energy sources, the development of renewable energy systems (RES) and energy management has attracted the attention of researchers due to its clean and renewable features [1]. RES contain different types of energy. Compared to fossil based energy systems, it is safer, reduces gas emissions that harm nature, increases efficiency, and reduces production costs [2]. With the development of new energy technologies in recent years, research on grid-connected photovoltaic (PV) panel systems, PV power generation and modeling has increased rapidly in the field of RES. PV power generation is discontinuous and unstable. Therefore, higher requirements are put forward regarding the control of the on-grid PV inverter [3].

The control of a conventional two-stage on-grid single phase PV inverter consists of maximum power point tracking (MPPT) algoritm and DC/AC inverter algoritm. Some of the conventional MPPT methods proposed in the literature consist of the Perturb-and-observe (PandO) [4], the hill climbing [5], the incremental conductance (IC) [6,7] and the incremental resistance [8]. In conventional methods, a reference signal is produced by comparing the new output power value calculated with the previous panel output power value. These methods are suitable for the MPPT algorithm where there is only one MPP under uniform solar irradiation.

In recent years, MPPT methods based on meta-heuristic optimization algorithms have been proposed [9]. These optimization methods are genetic algorithm [10], cuckoo search [11], particle swarm optimization [12], and ant colony optimization [13]. Optimization based methods usually determine the operating point at which maximum power is obtained from the PV panel system based on some biological properties. In these methods, the accuracy of the algorithms is variable according to the starting point of the algorithm and the selected parameters.

It is necessary to have more detailed information about the PV panel system in advance and to measure the parameters of the panel such as irradiation, temperature, open circuit and short circuit online. Some intelligent algorithms such as artificial neural networks (ANN) and fuzzy logic controller (FLC) are used in online methods. Adaptive neuro-fuzzy inference system (ANFIS) is a hybrid between ANN and FLC. ANFIS combines the advantages of both of the techniques in making itself the most powerful artificial intelligence technique [14,15]. It utilizes the learning capabilities of ANN with the ability of FLC to treat inaccurate data and this suits well for PV applications [16]. ANFIS is used as an MPP tracking algorithm that is applied both off-line and on-line. A buck-boost converter controlled by an adaptive neuro fuzzy inference system (ANFIS) MPPT algorithm is developed in [17].

In this study, an ANFIS-based MPPT control algorithm has been developed to continuously obtain maximum power from a on-grid double stage single phase PV inverter. Sugeno inference with three inputs and one output is used in the ANFIS algorithm, and irradiation and temperature data are chosen as input training data. In the algorithm, 3 membership functions (MF) are defined for each input. Accordingly, 9 output functions are defined for the ANFIS algorithm output. dq synchronous reference frame conversion is used to generate PWM signals of active switches in a single-phase inverter. The current control in the proposed algorithm is performed by the transformation at the fundamental grid frequency of an orthogonal pair which is the grid current and its time delayed component to a synchronous rotating frame from a stationary frame. Using the control algorithm developed based on dq and ANFIS, the PWM signal of the active switch used in the DC/DC boost converter is adjusted and a voltage of 400 V is obtained at the output. The obtained PV voltage is applied to the 2 kW single phase inverter and 220V 50Hz AC is obtained from inverter output. The control algorithm developed based on dq and ANFIS, while following MPP, provides maximum efficiency by increasing the power obtained from the PV panel and inverter, and provides the power demanded by the load in a stable and continuously.

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2. ON-GRID DOUBLE STAGE SINGLE PHASE PV INVERTER

The system model of a 2 kW on-grid double stage single phase PV inverter is shown in Figure 1. It basically consists of two parts. The first part is the DC/DC boost and the second part is the DC/AC inverter. The output voltage obtained from the PV panel system is increased by using the MPPT control algorithm in the DC/DC boost converter. In a DC/AC inverter, DC power is converted to AC power in the same phase and frequency with the grid voltage. MATLAB Simulink R2019a is used for the circuit simulation. The parameters of the system are given in Table 1.

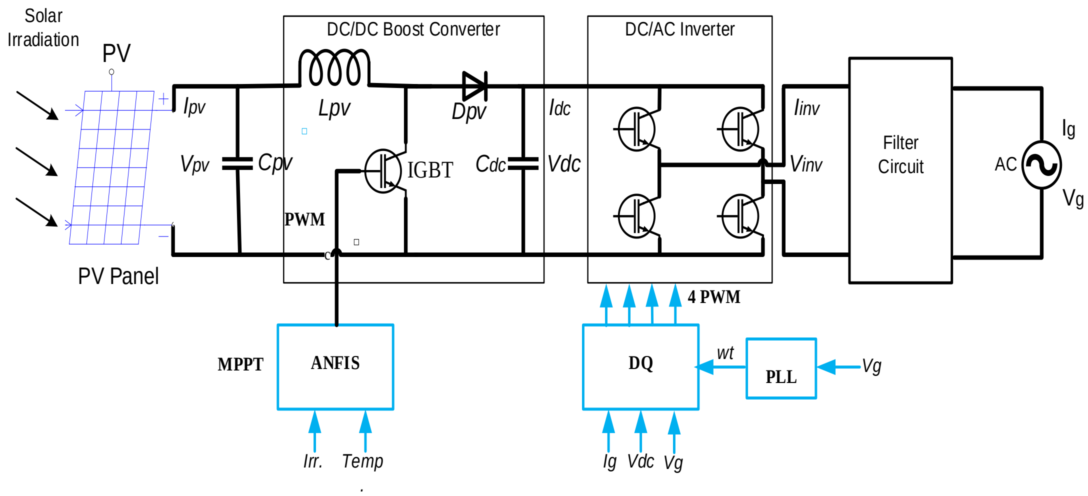

Figure 1. On-grid double stage single phase PV inverter with LCL filter.

Table 1. Parameters of the 2 kW on-grid double stage single phase PV inverter.

Parameters	Symbols	Values
Grid rms voltage	V_g	220 V
Grid operating frequency	f_g	50Hz
Boost DC/DC converter switching frequency	f_{pv}	10 kHz
Boost Inductance	L_{pv}	20 mH
Reference DC voltage	V_{ref}	400V
DC link capacitance	C_{dc}	500 µF
LCL filter	L_1 C_f L_2	4.06 mH 6.23 µF 4.06 mH

Inverter switching frequency	f_{inv}	20 kHz

2.1. PV Panel and DC/DC Boost Converter

They are devices that can convert the irradiation falling on PV panels into direct voltage. PV panels are formed by connecting panels in series or parallel. By connecting the panels in series, the voltage value of the PV system is increased, and by connecting the PV panels in parallel, the current value of the PV system is increased. Thus, it is possible to increase the nominal power of the PV system to the desired level [18]. The PV panel equivalent circuit is as given in Figure 2.

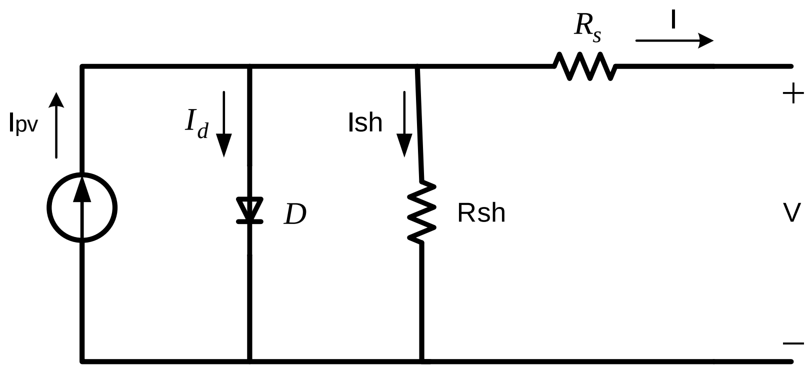

Figure 2. The PV panel equivalent circuit.

It is characterized with a current source and a diode connected in parallel to it. The series resistance R_s is used to define the contact resistance between the PV cell and its terminals, and it represents the resistance of the semiconductor that causes the voltage drop in the PV cell. The parallel resistance R_{sh} is used to show the leakage resistance in the PV panel. Current, voltage and temperature expressions describing the physical model of a PV panel are given in Eq. 1, Eq. 2, Eq. 3, Eq. 4 and Eq. 5 [19].

$$I = I_{ph} - I_d - V_d/R_{sh} \tag{1}$$

$$I_{ph} = I_{sc0}\,\frac{S}{S_0} + C_t(T - T_{ref}) \tag{2}$$

$$I_d = I_{s0}\left(\frac{T}{T_{ref}}\right)^3 \exp\left(\frac{qE_g}{Ak}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right)\left[\exp\left(\frac{qV_d}{AkT}\right) - 1\right] \tag{3}$$

$$T = T_a + k_s S \tag{4}$$

$$V_d = V - IR_s \tag{5}$$

Here, q electron charge value is 1.6022e-19, k Boltzmann constant value is 1.3806e-23, S is light intensity, T_a is ambient temperature, I is the output current of the PV panel, V is the output voltage between the ends of the PV panel, I_d is the average current through the diode, V_d is on the diode voltage, I_0 is diode saturation current, and n is the ideal diode factor. The parameters of the PV panel are given in Table 2.

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Table 2. PV panel parametparameters.

Model parameters	
Panel current I (A)	9.4447
Diode saturation current I_0 (A)	3.2328e-10
Ideal diode factor A	1.045
Parallel resistance R_{sh} (Ω)	47.9694
Series resistance R_s (Ω)	0.22828
Maximum power (W)	350
Number of cells (N_s)	80
Open circuit voltage V_{oc} (V)	51.5
Short-circuit current I_{sc} (A)	9.4
Voltage at maximum power V_{mpp} (V)	43
Current at maximum power I_{mpp} (A)	8.13
Temperature coefficient in V_{oc} (%/deg.C)	-0.36
Temperature coefficient in I_{sc} (%/deg.C)	0.09

In Figure 3, it is observed that the power obtained at the PV panel output changes with the solar irradiation. Maximum power can be obtained from the PV panel at a maximum voltage. This voltage is called the MPP voltage. For the simulated PV panel system, one panel is connected in parallel and six panels are connected in series, and the maximum power value is 2000 W, the voltage and current values at the MPP point are 258V and 8.13A, respectively.

In low power applications, the output voltage ratio of PV panels is limited. This affects the overall efficiency of the single stage inverter and is its main disadvantage. This problem is solved with the double stage inverter circuit. The PV panel voltage is increased to the desired level for the inverter by the DC/DC boost converter [20].

The DC/DC boost converter consists of a controllable active switch, inductor, capacitor and diode. The PV panel system can be operated in MPP by adjusting the duty cycle of the active switch. ANFIS was used in this study. The MPPT control structure for a boost converter is presented in Figure 4. ANFIS block generates reference voltage V_{ref} from PV panels at MPP. The V_{ref} signal obtained at the output of the ANFIS block is compared with the PV voltage signal and sent to the PI block. The proportional and integral values of the PI block are 9 and 0.009, respectively. PWM signals for IGBT active switches are obtained from the PI and PWM block.

The minimum input inductor and output capacitor values used in the DC/DC boost converter are calculated using Eq. 6, Eq. 7 and Eq. 8 [21].

$$I = I_L - I_d - V_{pv}/R_{shd} \tag{6}$$

$$L_{min} = \frac{D(1-D)^2 R}{2} \tag{7}$$

$$C \geq \frac{D}{R(\Delta V_0/V_0)f_s} \tag{8}$$

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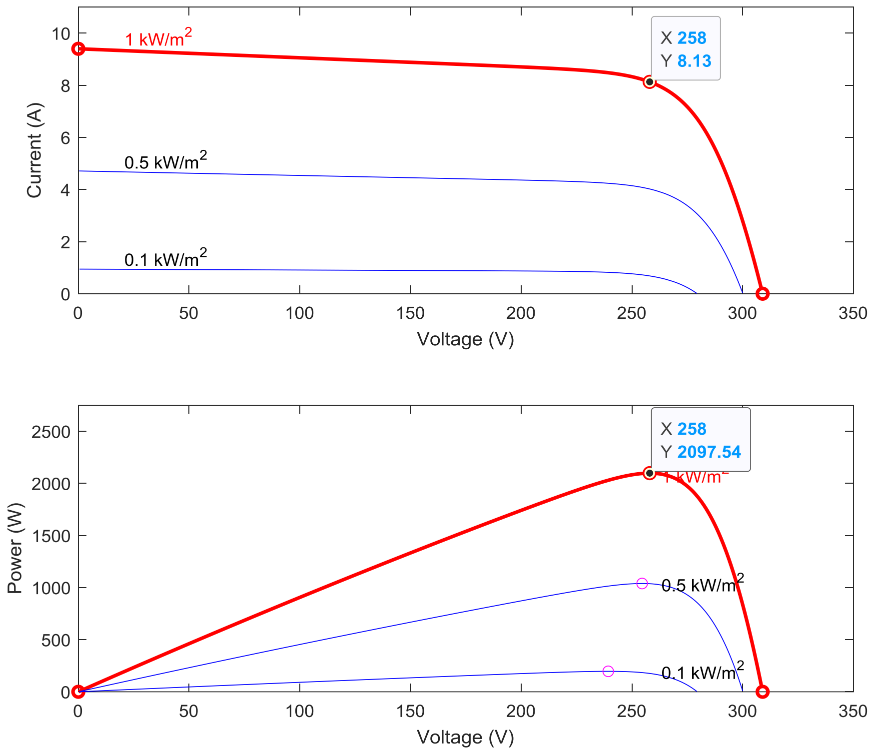

Figure 3. Current-voltage and power-voltage characteristics of the PV panel at 25°C for different solar irradiations.

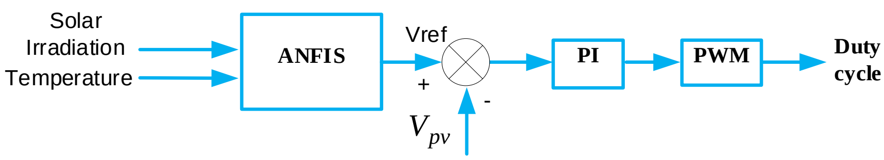

Figure 4. DC/DC boost converter control scheme based on ANFIS.

Here, V_0 is output voltage, V_{pv} is boost circuit input voltage, D is duty cycle, f_s is switching frequency, $\Delta V_0/V_0$ is voltage fluctuation ratio. Since the output resistance is not directly connected to the boost circuit output, it is expressed as $\frac{(V_0)^2}{P}$.

2.2. DC/AC Inverter

DC/AC inverter is used to transfer the DC produced in the PV system to the AC grid voltage. Bridge type DC/AC inverter consists of four controllable active power switches. Switches form two groups of branches and AC voltage is obtained by controlling the duty cycle of the switches.

Grid side control can be performed in a stationary frame $\alpha\beta$ or rotating dq reference frame [22]. Therefore, in this study, the grid part control is done in the dq reference frame. The αβ space to dq

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space transformation can be achieved by rotating the $\alpha\beta$ frame at the fundamental frequency effectively. For sinusoidal signals at fundamental frequency, the d and q vectors obtained in the rotating frame are fixed. Similar to the three-phase systems two orthogonal components that are similar to the $\alpha\beta$ components are required for the process of conversion to a synchronous frame. In the generation of the missing orthogonal vector the signal's quarter-period delayed version is used.

V_g is the grid voltage, I_g is grid current. The single phase grid voltage is represented in the $\alpha\beta$ axis system with $\pi/2$ lead in Eq.9 [23,24].

$$V_\alpha = V_g(t) = V_m sin(t)$$
$$V_\beta = V_g(t + \tfrac{\pi}{2}) = V_m cos(t) \tag{9}$$

The $\alpha\beta$ components of the grid current are defined 90 degrees lead of the current, as in the Eq. 10.

$$I_\alpha = I_g(t) = I_m sin(t)$$
$$I_\beta = I_g(t + \tfrac{\pi}{2}) = I_m cos(t) \tag{10}$$

The linear transformation dq corresponding to the transformation of the $\alpha\beta$ components of the grid current and voltage is given in Eq. 11 [25].

$$I_{dq} = \begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} sin(t) & -cos(t) \\ cos(t) & sin(t) \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix}$$

$$V_{dq} = \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} sin(t) & -cos(t) \\ cos(t) & sin(t) \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{11}$$

The block diagram of the single phase dq transformation is shown in Figure 5. First, the $\alpha\beta$ components are obtained by measuring the voltage V_g and the current I_g. Using the $\alpha\beta/dq$ transform, the dq components of the current and voltage are obtained. The V_q component is implemented as an input to the PLL circuit. In the PLL block, the phase of the new generated sinus signal is adjusted to be the same as the phase of the grid voltage. The V_q is compared with the q component of V_{ref} signal and sent to PI block. The proportional and integral values of the PI block are 10 and 50000, respectively. The signal obtained at the PI is sent to the integrator block. The ωt signal is obtained at the same frequency as the grid at the output of the PLL block.

The block diagram of the dq current control is shown in Figure 6. The V_{dc} obtained at the boost circuit output is compared with the V_{ref}. At the PI block output, the steady state voltage error is reset and the d component signal of the reference current is obtained. I_d and I_q currents are compared with reference values and steady state current errors are reset at the PI controller output. It provides the gain separation terms and the d and q components of the voltage are added. When $\alpha\beta$ is transformed to a stationary reference frame, the α signal and the sawtooth signal are compared to obtain the PWM signals of the single phase PV inverter.

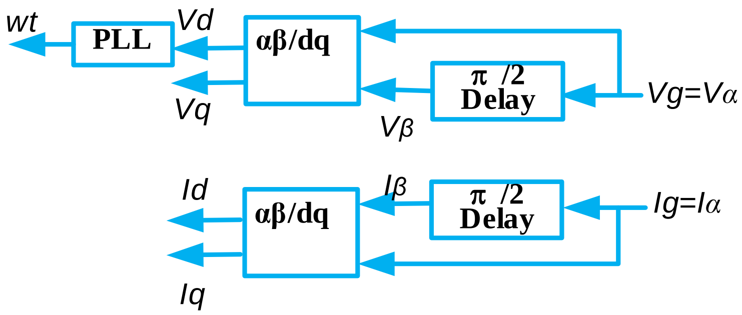

Figure 5. Single phase dq transform block diagram.

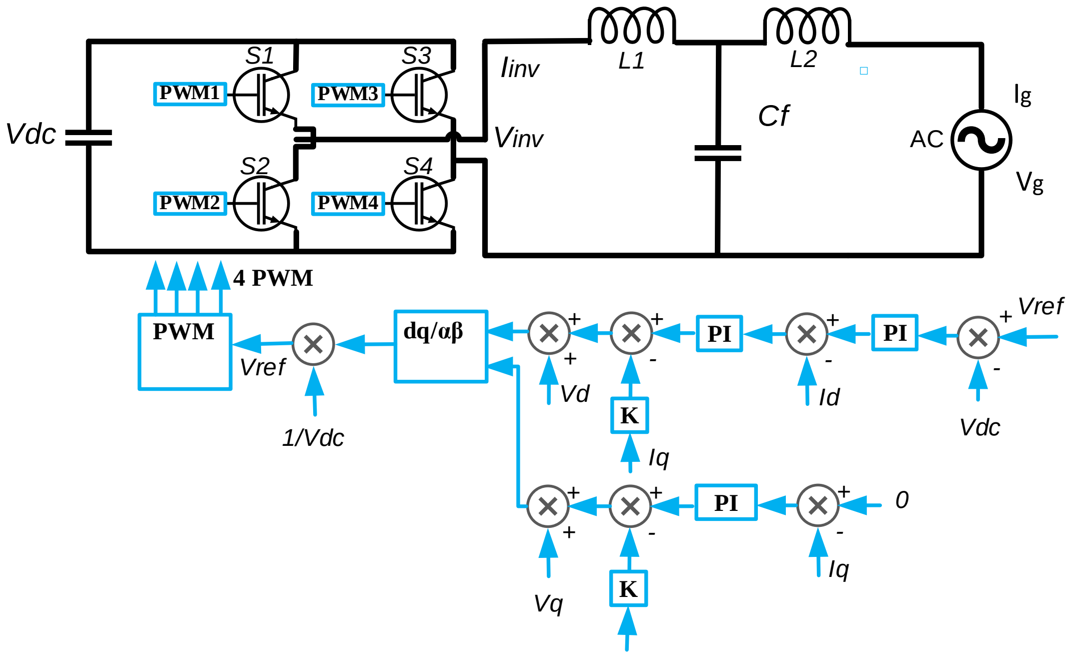

Figure 6. Single phase *dq* current control block diagram.

3. DEVELOPED ADAPTIVE NETWORK BASED FUZZY INFERENCE SYSTEM (ANFIS) BASED MPPT CONTROL ALGORITHM

ANFIS is a hybrid artificial intelligence method that uses the parallel computation and learning capability of artificial neural networks and the inference feature of fuzzy logic [26,27]. The ANFIS model uses the sugeno type fuzzy inference system and the Hybrid learning algorithm. Adaptive networks consist of directly connected nodes. Each node represents a processing unit. The connections between the nodes show a weight between them whose value is not clear. A few of the nodes are not adaptive. Non-adaptive nodes can be made adaptive using variable parameters[28].

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MPPT is obtained using ANFIS. ANFIS is trained to obtain the output voltage that provides the maximum power output from the PV panel system. Solar irradiation and temperature are given as inputs to ANFIS. In the developed ANFIS based MPPT algorithm, voltage control is performed by comparing the V_{ref} obtained at the ANFIS output with the PV voltage. Error signal is obtained with feed forward PI controller and PWM signal of DC/DC boost converter is adjusted. At constant temperature the solar radiation variations results in a large change in the output of PV panel current in the MPP. The MPPT controller provides a non-variable voltage at the output when the temperature does not change. Otherwise, the temperature variance causes a large change in the PV panel output voltage in the MPP, which greatly changes the DC voltage.

The simulation circuit of the developed ANFIS based MPPT algorithm has been confirmed using Matlab/Simulink. The PV panel temperature ranges from 15 °C to 40 °C and the solar irradiation varies between 0 and 1000 W/m. Using these temperature and irradiance values, data is obtained at the output of the simulation circuit, and some of the irradiation and temperature data is used off-line to train the ANFIS. Figure 7 shows the ANFIS structure. In the five-layer network structure, two inputs with solar irradiation and panel temperature are used.

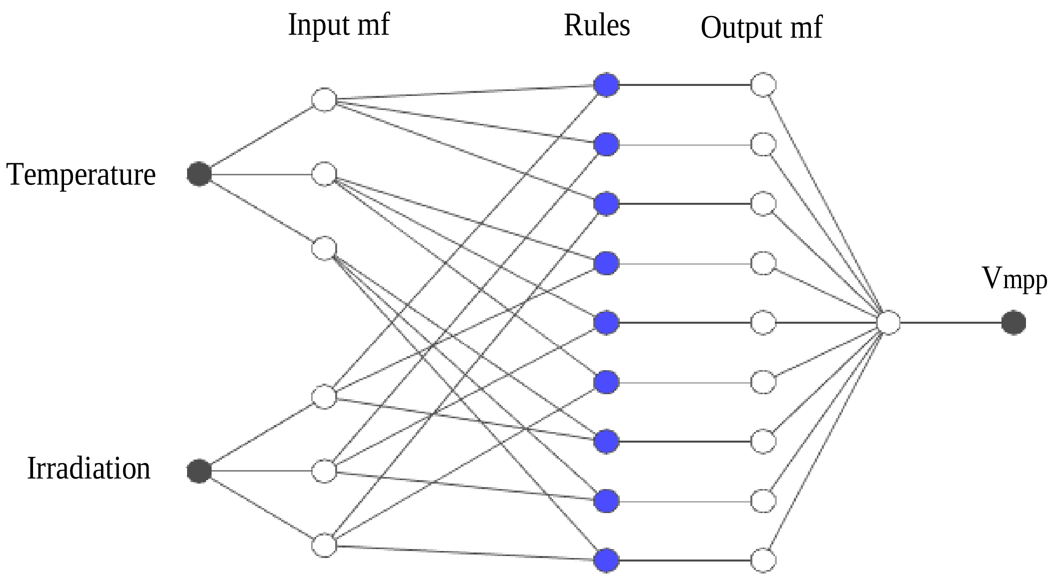

Figure 7. MPPT controller structure based on ANFIS.

The structure converts solar irradiation and temperature into three suitable MF as shown in Figure 8 and Figure 9.

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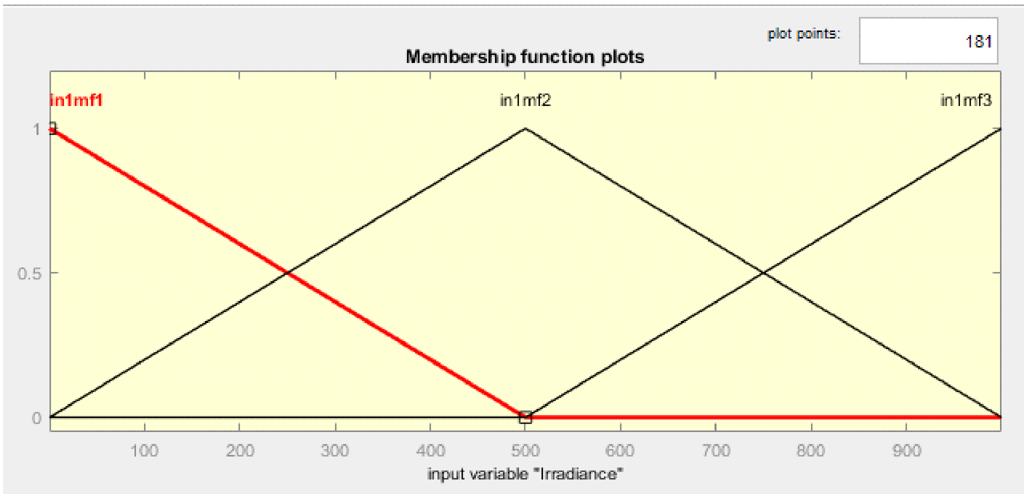

Figure 8. Solar irradiation MF.

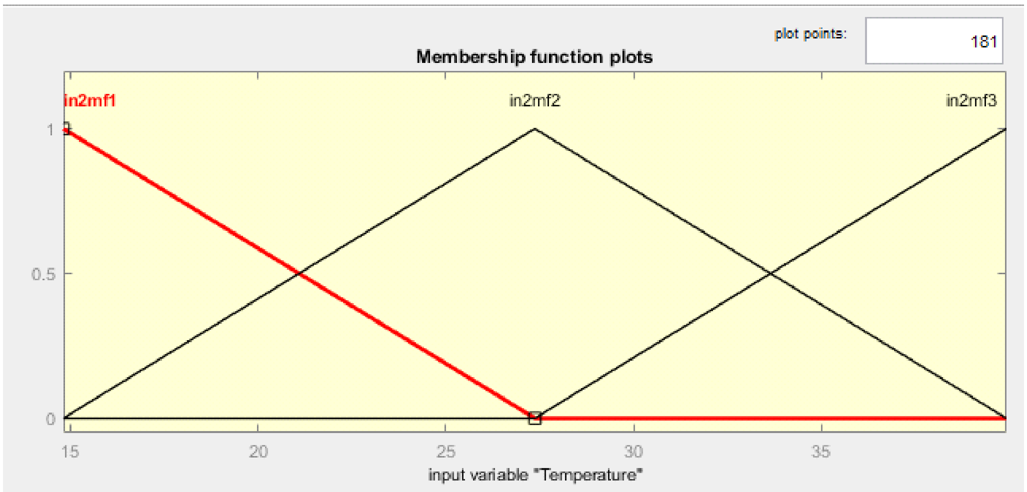

Figure 9. Temperature MF.

The form of these MF generated by the ANFIS controller varies during the training phase. The form of the MF obtained both during the training phase and at the end of the training phase are as given in Figures 8 and 9. The fuzzy rules for a temperature of 22.5 °C and solar irradiation of 500 W/m are shown graphically in Figure 10. The rules show the connection and matching between the variables. All conditions can be accessed by changing the slider on the shape. As shown in the last column, it is seen that the temperature varies between 5 °C and 40 °C, the solar irradiation varies between 0 and 1000W/m and the MPP voltage changes accordingly.

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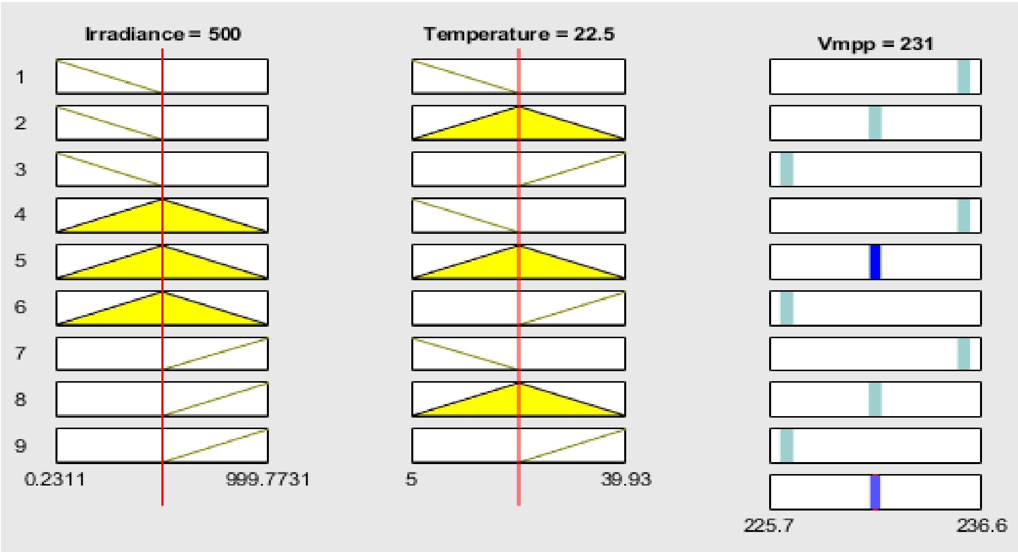

Figure 10. The rules of the ANFIS controller.

4. SIMULATION RESULTS

Considering the solar irradiation in a day, it changes at certain times of the day. Figure 11 shows the time-dependent variation of solar irradiance and temperature values. Initially, the solar irradiation starts with 1000W/m, then decreases to 600W/m between 0.5 s and 1.25 s. Increases to 800W/m between 1.25 s and 2 s and increases again to 1000 W/m irradiance between 2 s and 2.5 s. The temperature starts at 25 °C, then decreases to 5 °C between 0.5s and 1s. Increases to 40 °C between 1 s and 1.5 s and rises again to 25 °C between 1.5 s and 2.5 s. The simulation time interval was taken as 2.5 s.

To test the validity of the developed MPPT controller, system given in Figure 1 was simulated in MATLAB/Simulink. For the simulation of the system, the desired value of PV voltage is obtained by combining 6 serial and 1 parallel panels. For simulation, single phase grid voltage and frequency is simulated as 220V 50Hz. The parameters used for the system are given in Table 1 and section 2. The simulation is done for the different solar irradiation and the panel temperature values in Figure 11.

In the first simulation study, environmental conditions such as panel temperature and irradiation were changed and applied to the PV panel input, and the developed MPPT algorithm is compared with the conventional PandO algorithm. The voltage from the boost converter, PV panel power, reference power and algorithm efficiency signals were obtained from a result of the simulation.

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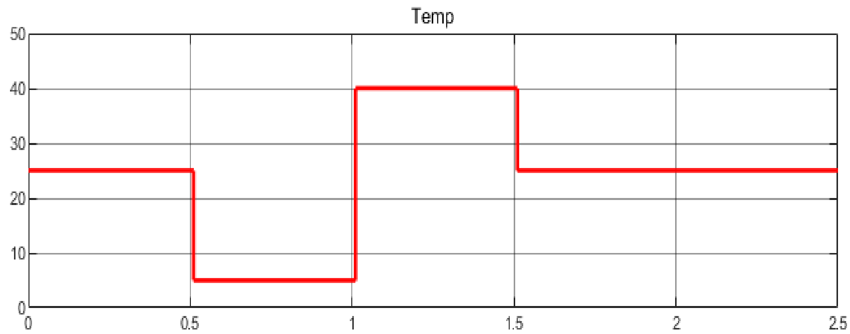

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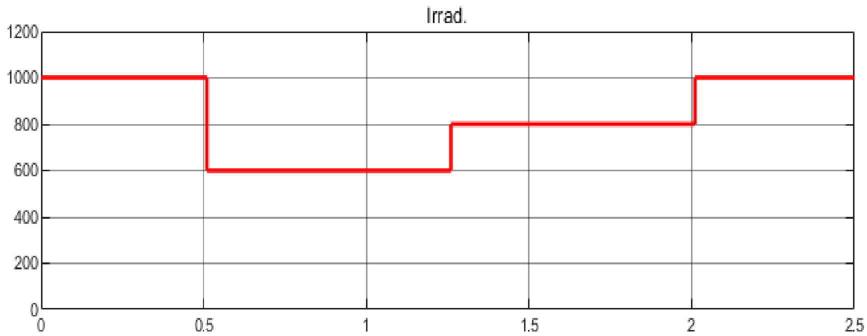
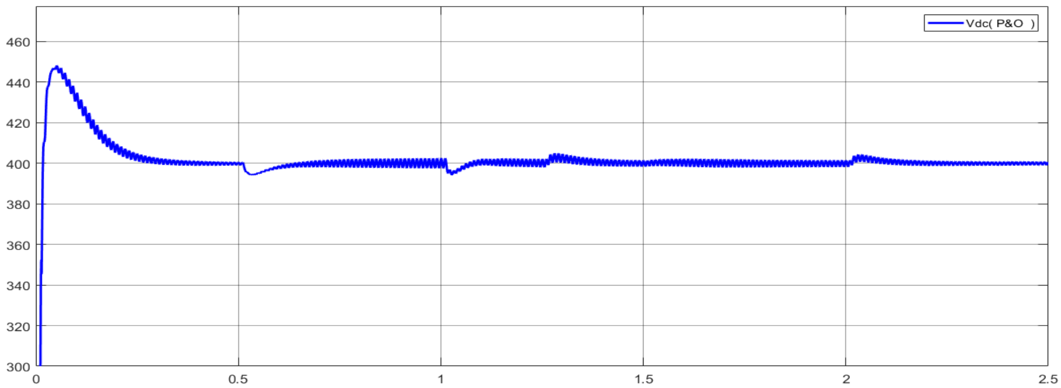


(b)

Figure 11. Variation curves of solar irradiation and panel temperature.

In Figure 12, boost converter output voltage, PV panel power, reference power and algorithm efficiency obtained using PandO based MPPT algorithm are shown.



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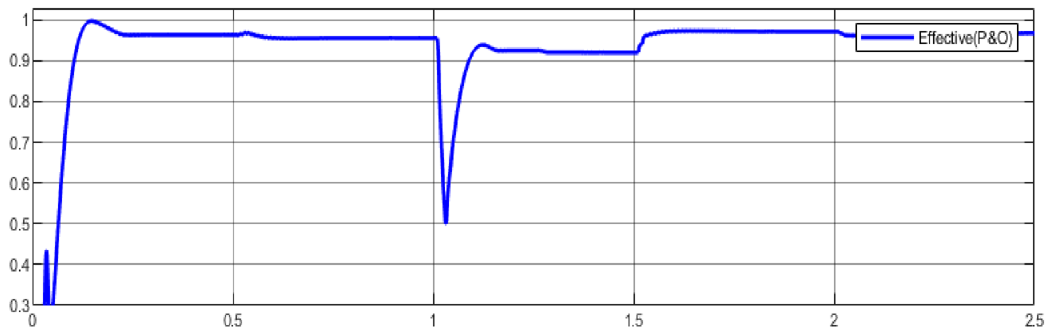

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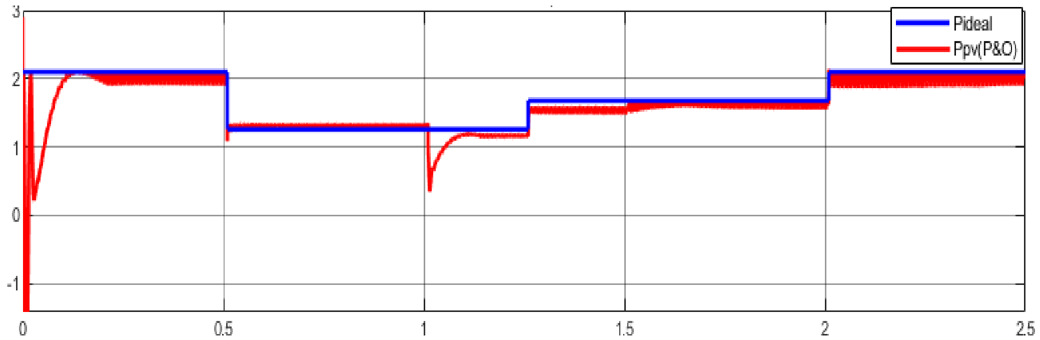

(c)

Figure 12. a) The output voltage of boost converter, b) the algorithm efficiency c) the PV panel power, reference power and obtained using PandO based MPPT algorithm.

In Figure 13, the boost converter output voltage, PV panel power, reference power and algorithm efficiency signals obtained using the ANFIS based MPPT algorithm are shown. The comparison results of the PandO algorithm and the ANFIS based MPPT algorithm are given in Table 2. The efficiency of the ANFIS based MPPT algorithm and the PandO algorithm efficiency are obtained as 0.8887 and 0.5079 at t=1.033s respectively. It can be seen from Figure 13 that the maximum power of the PV panel is particularly sensitive to solar irradiation and panel temperature, and the tendency of the power to change is consistent with the ideal power. In addition, the developed ANFIS based MPPT algorithm, when compared to the PandO algorithm, adapts to these changes faster and can follow the MPP power with less change. A reliable inverter control algorithm should be able to keep DC voltage and AC grid voltage constant when environmental conditions change.

Table 2. The comparison results of the PandO algorithm and the ANFIS based MPPT algorithm.

	Algorithm efficiency at t=1.033s
PandO algorithm	0.5079
ANFIS based MPPT algorithm	0.8887

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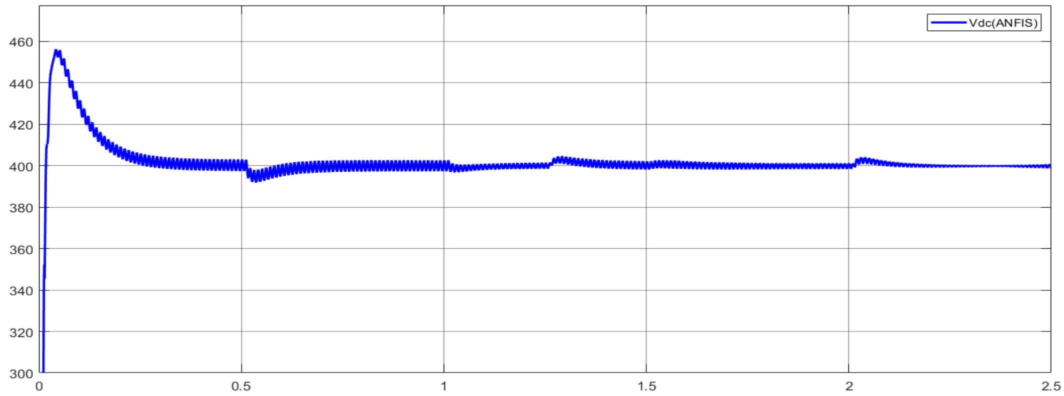

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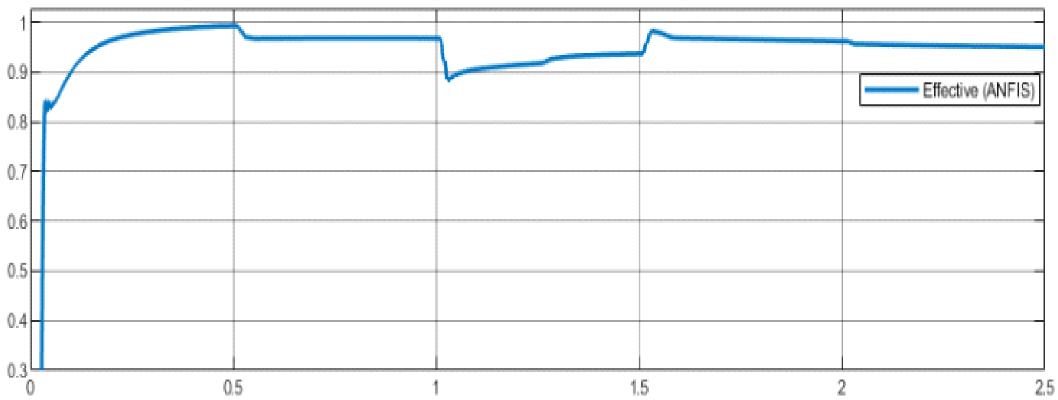

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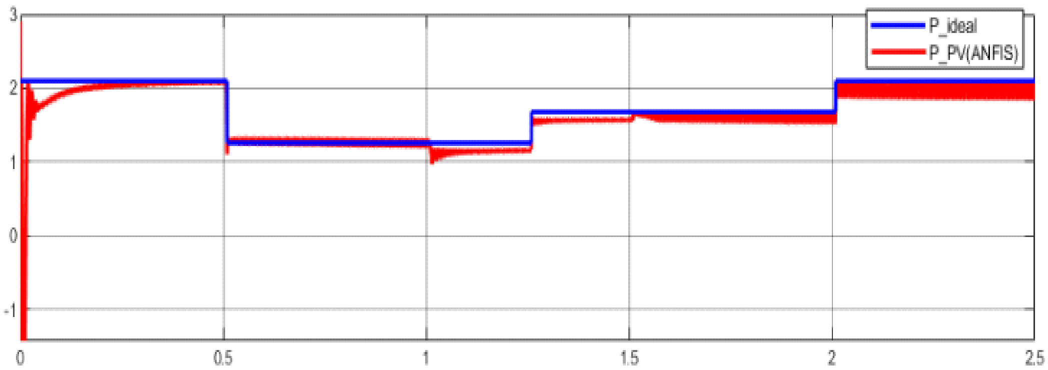

(c)

Figure 13. a) The output voltage of boost converter, b) the algorithm efficiency c) the PV panel power, reference power and obtained using ANFIS based MPPT algorithm.

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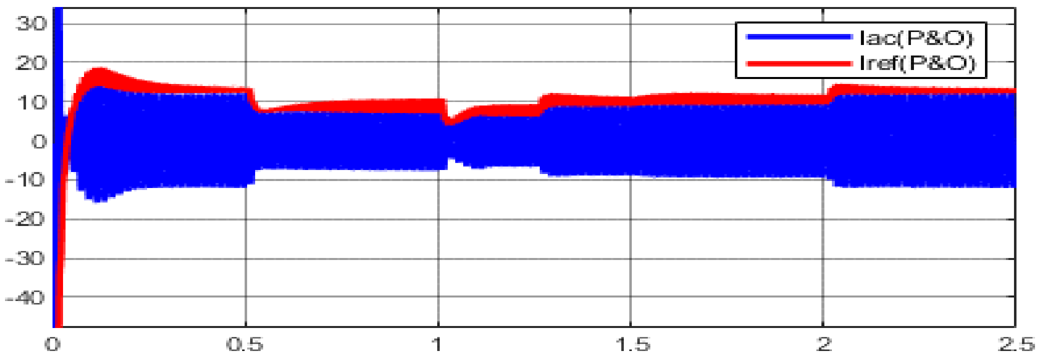
Figures 14 and Figure 15 show the reference current, grid current and PV panel current obtained using the PandO algorithm and the ANFIS-based MPPT algorithm respectively. From the Figures 14 and 15, when the developed MPPT algorithm is compared with the PandO algorithm, the AC output current of the inverter can follow the grid reference current with less fluctuation.



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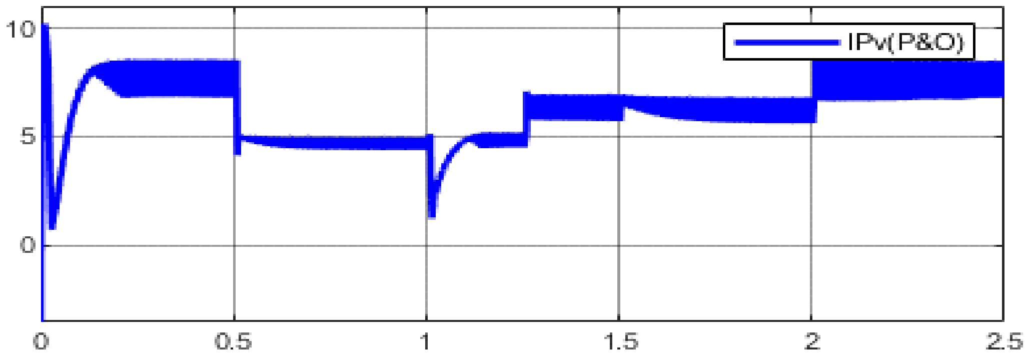
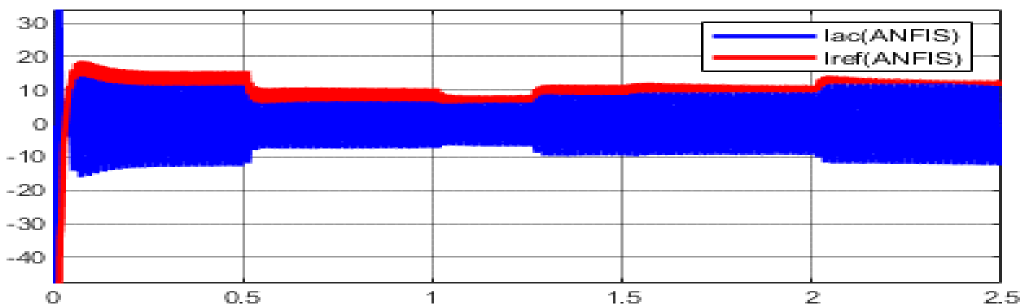


(b)

Figure 14. a) The reference current, the grid current and b) the PV panel current obtained using the PandO algorithm.



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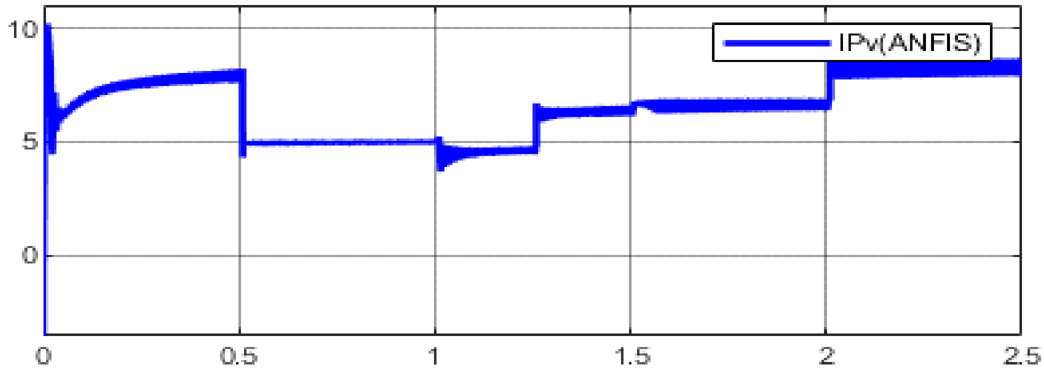

(b)

Figure 15. a) The reference current, the grid current and b) the PV panel current obtained using ANFIS based MPPT algorithm.

5. RESULTS

In this study, the ANFIS based MPPT control algorithm is development for a on-grid double stage 2KW single phase PV inverter. The voltage balancing between the PV panel system and the AC grid is performed by a DC/DC boost converter. The duty ratio of active switch is adjusted using the ANFIS based MPPT algorithm to track the MPP of the PV panel system. In the developed ANFIS algorithm, Sugeno inference with three inputs and one output was used and irradiation and temperature data were chosen as input training data. 400V constant MPPT voltage obtained from the DC/DC converter output was applied to input of the single phase inverter and 220V 50Hz AC voltage was obtained by using the dq algorithm. The voltage and frequency on the grid side are regulated by adjusting the PWM signal by the dq controller . Thus, simultaneous control in the PV panel system and the inverter ensures that the control aims are achieved. The validity of the developed algorithm was tested using the Matlab/Simulink simulation program.

ANFIS based MPPT algorithm and PandO algorithm were compared in simulation studies and algorithm efficiency was obtained as 0.8887 and 0.5079 at t=1.033s respectively. The simulation results show that the proposed ANFIS based control algorithm is adaptable to environmental changes and can quickly track MPP. The grid current tracking performance shows that the PV inverter is sensitive to irradiation and temperature changes and the reliability of the developed ANFIS algorithm. The comparison results with the PandO algorithm confirm the superiority of the developed ANFIS algorithm.

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