New improved MPPT based on artificial neural network and PI controller for photovoltaic applications

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Article Info

Article history:

Received Apr 21, 2022
Revised Jun 9, 2022
Accepted Jun 28, 2022

Keywords:

ANN-PI
Boost converter
MPPT
P&O
Photovoltaic application

ABSTRACT

This paper details an maximum power point tracking (MPPT) approach based on artificial neural network (ANN) to track the maximum power produced by a PV panel. This approach is rapid and accurate for following the maximum power point (MPP) during changes in weather conditions such as solar irradiation and temperature. A PV system structure including an MPPT controller is studied, designed, and simulated in this work. The aim of this paper is to use the artificial neural network (ANN) technique to develop a MPPT controller for PV applications. To increase the performance of the ANN-MPPT controller, a proportional integral (PI) controller is also included. In addition, the performance of an ANN-based MPPT controller is also compared to the conventional perturb and observe (P&O) method. To analyze the results, simulations are performed by using MATLAB software.

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1. INTRODUCTION

The world is always in need of new energy resources to reduce its dependence on fossil sources, and photovoltaic (PV) energy appears to be a viable solution. In fact, photovoltaic energy has proven to be an economical and clean energy source for many applications. Moreover, photovoltaic energy is clean, inexhaustible and low maintenance, making it the most suitable for many applications in remote areas such as water pumping, irrigation systems, battery charging, meteorological measuring devices, satellite feeding systems, island electricity supply system and telecommunication systems. The efficiency of a PV system is low when compared to other energy sources, therefore, the system would be more efficient if the maximum power output could be continuously tracked for any changes in meteorological conditions such as solar irradiation and temperature. As a result, the concept of tracking a PV system's maximum power output has been introduced.

The idea behind maximum power point tracking (MPPT) is to extract the maximum power from the PV module [1]-[4]. For this aim, the basic MPPT circuit includes a DC/DC power converter connected between the load and the PV module in order to adapt the resistance of the load seen by the PV module by varying the duty cycle of the DC/DC power converter [3], [5]. Nowadays, different MPPT approaches have been developed and published. Various algorithms are reviewed in [6]-[8], these algorithms contain fractional open-circuit voltage (OCV) [7], fractional short-circuit current (OSC) [8], incremental conductance (IC) [8], perturb and observe (P&O) and hill-climbing (HC) [6]. Because of the simplicity of (P&O) and (IC) algorithms, they have piqued the interest of the majority of scholars [9]. However, these approaches have a number of drawbacks, including a slower response time, high fluctuations in steady states and low efficiency under fast variations of solar irradiation [8].

Recently, artificial intelligence (AI) has become more and more popular in MPPT control systems for PV systems. MPPT controllers using fuzzy logic (FL) was proposed in [10]-[12]. Fuzzy logic can reduce the slower response time and high fluctuations in steady states around maximum power point (MPP) [13]. Combining FLC with the hill-climbing algorithms improves MPPT performance [14]. Fast and robust results of a fuzzy logic FLC controller based on the P&O method are presented in [15]. To improve the tracking of the global MPP, which is highly beneficial for partial shading, the genetic algorithm (GA) was applied in [16]. Other strategies, such as hybrid MPPT, combine traditional methodologies with artificial intelligence [17]-[19]. In [20], [21] have presented comparison and classification analysis of classical and artificial intelligence methods for MPPT.

Artificial neural networks (ANN) based MPPT are commonly employed as a robust, fast and efficient technique [22]-[24]. The main advantages of employing ANN technique with PV systems are that it does not need a profound understanding of the internal system characteristics and it has the ability to recognize nonlinear relationships between dependent and independent variables [25], [26]. The main contribution of this paper is the improvement of the ANN-based MPPT performance by using a supervised machine learning technique with softening through a PI controller. The second focus of this work is the simultaneous simulation of PV applications under different weather conditions. the simulation results were compared with the conventional P&O technique under changing of solar irradiance and temperature. The paper remaining is arranged in this fashion: the modelling of PV module is detailed in section 2, followed by the maximum power point tracking (MPPT) in section 3. Proposed PV system is descripted in section 4, the simulation results are detailed in section 5 and finally section 6 is dedicated to the conclusion.

2. PV MODELLING

Solar cells can be considered as a semiconductor element. When the sun's radiation penetrates the surface of the PV cells, a direct current flows through the photovoltaic panels [5]. The equivalent electric circuit is shown in Figure 1. This model, called one-diode model, is built with a current source, a single diode and a pair of resistors [4], [5].

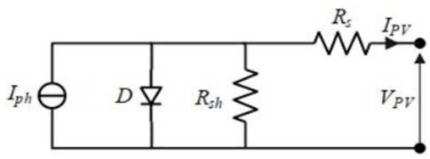


Figure 1. Electrical model of PV cell

The PV cell output current can be found using Kirchhoff's law, as illustrated in (1).

$$I_{PV} = I_{ph} - I_D - I_{sh} = I_{ph} - I_D - \frac{V_{PV}+R_S.I_{PV}}{R_{sh}} \quad (1)$$

The Current I_D can be described by the following Shockley in (2),

$$I_D = I_0.\left(e^{\frac{qV_D}{nKT}} - 1\right) = I_0.\left(e^{\frac{q(V_{PV}+R_S.I_{PV})}{nKT}} - 1\right) \quad (2)$$

where I_0 is the reverse current of saturation, K is the Boltzmann's constant, q is the elementary charge quantity, n is the ideality factor of the p-n junction and T is the temperature of the PV cell [2].

By inserting (2) into (1), the expression for the I-V characteristics of PV cell model is given by the formula below:
The photo generated current I_{ph} depends on the temperature T and the irradiance Ir as in (3).

$$I_{PV} = I_{ph} - I_0.\left(e^{\frac{q(V_{PV}+R_S.I_{PV})}{nKT}} - 1\right) - \frac{V_{PV}+R_S.I_{PV}}{R_{sh}} \quad (3)$$

$$I_{ph} = [I_{SC} + K_i(T - 298)].\frac{G}{1000} \quad (4)$$

Where G is solar irradiation, Isc is the short circuit current at 25°C and 1000W/m^2, and Ki is the temperature coefficient of Isc.

As shown in Figure 2, a PV module often is made of many PV cells in series or in parallel, in other words, the module is assembled using M PV cells wired in series and N PV cells wired in parallel. The output voltage V and output current I of the PV module are both determined as follows.

$$V = M.V_{PV} \tag{5}$$

$$I = N.I_{PV} \tag{6}$$

The expression of the output current of the PV module is determined by substituting (5) and (6) in (3):

$$I = NI_{ph} - NI_0.\left(e^{\frac{q\left(\frac{V}{M}+R_S\frac{I}{N}\right)}{nKT}} - 1\right) - \frac{\frac{N}{M}V + R_S.I}{R_{sh}} \tag{7}$$

which is the expression relating the output voltage and the output current of a PV module containing M × N cells. As detailed in (7), the I-V curves of a PV module are highly influenced by climatic conditions, especially changes in solar irradiance and temperature of PV module. Figures 3(a) and 3(b) present the I-V characteristics at various temperatures and at several different irradiation conditions. The problem of non-linearity of I-V characteristics is clearly observed at different conditions.

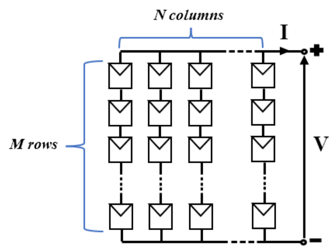
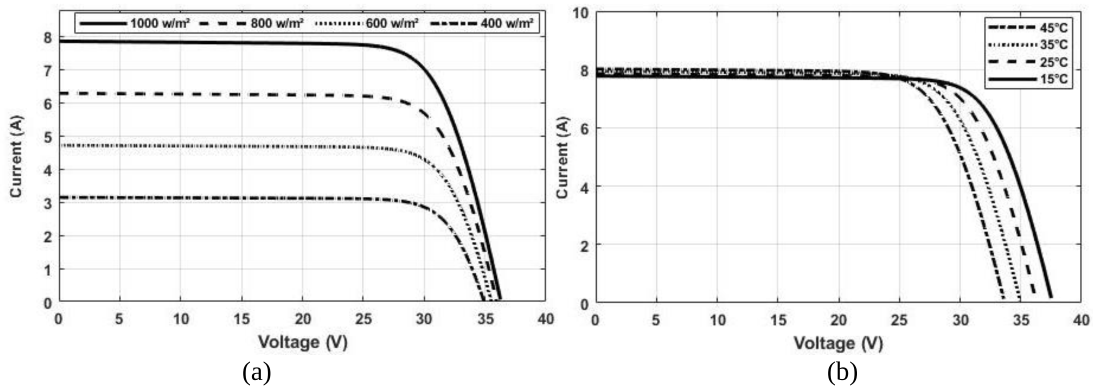


Figure 2. Association of PV cells (series-parallel)

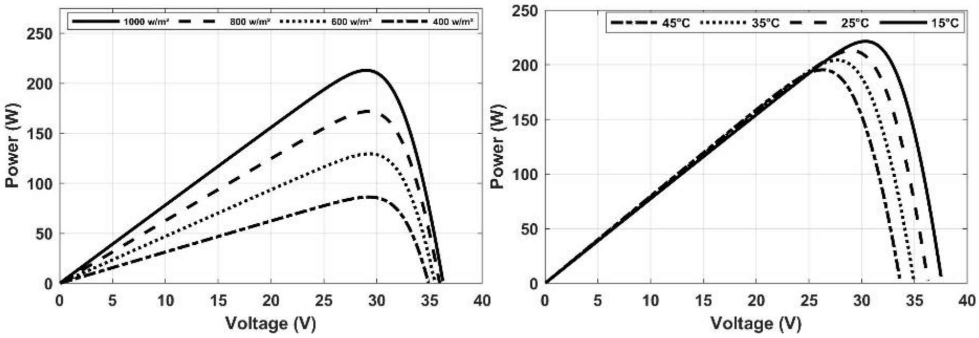


(a) (b)

Figure 3. I-V characteristics of the PV module (a) I-V characteristics at standard temperature (25 °C) and (b) I-V characteristics at standard irradiance (1000 W/m^2)

3. MAXIMUM POWER POINT TRACKING (MPPT)

As represented in Figures 4(a) and 4(b), There is only a single point on the P-V characteristics of the PV module where the power is at its maximum value, which is known as the maximum power point (MPP). The meteorological conditions influence the position of this point: power increases as irradiation increases, and a PV panel is better for a low temperature than a high temperature [27]. As mentioned in the introduction section, the MPPT technique is highly important to guarantee the function of the PV module at the MPP in various weather conditions [19]. Several methods have been developed for this purpose. In the following subsections, (ANN) and (P&O) techniques are detailed as they are the purpose of this study.



(a) (b)

Figure 4. P-V characteristics of PV module (a) P-V characteristics at standard temperature (25 °C) and (b) P-V characteristics at standard irradiance (1000 W/m^2)

3.1. Perturb and observe technique

Because of its simplicity, perturb and observe (P&O) is the most popular MPPT technique [20], [28]. Figure 5 illustrates the (P&O) flowchart. The principle of this method is to create a disturbance by changing the duty cycle of the power converter control signal and observing the power response at the output of the PV panel. If the present power P(n) is higher than the previously calculated power P(n-1), then the direction of the disturbance is maintained, otherwise the direction will be reversed. However, its main disadvantage is that it oscillates permanently around the maximum power point [29]. Although a variety of adaptive P&O algorithms were developed to increase the efficiency of the conventional method, the oscillation around the MPP is still a limitation for these methods.

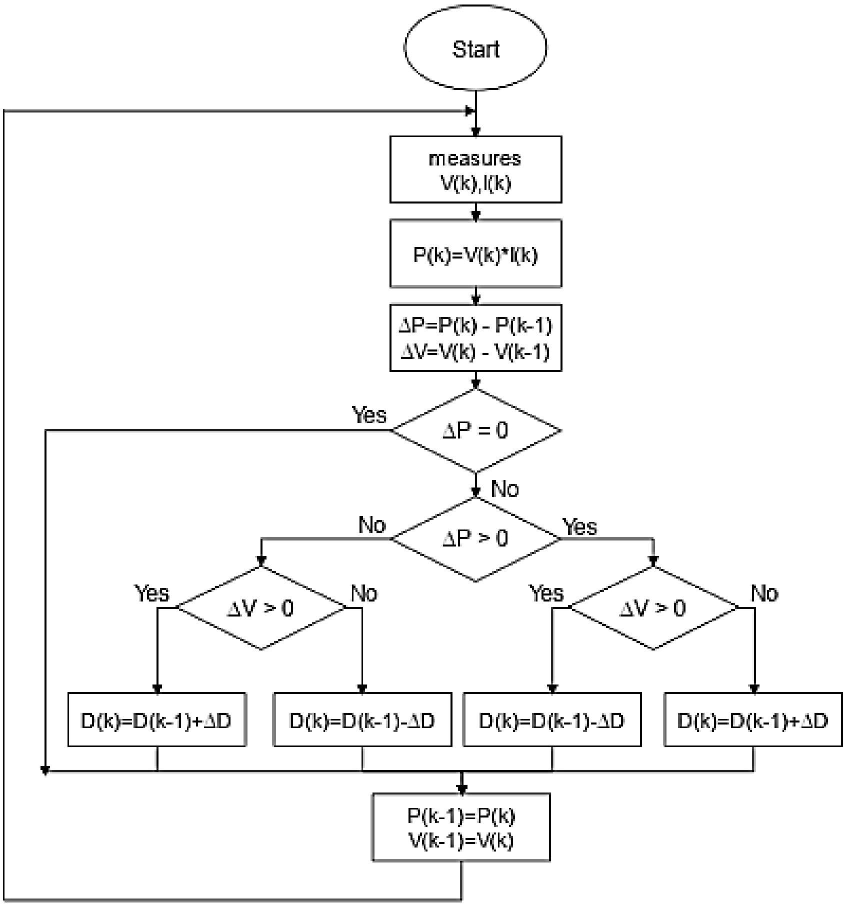


Figure 5. The P&O flowchart

3.2. Artificial neural network

With the purpose of developing high performance controller, we propose in this paper an optimized controller, by using artificial neural network technique. A typical feed-forward ANN structure is shown in Figure 6. It consists of several neurons which are analogous to brain biological cells. These neurons are organized in layers with a huge number of weighted connections with other neurons in successive layers [30]. Each input layer neuron receives a set of data from the input variables and sends them to the hidden layer neurons, which combine inputs to form a single result, which is then delivered to the output through an activation function. Finally, each output layer neuron adds the hidden layer's outputs to the bias and passes the result via the activation function to generate the final output.

As shown in Figure 6, x is the input of the ANN, y is the output of the ANN, and w represents weights and biases. The final output can be formulated by using linear activation for neurons of the input layers and the output layers and by using sigmoidal activation functions for neurons of the hidden layer.

$$y^1 = w2_{10} + w2_{11}z_1 + w2_{12}z_2 + \cdots + w2_{1n}z_n \quad (8)$$

Therefore, the generalized output equation can be expressed as follows,

$$y^1 = \sum_{j=0}^{n} w2_{1j}\, z_j \quad (9)$$

where:

$$z_0 = 1 \quad (10)$$

$$z_j = f(a_j) = \frac{1}{1+e^{a_j}} \quad (11)$$

$$a_j = \sum_{h=1}^{2} w1_{jh}\, x^h \quad (12)$$

during neural network training, the weights of layers are modified to achieve the target values with the goal of finding a set of weights that minimizes the error between the ANN's output and the target value. The mean square error (MSE) is the ANN network's performance function, which is determined in (13).

$$E_{mse} = \frac{1}{N}\sum_{i=1}^{N}(t_i - y_i^1)^2 \quad (13)$$

Where t_i represents the target at sample i, y_i represents the output signal at sample i, and N is the training number of models.

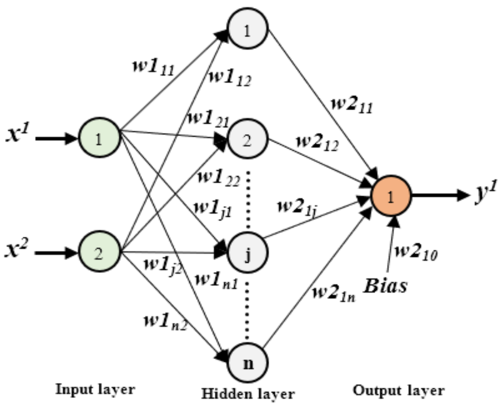


Figure 6. Structure of a typical feed- forward artificial neural network

4. PROPOSED PV SYSTEM

The proposed photovoltaic system is shown in Figure 7. The main components of this system are PV module, the load, and DC/DC boost converter driven by ANN-MPPT controller. The DC-DC converter is placed inside the PV module and the resistive load to extract the maximum power produced by the PV module. A pulse width modulation (PWM) generator controlled by the PI controller drives the DC-DC converter's output voltage. The ANN algorithm tracks the maximum power point (MPP) by estimating the voltage in this point (Vmpp) using instantaneous measurements of solar irradiation (Ir) and temperature (T).

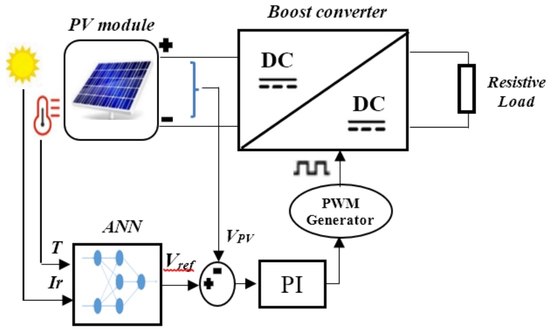


Figure 7. Block diagram of the proposed model

4.1. PV module

In this paper, a 215-W PV module (1Soltech 1STH-215-P) is chosen for the simulation. This PV module is tested under different levels of irradiations and temperatures. The main technical parameters of this PV module are listed in Table 1.

Table 1. Technical parameters of the module: 1Soltech 1STH-215-P

Technical parameter	Symbol	Value
Maximum power	P_{MAX}	213.15W
Output voltage at MPP	V_{MPP}	29V
Output current at MPP	I_{MPP}	7.35A
Open circuit voltage	Voc	36.3V
Short circuit current	Isc	7.84A
Temperature coefficient of Voc	Kv	-0.36%/°C
Temperature coefficient of Isc	Ki	0.102%/°C

4.2. Artificial neural network

An ANN model is developed in the MATLAB/Simulink environment using a feed-forward ANN network with three layers. Irradiance and temperature are the inputs to the ANN-based MPPT, and the reference voltage at the point of maximum power is the output. For this model, the neural structure is, i) input layer: 2 neurons, ii) hidden layer: 10 neurons, and iii) output layer: 1 neuron.

The ANN model has two modes of operation:

- The offline mode: the ANN model is trained by using a database of inputs (irradiation and temperature) to find the optimal target values (reference voltage) by using the Levenberg-Marquardt algorithm.
- The online mode: using this optimal ANN model to track the MPP.

The performance of the ANN network is shown in Figure 8. It's clear that the performance is accepted which present an error of 1.305E-11.

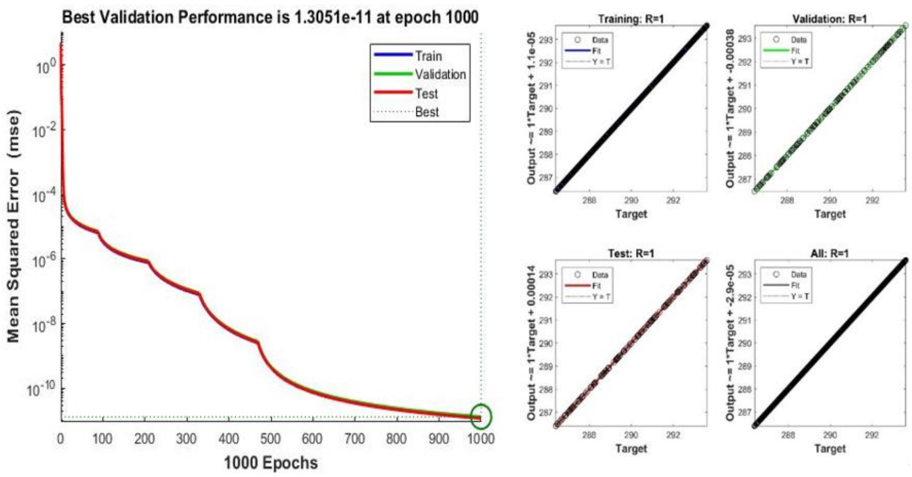


Figure 8. Training performance of the ANN network

4.3. PI controller

The PI controller seeks to correct the error between a measured voltage and the desired setpoint by determining the difference and then taking a corrective action to adjust the process accordingly [22]. A PI controller regulates the process using two parameters: proportional (P) and integral (I). Although the proportional gain is good at reducing the response time, it is not an ideal solution for reducing the steady-state error. That's why adding the integral action is an effective way to eliminate the steady-state error. Table 2 shows parameters of PI controller which are calculated by Ziegler-Nichols method.

Table 2. Parameters of PID controller

PI parameter	Value
Kp	0.001
Ki	0.1

4.4. DC-DC boost converter

A DC/DC converter is a power electronic circuit placed between the PV generator and the load to obtain the highest power produced by the PV generator [3]. A DC/DC converter type boost is chosen which increases the voltage at the input to the desired voltage at its output. A boost converter is formed by switching devices, an inductor and two capacitors, as shown in Figure 9. The transistor (T) is switched at a high frequency by applying a PWM signal to the transistor gate. The output voltage level is controlled by changing the duty cycle value (α) which is given in (14). The different electrical parameters of the boost converter are shown in Table 3.

$$V_{out} = \frac{1}{1-\alpha} V_{in} \tag{14}$$

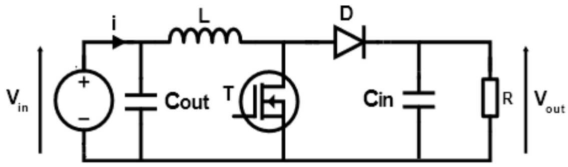


Figure 9. Boost converter

Table 3. Electrical parameters of the boost converter

Electrical parameter	Value
Input capacitor C_{in}	0.2 mF
Output capacitor C_{out}	0.5 mF
Inductor L	0.2 mH
Switching frequency f	40 KHz

5. SIMULATION RESULTS

A simulation model is developed using MATLAB/SIMULINK software to validate the proposed PV system described above. The SIMULINK model is shown in Figure 10. In order to estimate the act of the ANN based MPPT controller, this simulation model is tested under different weather conditions, as shown in Figures 11(a) and 11(b). In fact, during the first-time interval [0s, 0.6s], the PV module is considered under standard weather conditions (1000 w/m² and 25 °C). During the second time interval [0.6s, 1s], the irradiance drops from 1000 w/m² to 300 w/m², while the temperature increases from 25 °C to 27 °C then decreases from 27 °C to 26 °C. In the last time interval [1s, 2s], the irradiance increases from 300 w/m² to 600 w/m² and then increases to 800 w/m², while the temperature remains constant (26 °C). Additionally, to demonstrate the effectiveness of the ANN-based MPPT, a comparison to the traditional P&O technique was performed. These results are shown in Figures 12, 13 and 14.

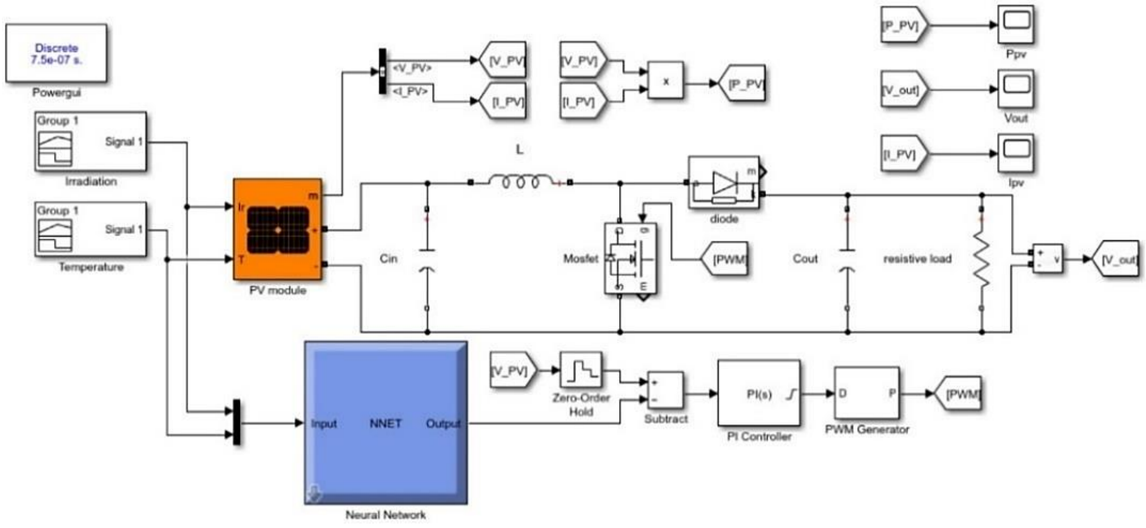


Figure 10. Simulation model of proposed system

(a) (b)

Figure 11. Input weather conditions for PV panel (a) irradiance pattern and (b) temperature pattern

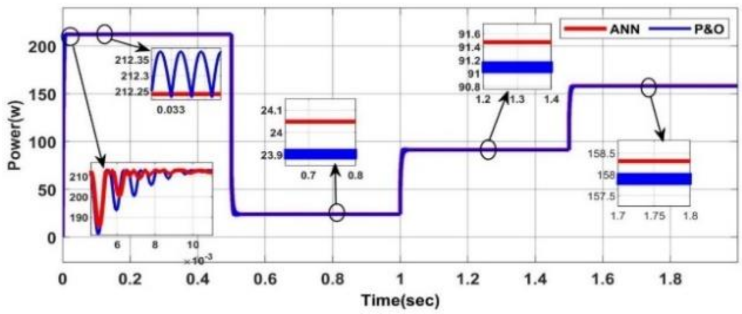


Figure 12. Output power for ANN based MPPT and P&O methods under different weather conditions

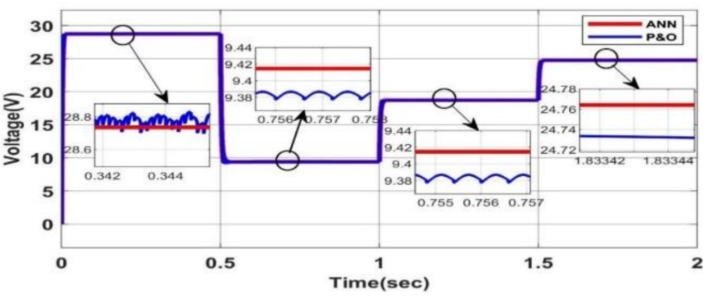


Figure 13. Output voltage for ANN based MPPT and P&O methods under different weather conditions

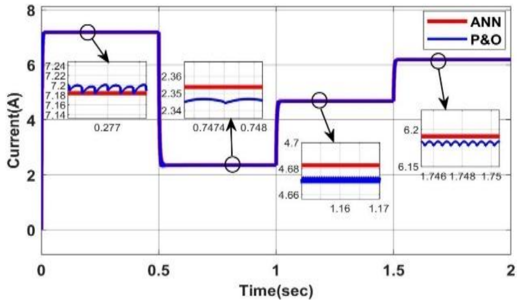


Figure 14. PV current curves for ANN based MPPT and P&O methods under different weather conditions

Table 4 shows the comparison results for both MPPT algorithms, as can be seen, the ANN method is more accurate than the P&O method because it precisely tracks the PPM. Moreover, the ANN approach yields faster responses despite changes in solar temperature and irradiance conditions. As a result, ANN achieves PPM with a high accurate, a short response time and a better robustness to climate change. As shown in Figure 12, there are oscillations around the MPP for the P&O technique. This is because the operational voltage is continuously perturbed in order to reach the MPP. On the other hand, the ANN-based MPPT technique avoids this oscillation problem by keeping the power, voltage and current signals essentially constant.

Table 5 presents the PV system efficiency and accuracy obtained in four irradiation levels by the algorithms ANN - PI and $P\&O$. The efficiency is defined as:

$$E(\%) = \left(\frac{P_{MPPT}}{P_{th}}\right) \times 100 \tag{15}$$

where P_{MPPT} is the power at the output of the PV panel and P_{th} is its maximum theoretical power.

Table 4. Results of the comparison between P&O and ANN-PI

MPPT algorithms	Irradiance (1000 W/m²)		Irradiance (300 W/m²)		Irradiance (600 W/m²)		Irradiance (800 W/m²)	
	Tracking Speed time(ms)	Power Oscillation (w)	Tracking Speed time(ms)	Power Oscillation (w)	Tracking Speed time(ms)	Power Oscillation(w)	Tracking Speed time(ms)	Power Oscillation(w)
P&O	15	0.4	6	0.17	5	0.46	6	0.55
ANN-PI	13	0.02	5	0.003	5	0.01	5	0.002

Table 5. Results of the comparison between P&O and ANN-PI

PPT algorithms	Irradiance (0 W/m² to 1000W/m²)		Irradiance (1000 W/m² to 300 W/m²)		Irradiance (3000 W/m² to 600 W/m²)		Irradiance (600 W/m² to 800 W/m²)	
	Traking Accuracy	Power Effeciency	Traking Accuracy	Power Effeciency	Traking Accuracy	Power Effeciency	Traking Accuracy	Power Effeciency
P&O	Moderate	99.54%	Moderate	98.32%	Moderate	98.99%	Moderate	99.27%
ANN-PI	Moderate	99.57%	Good	98.93%	Good	99.42%	Good	99.56%

6. CONCLUSION

In this work, an ANN based MPPT approach has been presented. The ANN inputs are irradiance and temperature. The optimal voltage of the PV panel is the output of the neural network. In addition, a PI controller is used to improve system performance to track the maximum power point (MPP) under fast variations of weather conditions.

Simulation results are presented under a variety of meteorological conditions, with a focus on several indexes performance. Based on the results obtained, we can confirm that the proposed neural network-based PI controller gives better performance compared to the conventional P&O, especially in terms of low oscillation and short response time. The simulation results also showed that the proposed MPPT algorithm yields better power output with minimum oscillation in steady state.

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