Dynamic Behaviour Analysis of ANFIS Based MPPT Controller for Standalone Photovoltaic Systems

Dilovan Haji*, Naci Genc**‡

* Mechanical Engineering Department, Collage of Engineering, University of Zakho, Zakho, Iraq

** Electrical and Electronics Engineering Department, Faculty of Engineering, Van Yuzuncu Yil University, 65080, Turkey

(dilovan.haji@uoz.edu.krd, nacigenc@yyu.edu.tr)

‡ Corresponding Author; Naci Genc, Faculty of Engineering, Van Yuzuncu Yil University, 65080, Turkey,

Tel: +90 555 418 0321, nacigenc@yyu.edu.tr

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Abstract- This paper proposes dynamic behavior analysis of Adaptive Neuro Fuzzy Inference System (ANFIS) based Maximum Power Point Tracking (MPPT) controller for a standalone photovoltaic (PV) system under various weather conditions such as different level of irradiance and temperature. Also, the dynamic behavior analysis of the system has been done by using different MPPT techniques which are ANFIS, Perturb and Observation (P&O) and Fuzzy Logic Controller (FLC). Based upon the results, the ANFIS based MPPT controller can track the maximum power point faster than other suggested controllers under various weather circumstances. It also observed that the intelligent based MPPT algorithms have lower rippling in power compared with conventional P&O algorithm. In addition, the dynamic behavior analysis of proposed MPPT controller shows that the system could stay operating at MPP during changes occurring to the load by changing PV voltage and current to extract the desired maximum power.

Keywords PV, MPPT, Fuzzy Logic, ANFIS, P&O.

1. Introduction

Solar energy which is used in photovoltaic systems, as a renewable energy source, is a good choice for electric power generation due to its availability and cleanliness. On the other hand, low energy conversion efficiency and high fabrication cost are the main drawbacks of photovoltaic systems [1]. MPPT controller is required to overcome these disadvantages by extracting the maximum produced power from the PV systems which lead to increase the efficiency of the system [2-3]. These systems are one of power sources that rapidly evolving and vastly used in modern electric technologies. The generated power in photovoltaic applications are produced by solar panel [4-5]. Maximum Power Point Tracking techniques are essentially an electronic system which imposes the PV modules, making the modules sufficient to produce the maximum power [6-8].

A DC/DC power converter stage is connected with MPPT controls to allow a photovoltaic generator produce the maximum power, at any value of the metrological terms (irradiance, temperature) [9-12]. MPPT control technique that is widely used to be performed on the duty cycle automatically to place the PV module at its best and optimal output value whatever the differences of the weather conditions or the change in the value of loads which can happen at any moment [10, 13]. By examining the MPPT tracking algorithm point of view, many techniques of MPPT can be applied. These methods are hill climbing, voltage feedback, perturb and observation, current feedback, incremental conductance, fuzzy logic and neural network [14, 15]. While the authors in [16] have introduced inexpensive current based MPPT algorithm. Among these methods, hill climbing and voltage feedback are easy to stratify but inefficient in the maximum power point tracking with various environment conditions. On the other hand, perturb and observation technique has hitched as it processes an extra P-I control loops which result slow tracking process [17-18]. One of the most efficient techniques in maximum power point is the (ANFIS) based algorithm. ANFIS combines the benefits of the two machine learning techniques (Fuzzy Logic and Neural Network) into a single technique and it works by applying Neural Network learning methods to tune the parameters of a Fuzzy Inference System (FIS) [19-21].

This study proposes MPPT controller using several techniques, including P&O, FLC, and ANFIS. The dynamic behavior of the system is compared by using the MPPT techniques which include ANFIS, P&O and FLC methods.

2. Modeling of the Standalone PV System and MPPT Techniques

2.1. SIMULINK Modeling of Photovoltaic Module

Basically, there are two mathematical models of PV panel which are single-diode and two-diode model. In this paper, the proposed model applied is the single-diode since it is accurate and simple [22]. The parameter for the PV module depends on the electrical characteristics' datasheet of YGE Solar YL250P-29b PV module shown in Table 1, while Fig. 1 shows the equivalent circuit of a single diode solar cell.

Table 1. Electrical characteristics of YL250P-29b module

Electrical Characteristics	**Symbol**	**YL250P-29b**
Power output	P_{max}	250 W
Power output tolerances	ΔP_{max}	-5 / + 5 W
Module efficiency	η_m	15.3 %
Voltage at P_{max}	V_{mpp}	29.8 V
Open-circuit voltage	V_{oc}	37.6 V
Current at P_{max}	I_{mpp}	8.39 A
Short-circuit current	I_{sc}	8.92 A
Temperature coefficient of P_{max}	Γ	-0.42 %/°C
Temperature coefficient of V_{oc}	β_{Voc}	-0.32 %/°C
Temperature coefficient of V_{mpp}	β_{Vmpp}	-0.42 %/°C
Temperature coefficient of I_{sc}	α_{Isc}	0.05 %/°C
Max. system voltage		1000 V_{DC}

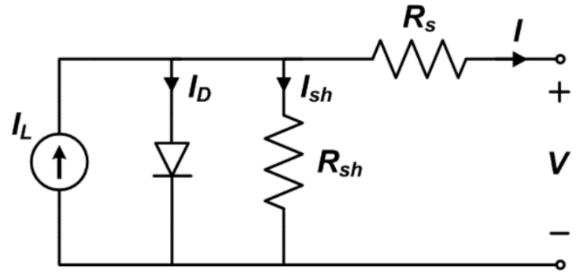

Fig. 1. Single-diode solar cell.

The symbols in Fig. 1 are defined as below:

I_L = Iph: Photocurrent
V: Output voltage
I_D: Parallel diode current
R_{sh}: Shunt (parallel) resistance
I_{sh}: Shunt current
R_s: Series resistance
I: Output current

The output current (I) can be calculated as the following equation:

$$I = I_{ph} - I_s\left[e^{\left(\frac{V+I.R_S}{A.N_S.V_T}\right)} - 1\right] - \frac{V+IR_S}{R_{sh}} \qquad (1)$$

And the PV saturation current is given by:

$$I_s = I_{rs}\left(\frac{T_{op}}{T_{ref}}\right)^3\left[e^{\left(\frac{-q\varepsilon_G}{A.k}\left(\frac{1}{T_{op}}-\frac{1}{T_{ref}}\right)\right)}\right] \qquad (2)$$

While the reversed saturation current is described in equation (3)

$$I_{rs} = \frac{I_{sc}}{\left[e^{\left(\frac{V_{OC}}{A.N_S.V_T}\right)}-1\right]} \qquad (3)$$

Moreover, the photon current of PV equivalent equation is shown below:

$$I_{ph} = \left(\frac{G}{1000}\right)\left(I_{sc} + \alpha_{I_{sc}} \cdot \Delta T\right) \qquad (4)$$

Where:

G: Irradiance (W/m^2).

$\Delta T = T_c - T_{c,ref}$ (Kelvin).

T_c: operating cell temperature (K).

$T_{c,ref}$: Cell temperature at STC = 25 + 273 = 298 K.

I_{sc}: Short circuit current (A) at STC.

α_{Isc}: Coefficient temperature of I_{sc} = 0.05% A/K) for proposed PV Module.

I_{rs}: Diode reverse saturation current (A).

ε_G: Physical band gap energy (eV), (1.12 eV for Si).

k: Boltzmann constant 1.38×10^{-23} J/K.

q: Charge of Electron 1.602×10^{-19} C.

Ns: Number cells connected in series, for proposed PV panel it is 60 cells.

A: Ideality factor, which is 1.2 for si-mono.

In order to make the implemented PV module more reliable, the value R_P and R_S should be estimated [22]. They were chosen so that the computed P_{mp} is equivalent to the experimental one $P_{mp,ex}$ at STC [23]. Using equations (1) - (4), the electrical characteristics and equivalences has been applied into MATLAB/Simulink subsystems; the overall PV panel module is shown in Fig. 2. The generated outputs have been verified based on the electrical characteristics provided by YGE Solar. Fig. 3 shows P-V cure with its corresponding MPP of the implemented PV module under constant temperature.

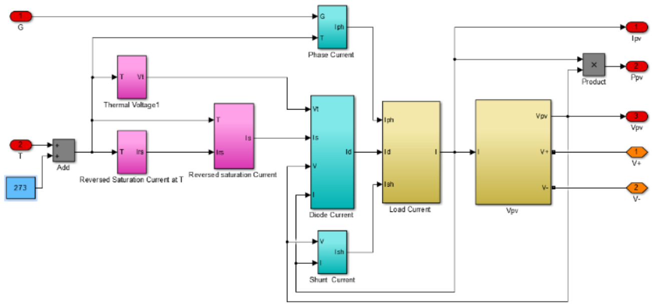

Fig. 2. PV panel Simulink model.

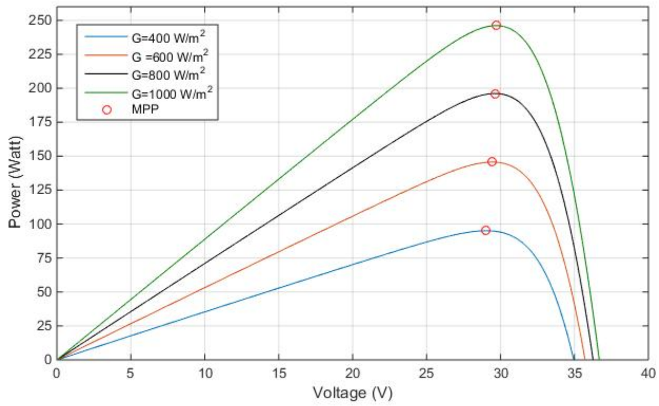

Fig. 3. P-V curve of YL250P-29b PV under constant temperature (25C°).

2.2. MPPT techniques

The main aim of MPPT systems to track the maximum power of the PV panel. Dealing with many changeable temperature and solar radiation, the MPP is also varies. Thus, so as to dynamically set the MPP like an operating point for vast range of inputs (solar radiation and temperature), (MPPT) technique is demanded. MPPT application is essentially a DC/DC converter [24-26] laid in between the load governed by tracking algorithm and the photovoltaic modules [27] as displayed in Fig. 4.

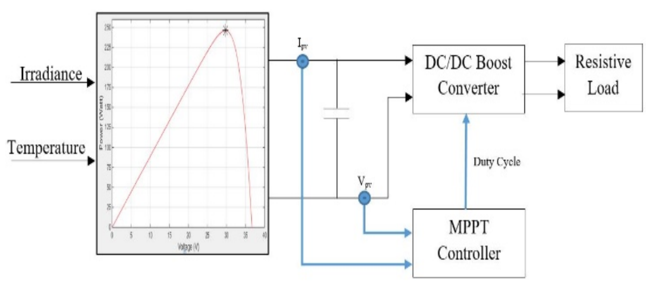

Fig. 4. MPPT system contain the tracking controller and DC/DC converter.

Essentially the tracking algorithm will get the inputs which are PV module current and voltage and collaborate with dc-dc converter duty cycles that will set the system operating point of MPP [4].

A. Fuzzy controller

Fuzzy logic is embroiled in the imperfect knowledge and handling; it takes place as an effective substitution. FLC based MPPT method do not require the knowledge of the precise model. FLC controllers generally made of three stages: Fuzzification, rule base, and Defuzzification [28]. The inputs of this controller are variations of error and errors; the result is the duty ratio variation of DC-DC Boost converter. Equation (5) and (6) explains inputs of fuzzy controller:

$$e(t) = \frac{\Delta P(t)}{\Delta V(t)} = \frac{P(t)-P(t-1)}{V(t)-V(t-1)} \quad (5)$$

$$\Delta e(t) = e(t) - e(t-1) \quad (6)$$

The major fuzzy rule, in which results are looked as linear mishmashes of controller inputs, are [29]:

$$if\ x\ is\ A_1\ and\ y\ is\ B_1\ then\ f_1 = p_1 x + q_1 x + r_1 \quad (7)$$

In this paper, for fuzzification we used 5 triangular membership functions for all inputs and outputs. The inputs and variable were converted to linguistic values. In this work five subsets were used which are: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB). The membership functions of inputs and the output shown in Fig. 5.

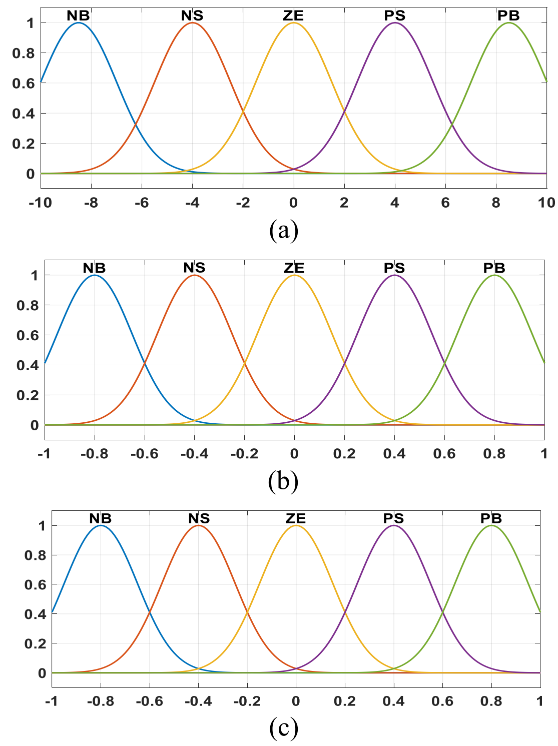

Fig. 5. Fuzzy Membership Function of (a) Error (e), (b) Variation in Error (Δe), (c) Variation of Duty Cycle dD.

Mamdani's method is used for fuzzy inference, while the output is calculated by using equation (8). In defuzzification, we choose the centroid method to calculate the output of the proposed FLC. The rule base of Table 2 is used to find the output which is supply to the DC/DC Boost converter.

$$dD_i = \frac{\sum_{i=1}^{n} \mu(D_i) - (D_i)}{\sum_{i=1}^{n} \mu(D_i)} \tag{8}$$

Table 2. Fuzzy Logic Rule Base

$e \longrightarrow$ $\Delta e \downarrow$	NB	NS	ZE	PS	PB
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	ZE	NS
PS	NS	NS	NS	ZE	ZE
PB	NB	NB	NB	ZE	ZE

B. ANFIS controller

ANFIS technique is combining the Artificial Neural Network (ANN) learning methods and the fuzzy inference system (FIS). ANFIS, proposed by Jang [30], constructs an input-output mapping based on human knowledge (in the form of fuzzy if-then rules) and generated input-output data pairs using a hybrid algorithm who is a part the least squares and part back propagation gradient descent method [31]. Generally, it consists of five layers as shown in Fig. 6. The inputs of the suggested ANFIS controller are the same of fuzzy controller, which can be calculated using equation (5) and (6) respectively. While the output is the duty ratio 'D' to drive the boost converter so it can operate the PV at maximum power point. Duty cycle of boost converter can be calculated as follows:

$$\frac{V_O}{V_{PV}} = \frac{1}{(1-D)} \Rightarrow D = \frac{V_O - V_{PV}}{V_O} \tag{9}$$

Where V_O is the output voltage and V_{PV} is the input voltage of the boost converter. To calculate duty cycle, V_O is the desired output voltage which in our case is V_{mpp} (29.8V) under STC condition and it called $V_{optimal}$, and V_{PV} is the actual output voltage of the PV panel.

Tracking the MPP using ANFIS needs sets of input and output data. These data sets are obtained from the system operating results and they called training data. In this work the training data were collected from simulation after implementing and verifying the PV module.

The collected input and output data ('e' 'Δe' and 'D') saved as an array, and by using neuro fuzzy toolbox a (.fis) file have been generated. The equivalent neural scheme of the proposed ANFIS is given in Fig. 6. Five Gaussian membership functions have been chosen for each input. The structure of error (e) and variation of error are illustrated in Fig. 7. In total the neuro fuzzy inference system has 25 fuzzy rules. The network is trained for 100 epochs to minimize the error to 0.0066%.

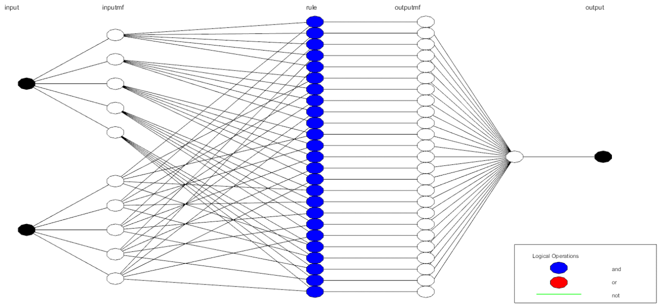

Fig. 6. Neural Structure of ANFIS controller.

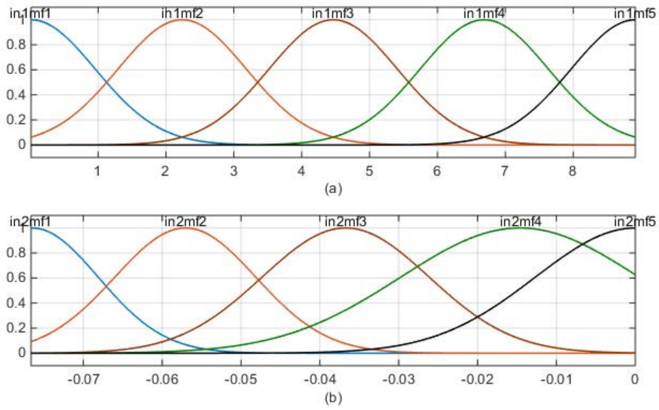

Fig. 7. ANFIS inputs membership functions: (a) error (e), (b) variation of error (e).

C. P&O controller

Perturb and Observation method is the widespread MPPT techniques and can be considered as the easiest to use [21]. The flowchart of this technique is shown in Fig. 8, running the PV system in the direction where the gained power from the PV system increases is the basic idea of P&O.

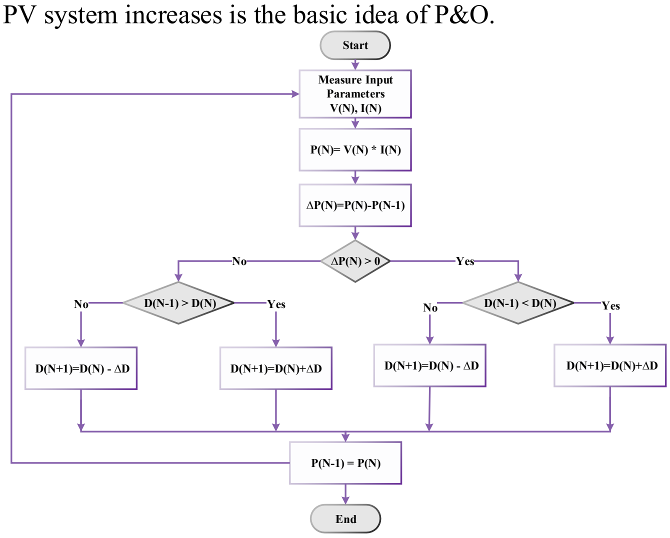

Fig. 8. P&O method flowchart.

The change of power is represented in equation (10) and it describes the technique of P&O algorithm.

$$\Delta P = P(N) - P(N-1) \tag{10}$$

Depending on above equation and by using the flowchart of the method, in case the alteration of power is positive, the incremental of duty cycle (D) will remain the same to decrease or increase the PV voltage, but if the alteration is negative, the direction of incremental duty cycle command will reverse.

The MPPT controller is applied to a boost converter which structure is showing in Fig. 9. The DC-DC boost converter consists of one active switch (*M*); *L* inductor for boosting; D_o diode; C_o capacitor. The boost converter voltage gain and passive circuit parameters (L_{min}, C_{min}) which are the minimum design parameter values of the converter can be calculated using below equations [24-26].

$$\frac{V_O}{V_{PV}} = \frac{1}{1-D} \quad (11)$$

$$L_{min} = \frac{(1-D^2)\cdot D\cdot R_o}{2\cdot f_s} \quad (12)$$

$$C_{min} = \frac{D}{2\cdot f_s\cdot R_o} \quad (13)$$

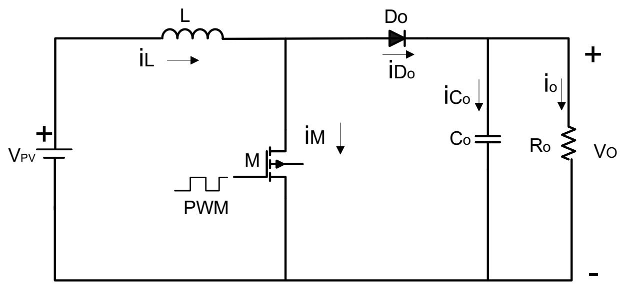

Fig. 9. Structure of the boost converter

All three suggested controllers were implemented and simulated using MATLAB/Simulink. Fig. 10 shows the complete structure of proposed system.

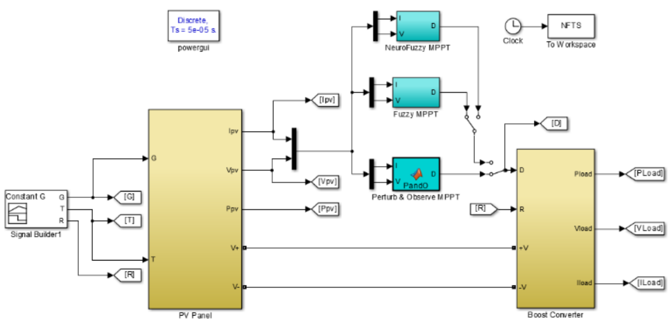

Fig. 10. Model of proposed system using Simulink.

3. Results and Discussion

The proposed MPPT controllers simulated using MATLAB/Simulink. The controllers are applied to Boost converter which in its place connected to changeable resistive load. Fig. 11 shows PV outputs (I_{pv}, V_{pv}, P_{pv}) under STC condition with constant resistor as a load. Then the system has simulated in two phases, the first one using MPPT controllers and in the second one by direct coupling same resistor. In both cases the system was simulated under various circumstances, firstly the simulation has been done under constant temperature of (25C°) and resistor (60Ω) with fast changes in irradiation, (400W/m²-1000W/m²) then secondly the irradiance and load resistor were constant (1000W/m², 60Ω) but varying in temperature level. To study the dynamic behavior of the controller, the resistor was changed once from (60Ω) to (30Ω) and with keeping the irradiance and temperature constant. Lastly for further analysis, the system has been simulated under changeable three parameters (T, G and R). Figure 11 shows that by using proposed controlling methods, the PV is running in the MPP voltage and current in which they present the power of the maximum power point. By referring to manufacturer datasheet, the obtained results match the electrical performance of YGE Solar YL250P-29b under STC. The simulation results show that P&O has large ripple of panel power (zoomed area) compared with FLC and ANFIS algorithms. While ANFIS have the fastest time response.

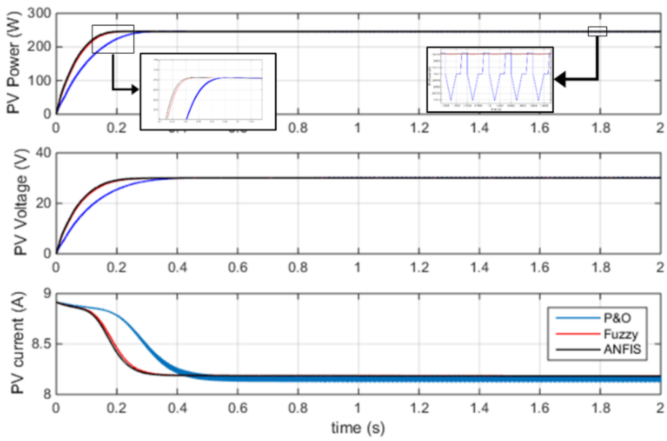

Fig. 11. PV outputs under standard test conditions temperature=25 C°, (irradiance=1000W/m²) with constant load resistor (R=60Ω).

The performance parameters (MSE and rise time) comparisons of the three methods are given in Table 3.

Table 3. The performance parameters (MSE and rise time) comparisons

Parameters	P&O	FLC	ANFIS
MSE	0.02895	8.32346x10^{-5}	1.41536x10^{-6}
Rise time	0.18241	0.11783	0.11245

Performances of the PV system model under constant temperature and changing in irradiance are shown in Fig. 12 and Fig. 13. These simulation outcomes show that Fuzzy logic controller and ANFIS can track the maximum power point faster with less variation around it comparing with P&O algorithm under fast varying in weather circumstances. However, it is observed that ANFIS algorithm can produce more power to the load than other two proposed algorithms.

Figure 14 shows the part of produced PV voltage and current with corresponding load voltage. It can be concluded that proposed controller can track the MPP in case fast change in the load happens. The PV current and voltage changes to track the maximum power point and produce the desired maximum power point.

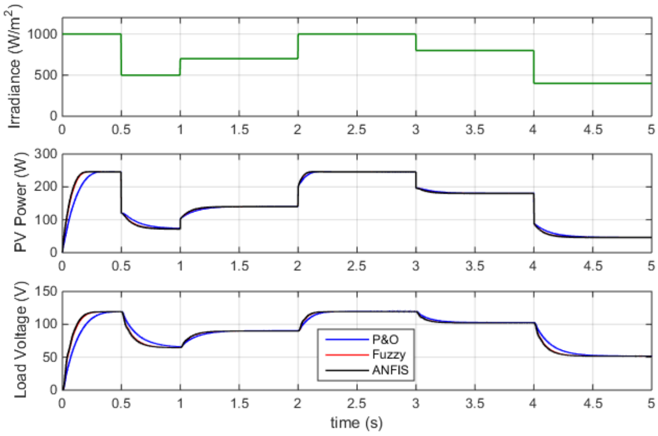

Fig. 12. Performance of PV system under constant temperature and changing in irradiance.

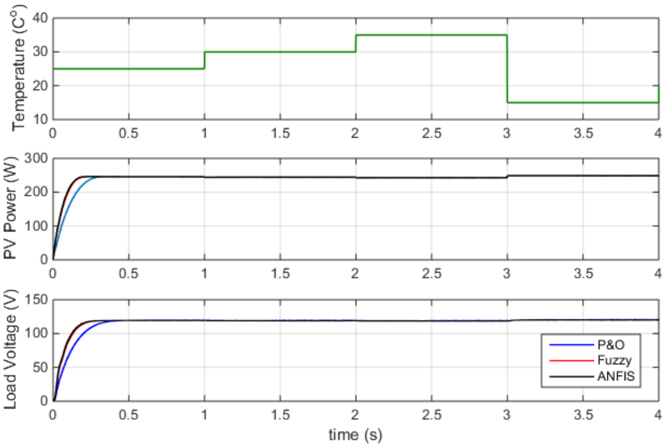

Fig. 13. Performance of PV system under constant irradiance and changing in temperature.

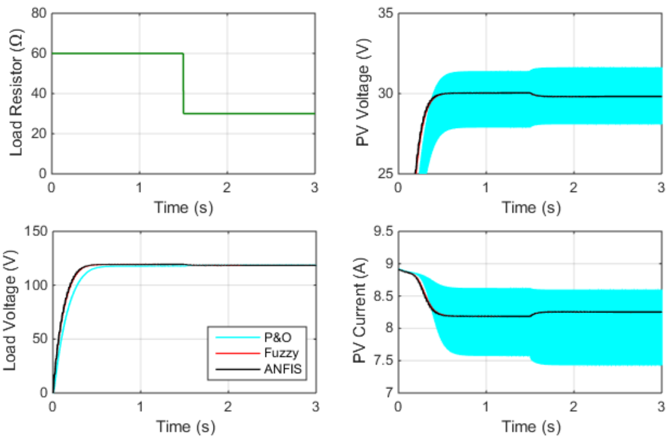

Fig. 14. Performance of PV system under constant irradiance and temperature with fast change in load resistor.

In the last case, the simulation implemented under varies irradiance and temperature with changing resistive load. Figure 15 shows decreasing and increasing in irradiance and temperature in many cases, the irradiance starting from 100 W/m^2 and increasing to 1000 W/m^2 in its maximum value, while the temperature is starting from under 20 C^o and reaches over 40 C^o. this case represent many weather conditions to analysis the MPPT controller response. While the resistor starts as constant (60Ω) and changes immediately to (20Ω) then it slowly increases and decreases and at the end it becomes constant again.

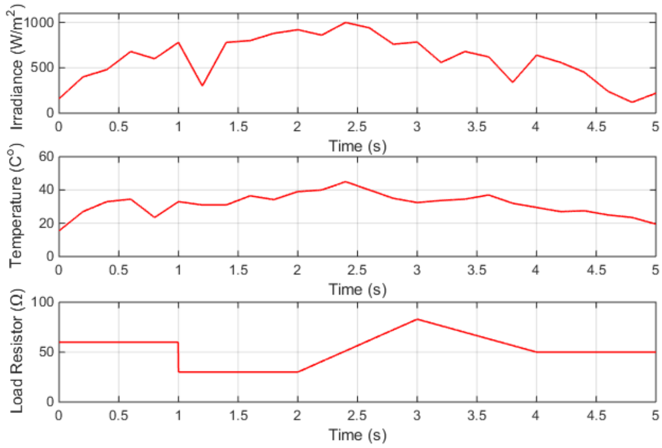

Fig. 15. Changing in PV Parameters.

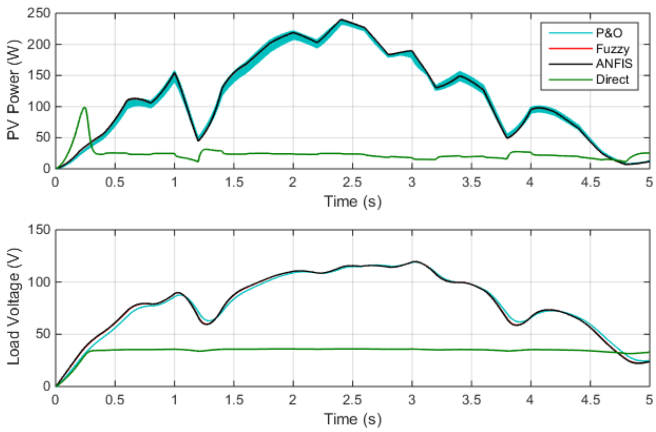

Fig. 16. Outputs under various T and R and G.

It can be noticed from Fig. 16, that using controlling algorithm succeed to track maximum power point under various circumstances. Also, it's clear that the observed power under high irradiance and by using MPPT controllers is up to five times higher than direct connecting the load.

4. Conclusion

Three MPPT techniques for PV systems were presented and compared in this paper. The first two techniques are intelligent based algorithms the Fuzzy Logic Controller and ANFIS, while the third one is a conventional strategy Perturb & Observation. The suggested controllers are connected to power stage and control the duty cycle of the Boost converter. MATLAB/Simulink has been used to model and simulate the system. The performance parameters (mean square error and rise time) of the three methods were also compared. The results given in Table 3 show that the ANFIS method has lower MSE value than the others. All simulation results show that intelligent based techniques show better dynamic performance and can produce more power with less repelling power compared with P&O algorithm. It is observed that the obtained results are in good agreement with literature ones.

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