Erzincan Üniversitesi
Fen Bilimleri Enstitüsü Dergisi
2022 15(1), 242-257
ISSN: 1307-9085, e-ISSN: 2149-4584
Araştırma Makalesi

Erzincan University
Journal of Science and Technology
2022, 15(1), 242-257
DOI: 10.18185/erzifbed.1002823
Research Article

Artificial Neural Network based MPPT Algorithm with Boost Converter topology for Stand-Alone PV System

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Geliş/Received: 30/09/2021 Kabul/Accepted: 15/12/2021

Abstract

The increasing energy need in parallel with the technology development and the depletion of the resources have increased the importance of alternative energy resources. Solar energy systems are frequently preferred due to their advantages such as not having moving parts, being reliable and working without noise. Production of electricity from solar energy is obtained by serial or parallel connection of photovoltaic (PV) panels, depending on the desired voltage and current values. DC-DC converters are used to convert the energy obtained from the PV panels to the desired grid values. Maximum power point tracking (MPPT) algorithms are used in order to obtain the highest possible efficiency from the PV panels. MPPT algorithms control the duty period (D) ratio of DC-DC converters and obtain maximum energy. In this study, an Artificial Neural Network (ANN) based MPPT algorithm is proposed. Firstly, the temperature and irradiance data at the PV panel input are trained using the Levenberg-Marquardt algorithm. As a result, a reference voltage is generated and MPPT is realized by comparing it with the voltage produced by the PV panel. In order to evaluate the performance of the proposed algorithm, it is compared with the traditional MPPT methods such as Perturb & Observe (P&O) and Incremental Conductance (INC). As a result of the simulation studies, it has been observed that ANN based MPPT is more successful than P&O and INC algorithms for several irradiance and temperature conditions.

Keywords: Artificial neural network, maximum power point tracking, DC-DC converter, incremental conductance algorithm, perturb & observe algorithm, renewable energy sources.

Müstakil çalışan PV Sistem için Yükselten Tip Dönüştürücü topolojisine sahip Yapay Sinir Ağı tabanlı MPPT Algoritması

Öz

Teknolojinin gelişmesine paralel olarak artan enerji ihtiyacı ve kaynakların tükenmesi, alternatif enerji kaynaklarının önemini artırmıştır. Güneş enerjisi sistemleri hareketli parça olmaması, güvenilir olması ve gürültüsüz çalışması gibi avantajları nedeniyle sıklıkla tercih edilmektedir. Güneş enerjisinden elektrik üretimi, istenilen gerilim ve akım değerlerine bağlı olarak fotovoltaik (PV) panellerin seri veya paralel bağlanması ile elde edilmektedir. PV panellerden elde edilen enerjiyi arzu edilen şebeke değerlerine dönüştürmek amacıyla DC-DC dönüştürücüler kullanılmaktadır. PV panellerden mümkün olan en yüksek verimi elde etmek için maksimum güç noktası izleme (MPPT) algoritmaları kullanılmaktadır. MPPT algoritmaları DC-DC dönüştürücülerin görev periyodu (D) oranını kontrol edip maksimum enerji elde etmektedirler. Bu çalışmada, Yapay Sinir Ağı (YSA) tabanlı bir MPPT algoritması önerilmiştir İlk olarak PV panel girişindeki sıcaklık ve ışınım verileri Levenberg-Marquardt algoritması kullanılarak eğitilmiştir Sonuç olarak, bir referans voltajı üretilir ve PV panel tarafından üretilen voltaj ile karşılaştırılarak MPPT gerçekleştirilmektedir. Önerilen algoritmanın performansını değerlendirmek için geleneksel MPPT yöntemlerinden Değiştir & Gözle (P&O) ve Artırılmış iletkenlik (INC) ile karşılaştırılmıştır. Benzetim çalışmaları sonucunda YSA tabanlı MPPT'nin çeşitli ışınım ve sıcaklık koşulları için P&O ve INC algoritmalarından daha başarılı olduğu gözlemlenmiştir.

Anahtar Kelimeler: Yapay sinir ağı, maksimum güç noktası takibi, DC-DC dönüştürücü, artırılmış iletkenlik

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algoritması, değiştir & gözle algoritması, yenilenebilir enerji kaynakları.

1. Introduction

The rapid development of technology increases the need for electrical energy. Because of the depletion of fossil energy fuels, environmentally friendly renewable energy sources are used more for electrical energy generation. Today, the most preferred renewable energy types can be counted as geothermal energy, hydroelectric energy, wind energy and solar energy. Due to the advantages of PV panels such as low maintenance cost and no moving parts, solar energy systems are often preferred. PV cells are made of from semiconductor materials. The surfaces of these materials are in the form of circular, rectangular and square shapes (Aydoğan, 2019). The electrical energy produced by the panels varies according to the irradiance coming to the surface and the temperature. Many studies have been carried out to increase the well-known low efficiency of the PV panels. For the energy continuity of the load, PV panels must operate at the maximum power point (MPP). MPPT algorithms have been developed for the load to work in MPP. These algorithms basically play an active role in transferring the energy obtained from the PV panel to the load through power electronic circuits. Due to their advantages such as simple structure and easy applicability, the most preferred MPPT algorithms are INC and P&O algorithms. However, these algorithms are insufficient in achieving the global maximum under partial shading conditions (PSC), although they are quite efficient in the uniform radiation and temperature conditions (Danandeh, 2018). There are many studies on MPPT algorithms in the literature. For instance, Mohamed et al. propose a Fuzzy Logic Controller (FLC) based MPPT algorithm in order to increase the efficiency of the PV panels. The authors aim to provide maximum energy to the load under PSC. As a result, it has been observed that the proposed method reaches global MPP rapidly under PSC and there is negligible oscillation in output power (Mohamed et al., 2018). Systems that meet the electricity needs of the end user via PV panels without being connected to an outer network are called Stand-Alone PV systems. Thueampangthaim et al. propose a current-based MPPT algorithm for stand-alone PV systems. The performance of the proposed algorithm is compared with P&O. As a result, the authors observe that the current-based MPPT technique is more successful than the P&O algorithm in terms of transient and steady-state responses (Thueanpangthaim et al., 2017). Moreover, Gündoğdu and Çelikel propose an Artificial Neural Network (ANN) based MPPT algorithm in order to obtain high efficiency from PV panels. The proposed method under PSC is compared with the INC and P&O algorithms. It is observed that the ANN based MPPT algorithm is superior to the other two algorithms in MPP tracking. In addition, among the algorithms used, the ANN-based MPPT algorithms is seen to have the highest efficiency algorithm (Gündoğdu and Çelikel, 2020). Similarly, Divyasharon et al. propose an ANN-based MPPT algorithm under PSC. The performance of the DC-DC converters is evaluated by applying the proposed algorithm to Cuk converter and boost converter. The results of the paper suggest that the proposed algorithm produces good results in MPP tracking for both converters. In addition, it is determined that the Boost converter has high irradiance value and the Cuk converter is efficient under all climatic conditions (Divyasharon et al., 2019). Avila et al. propose a Deep Reinforcement Learning (DRL) based MPPT algorithm in order to obtain maximum power from PV systems, which are becoming widespread day by day. The performance of the proposed algorithm is evaluated under various conditions. One may observe from the algorithm results that the RL-based MPPT algorithm follows MPP with a deviation of less than 1% (Avila et al., 2020). Irmak and Güler also propose a new algorithm by combining the MPPT methods P&O and Model Predictive Control (MPC) to increase the dynamic performance of the boost converter used in PV applications. The authors claim that the proposed algorithm not only gives very good results in terms of dynamic performance but also eliminates overshooting (Irmak and Güler, 2020). Besides, Yılmaz and Çorapsız perform maximum power point tracking for different irradiance values of PV panels. For power point tracking, an Adaptive Neuro-Fuzzy Inference System (ANFIS) which is a heuristic optimization technique, and INC algorithm which is a traditional optimization technique are used in parallel. Consequently, authors state that the ANFIS algorithm is more successful than INC in terms of both percent overshooting and settling time at different irradiance values (Yılmaz and Çorapsız, 2021). Likewise, Zafar et al. compare swarm-based Marine Predator algorithm (MPA) and Mayfly Optimization algorithm (MFA) with several algorithms such as Grasshopper Optimization (GOA), Cuckoo Search (CS) Algorithm, Gray Wolf Optimizer (GWO), and Particle Swarm Optimization (PSO) algorithms for varying irradiance conditions. In order to increase the voltage value obtained from the PV panels, a boost converter is used. The authors observe that MPA and MFA are more successful than other algorithms in performance parameters such as tracking and settling time, and reduced oscillations around the global maximum (Zafar et al., 2021). Charin et al. propose a hybrid algorithm for MPPT in PV panels in which PSO and Levy Flight Optimization (LFO) algorithms are combined in order to make use of strong sides of both algorithms. Three different irradiation conditions are taken into account during the studies. Results of the runs indicate that Levy Flight Particle Swarm Optimization (LPSO) algorithm is more successful than PSO and LFO algorithms in terms of performance criteria such as steady state oscillation, efficiency and stability (Charin et al., 2021). Fares et al. also propose a new approach for MPPT by updating the Squirrel Search algorithm (SSA). The proposed algorithm is then compared with Genetic Algorithm (GA), PSO and classical SSA algorithms for 5 different irradiance conditions. It is observed that the proposed algorithm gives better results than other algorithms for all cases, follows the MPP which is faster only by 0.66 sec., and is more efficient and reduces the oscillation by more than 50% at the global maximum point (Fares et al., 2021). In their study, Javed et al. propose an algorithm for MPPT under partial shading conditions. The proposed algorithm is obtained by making two parameters of the PSO algorithm adjustable. Cuk converter is used as a DC-DC converter. As a result of the simulation and experimental studies carried out for three different cases, it is seen that the proposed algorithm is robust and reliable (Javed et al., 2021). In addition, Samani and Mirzaein come up with a new algorithm for tracking the MPP in PV systems by updating the MPC method. They claim that their algorithm gives more accurate and faster results compared to MPC. It is also determined that the algorithm reduces the fluctuations at around the MPP (Samani and Mirzaein, 2021). Another study is due to Tang et al. in which the authors propose the Fuzzy Information Diffusion technique as a solution to the MPPT problem under PSC. The proposed method is compared with the classical optimization algorithms such as Ant Bee Colony (ABC) and PSO. The success of the proposed method is then demonstrated by the simulation and real-time results obtained (Tang et al., 2021). On the other hand, Khalil et al. propose a new algorithm that can be viewed as an alternative to traditional MPPT algorithms. The proposed algorithm is compared with the Firefly Algorithm (FA) and P&O algorithms for three different cases. It is observed that the simulation and real-time results coincides with each other (Khalil et al., 2021). Bypass diodes used in PV panels under partial shading conditions cause local and global maximum points to occur. Finally, Eltamaly updates the CS algorithm to propose a new algorithm for maximum power transfer to the load. The most important advantage of the proposed algorithm is its low computational complexity. As a result of the experimental studies carried out, it is stated that the proposed algorithm follows the maximum point faster than the PSO, CS, GWO and ABC algorithms and does not oscillation around the maximum power point. (Eltamaly, 2021).

2. Material and Methods

PV systems consist of a combination of load, MPPT controller, DC-DC converter and PV panels. The voltage obtained from the PV panel is converted to the desired voltage levels through DC-DC converter. While performing this conversion process, the duty period of the DC-DC converter switching element is adjusted to provide maximum energy to the load using MPPT algorithms. The Stand-Alone PV system block diagram designed using the MPPT algorithm is shown in Figure 1.

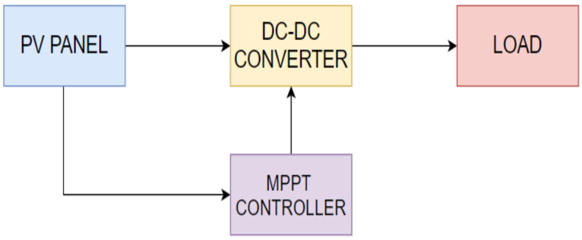

Figure 1. Stand-Alone PV system

2.1. PV Cell Model

PV cells consist of p-n semiconductor elements combined as a thin layer. When PV cells are exposed to light, they generate direct current as a result of electron movement. Single diode general electrical equivalent circuit of PV cells is illustrated in Figure 2.

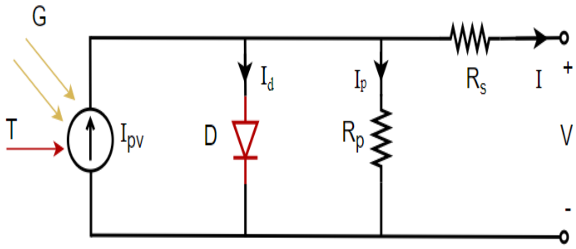

Figure 2. Equivalent circuit of cell with one diode

Single diode PV cell consists of one diode (D), one current source (I_{pv}), one parallel resistor (R_p), and one series resistor (R_s). In Figure 2, the current generated by I_{pv} light photons represent the I_d diode current. Mathematical equations of the PV cell model are shown in the equations between Equation 1 and Equation 5.

$$I_{pv} - I_d - I_p - I \tag{1}$$

$$I_d = I_0\left(e^{\frac{qV_d}{kT}} - 1\right) \tag{2}$$

$$V_d = V + IR_S \tag{3}$$

$$I_d = I_0\left(e^{\frac{q(V+IR_S)}{nkT}}\right) \tag{4}$$

$$I = I_{pv} - I_0\left(e^{\frac{q(V+IR_S)}{nkT}}\right) - \frac{V + IR_S}{nkT} \tag{5}$$

where I_0 represents reserve saturation current (A), q represents the electron charge (C), k is the Boltzman constant (J/K), T stands for the cell temperature (K) and finally n represents the diode idealty constant.

2.1.1. The effect of temperature and irradiance on the PV panel

The two most important parameters affecting the output power of a PV panel are the temperature and irradiance values. The necessary conditions for obtaining the maximum power in PV panels are $1000\ W/m^2$ irradiance value and $25\ ^\circ C$ temperature value. However, these values may not be achieved depending on the angle of incidence of the sun and under PSC. In these cases, the power obtained from the PV panel naturally decreases.

The change in irradiance at constant temperature value $(25\ ^\circ C)$ affects the amount of current obtained from the PV panel. The amount of current obtained from the panel increases with the irradiance value. The irradiance is directly proportional with the power value since the output power of the PV panel depends on the current and voltage values generated in the panel. I-V and P-V characteristic of a panel type 1 Soltech 1STH-250-WH for constant temperature and variable irradiance values are illustrated in Figure 3, below.

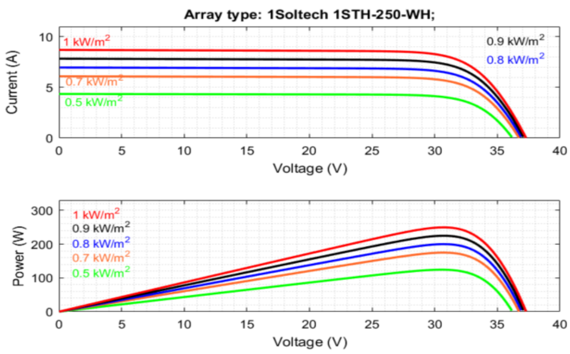

Figure 3. I-V and P-V curves of the PV system; at a constant *25°C*

The voltage generated by the PV panel varies at constant irradiance value of 1000 W/m^2 under variable temperature. If the temperature value increases, the voltage value generated from the panel decreases and vice versa. The voltage decreases leading to a decrease in the output power value as a result of an increase in the value of the temperature since the output power of the PV panel depends on the current and voltage. On the contrary, decrease in temperature increases the output power. I-V and P-V characteristics of 1 Soltech 1STH-250-WH constant irradiance and variable temperature values are shown in Figure 4.

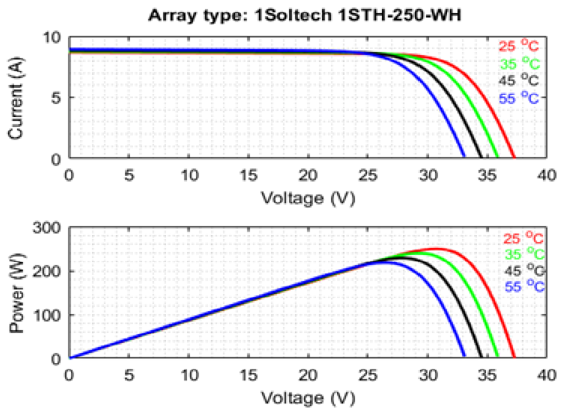

Figure 4. I-V and P-V curves of the PV system at constant *1000 W/m²*

2.2. Boost Converter

Boost converter are circuit topologies that transfer DC input voltage to output at a higher level (Srinivasan et al., 2021). Boost converters basically consist of one diode, one capacitor, one switching element, one inductance and load. The circuit topology of boost converter is shown in Figure 5.

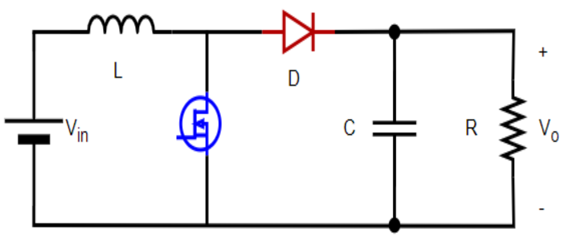

Figure 5. The circuit topology of boost converter

2.2.1. Ideal Boost Converter Switching Element is Closed

If switching element is closed, the diode is reverse polarized and shows open circuit feature. The inductance L is charged by the source voltage V_{in}. The energy stored on the capacitor C supplies energy to the load R. The circuit topology of the switching element is closed as shown in Figure 6. The dynamic equations for this situation are given in Equation 6 and Equation 7.

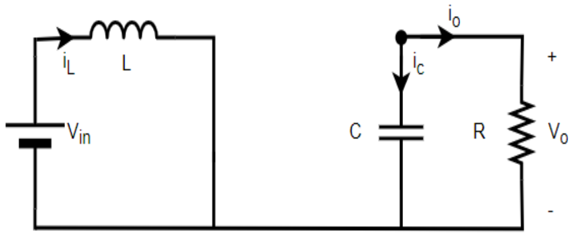

Figure 6. Situation when the switching element is closed

$$\frac{di_L}{dt} = \frac{V_{in}}{L} \tag{6}$$

$$\frac{dV_0}{dt} = \frac{1}{C}\left(\frac{-V_0}{R}\right) \tag{7}$$

2.2.2. Ideal Boost Converter Switching Element is Open

When switching element is open, the diode is forward polarized and that means we have a short circuit at hand. The load is supplied by the V_{in}source voltage and the L inductance. The circuit topology is illustrated in Figure 7 for the situation in which the switching element is open. Equation 8 and Equation 9 are the dynamic equations representing this situation.

$$\frac{di_L}{dt} = \frac{1}{L}\,(V_{in} - V_0) \tag{8}$$

$$\frac{dV_0}{dt} = \frac{1}{C}\left(i_L \frac{V_0}{R}\right) \tag{9}$$

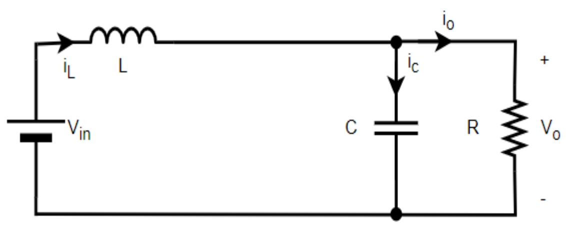

Figure 7. Situation when the switching element is open

On the other hand, equation for the output voltage of boost converter is given below as Equation 10 and Equation 11;

$$\mathrm{DT}\frac{\mathrm{V_{in}}}{\mathrm{L}} + \frac{1}{\mathrm{L}}\,(\mathrm{V_{in}} - \mathrm{V_0})\,(1 - \mathrm{D}) = 0 \tag{10}$$

$$V_0 = \frac{V_{in}}{1 - D} \tag{11}$$

where V_0 Output voltage (V), V_{in} represent input voltage (V), i_L is the inductance current (A), D represent duty period, L inductance value (H), C capacitance value (F), T switching period (s) and finally R represent load value (Ω).

2.3. MPPT Algorithms

The power value generated in PV systems varies depending on environmental factors. In PV panels, the system is required to work in MPP under all conditions. Various MPPT algorithms are available for PV systems to operate MPP under variable environmental factors such as temperature and irradiance. MPPT algorithms used in this study are given as;

- Incremental Conductance (INC) Algorithm
- Perturb &Observe (P&O) Algorithm
- Artificial Neural-Network (ANN) Algorithm

2.3.1. Perturb &Observe (P&O) Algorithm

P&O algorithm is a frequently preferred MPPT method in PV applications due to its advantages such as having a simple structure, easy applicability and few parameters. The main working principle of P&O algorithm is basically based on the P-V characteristics of the PV panel. The operating current and voltage of the PV panel are measured instantly through sensors. The generated power value is calculated according to the measured current and voltage values. Power difference *(ΔP)* and voltage difference *(ΔV)* values are then observed by changing the operating voltage slightly in small steps. According to these values, the duty period rate is changed by (*Δd*) and MPPT is realized. The procedure can be summarized as follows

- *If $\Delta P>0$ & $\Delta V > 0$, then duty period is reduced by Δd,*
- *If $\Delta P>0$ & $\Delta V < 0$, then duty period is increased by Δd,*
- *If $\Delta P<0$ & $\Delta V < 0$, then duty period is increased by Δd,*
- *If $\Delta P<0$ & $\Delta V > 0$, then duty period is reduced by Δd,*

If the amount of change is zero, the algorithm returns to its initial step. The flow chart of the P&O algorithm is also illustrated in Figure 8 (Dorji et al., 2020).

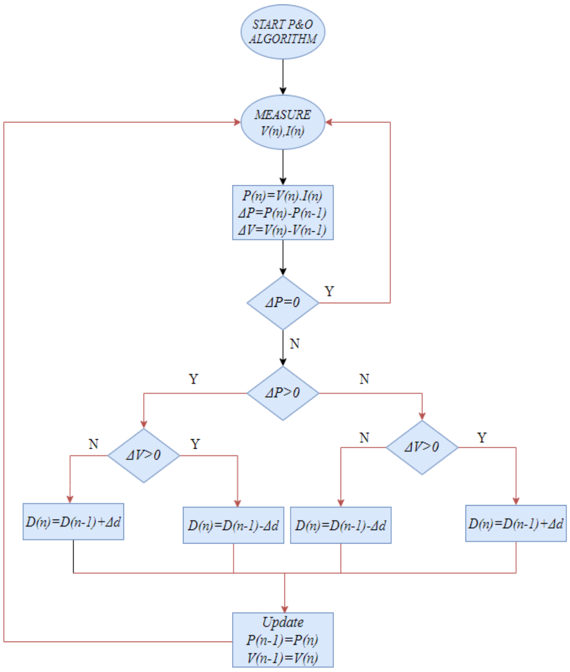

Figure 8. P&O Algorithm

2.3.2. Incremental Conductance (INC) Algorithm

The INC algorithm is generally preferred because it quickly responds to variable environmental conditions. The basic operating principle of the INC algorithm is based on the principle that the derivative of the generated power according to the voltage is always zero in the P-V characteristic of the PV panel. The operating voltage and current of the PV panel are measured instantly by means of sensors. The *(ΔV)* and *(ΔI)* values are obtained by comparing the current and voltage values at hand against previous values of current and voltage (Boyar, 2018). MPPT is realized by changing the duty period according to these values. The procedure can be summarized as follows;

- *If $\Delta V=0$ & $\Delta I>0$, then duty period is increased by Δd,*
- *If $\Delta V=0$ & $\Delta I<0$, then duty period is reduced by Δd,*
- *If $\Delta V \neq 0$ & $\frac{dI}{dV} > -\frac{I}{V}$ then duty period is increased by Δd,*
- *If $\Delta V \neq 0$ & $\frac{dI}{dV} < -\frac{I}{V}$ then duty period is reduced by Δd,*

Besides the rules given above, if the amount of change in current and voltage values is zero, the algorithm returns to the first step. The flowchart of the INC algorithm is also shown in Figure 9 (Shahid et al., 2018).

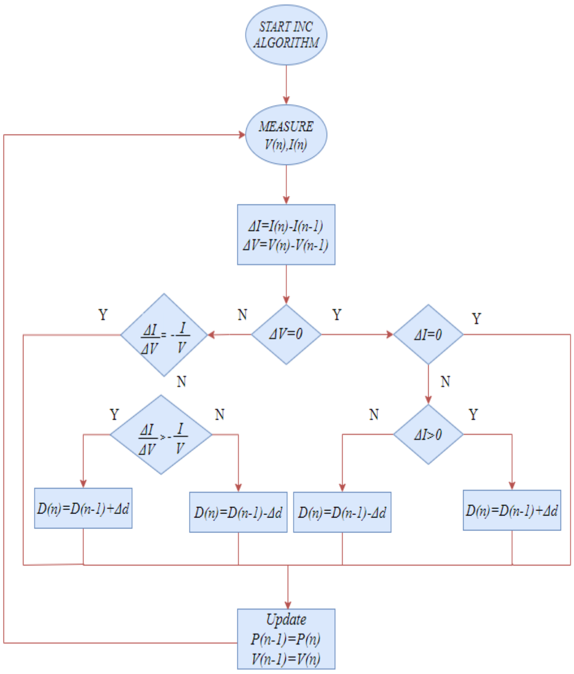

Figure 9. INC Algorithm

2.3.3. Artificial Neural Network (ANN) Algorithm

ANN is an information processing technology inspired by the human brain's ability to learn. It generally consists of 5 sections (Kubat, 2017) which are listed and described below as;

Inputs: Data sent to be collected in the neuron nucleus are called inputs.

Weights: To adjust the effect of inputs on the output, the connection they come from is multiplied by the weights and sent to the core.

Joining Function (NET): The function that calculates the net input of a cell is called the joining function. The sum of the inputs multiplied by their weights gives the net input function.

Activation Function: It is the part where the NET obtained in the combining function is sent to form the total cell output. When choosing the activation function, the processing speed should be ensured to be easily differentiable.

Outputs: The value obtained as a result of the activation function expresses the output of the current neuron. Not only the values of the outputs are used as a result of ANN, but also they can be sent back to the network structure for further learning.

The ANN structure used in the study is shown in Figure 10.

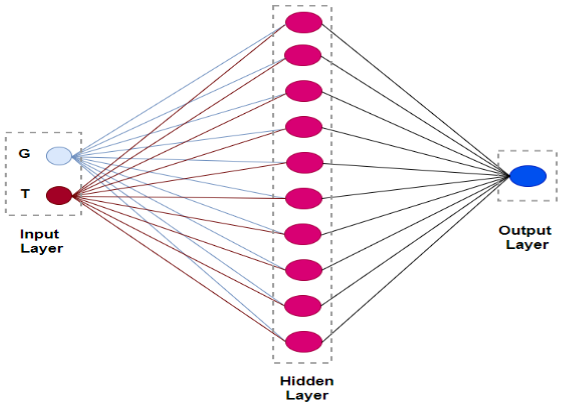

Figure 10. ANN Structure

We refer to Levenberg-Marquardt algorithm to train the temperature and irradiance information. The total data is divided into three parts so that the *70%* of the data is assigned for training, *15%* of the data is allocated for testing and the rest of the data is used for validation purposes. Mean Squared Error (MSE) found training process is shown in Figure 11 and R^2 accuracy rate details are shown in Table 1.

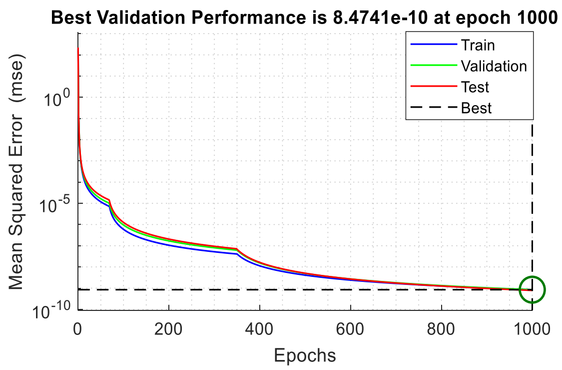

Figure 11. MSE

Table 1. Training results

	MSE	$\mathbf{R^2}$
Training	$8.4\text{x}10^{-10}$	0.99
Test	$8.47\text{x}10^{-10}$	0.99
Validation	$7.85\text{x}10^{-10}$	0.99

3. Simulation Results

In order to evaluate the performance of ANN based MPPT algorithm, a system is designed consists of a PV panel, a load and a DC-DC boost converter. The simulation model of the designed system is shown in Figure 12.

The specifications of the PV panel used in the study are summarized in Table 2 for the sake of convenience while Table 3 includes the parameters of the DC-DC boost converter.

Table 2. PV Panel Specifications

PV Panel Characteristics	**Value**
Maximum Power	250.205 W
Open Circuit Voltage	37.3 V
Voltage at MPP Vmp	30.7 V
Short-Circuit current Isc	8.66 A
Current at MPP Imp	8.15 A

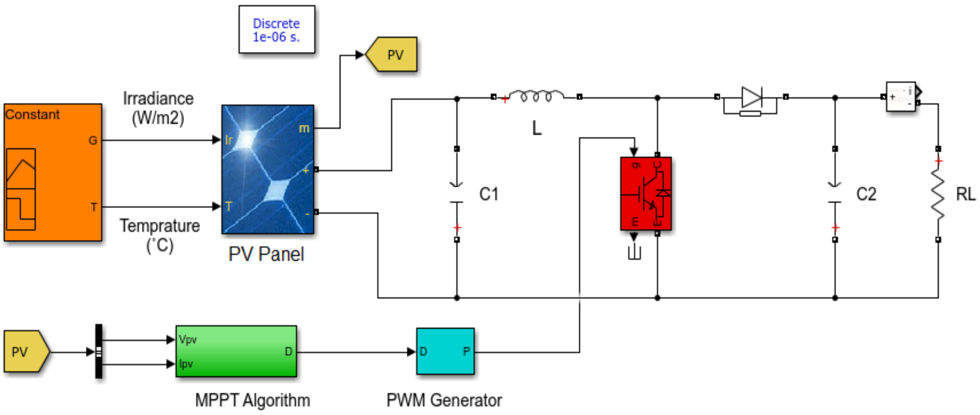

Figure 12. Designed system simulation model

Table 3. The parameter of boost converter

Component	**Value**
Inductance (L)	*1.14 µH*
Capacitors (C_1 and C_2)	*3300 - 0.46 mF*
Load (RL)	*10 Ω*
Switching Frequency	*50 kHz*

The performance of the proposed algorithm is tested under three different conditions for which the characteristics are given in the following.

Condition 1: Constant Temperature and Constant Irradiance

First of all, irradiance value is fixed at *1000 W/m^2* and the temperature value is fixed at *25 °C*. Under these conditions, all algorithms are performed under maximum power point tracking. It is observed that the ANN algorithm performs MPPT in a shorter amount of time than the INC and P&O algorithms without overshoot. The simulation results for constant irradiance and temperature values is shown in Figure 13. The maximum power that can be obtained from the panel at *1000 W/m^2* radiation value and *25°C* temperature value is *250.205 W*.

Condition 2: Constant Temperature and Variable Irradiance

In the second case, the temperature value is fixed at constant *25 ˚C* while irradiance value is allowed to take four different values such as *1000 W/m^2*, *800 W/m^2*, *600 W/m^2* and *400 W/m^2*. Under these conditions, the maximum power that can be obtained from the panel is *250.205 W*, *199.9 W*, *149.6 W* and *98.97 W* respectively. Under these conditions the ANN algorithm is observed to reach the MPP in the shortest amount of time for all situations without overshoot compared to other two alternatives. Moreover, another observation suggests that as the irradiance value of the P&O algorithm is decreased, the MPPT performance also. The simulation results constant temperature and variable irradiance is illustrated in Figure 14.

Condition 3: Constant Irradiance and Variable Temperature

In the third case, we consider a constant *1000 W/m^2* irradiance value and we let the temperature value to vary among *25°C, 35°C, 45°C* temperature values. Under these conditions, ANN is observed to perform the fastest MPPT. The simulation result of this situation is shown in Figure 15.

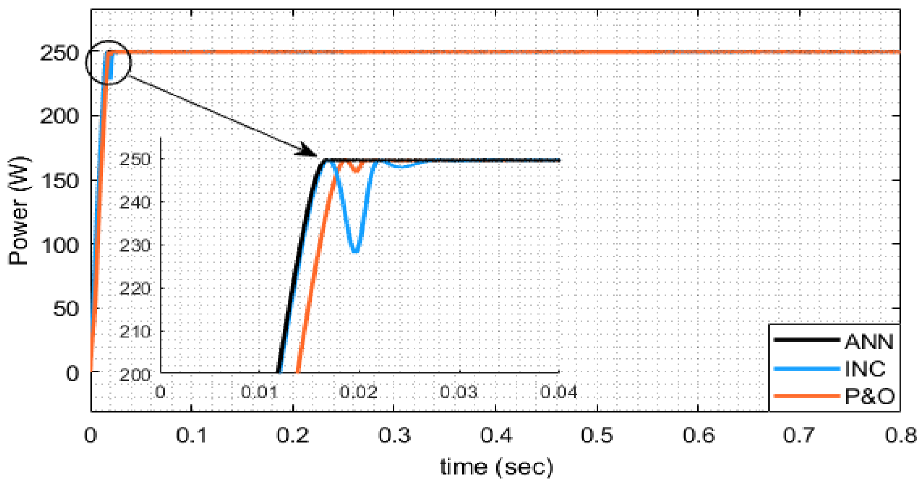

Figure 13. A fixed irradiance and temperature

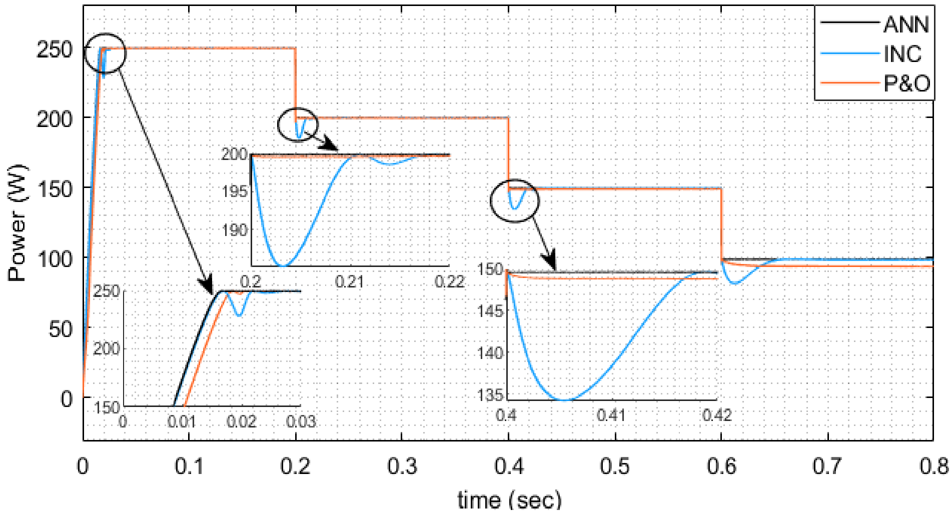

Figure 14. Constant temperature and variable irradiance

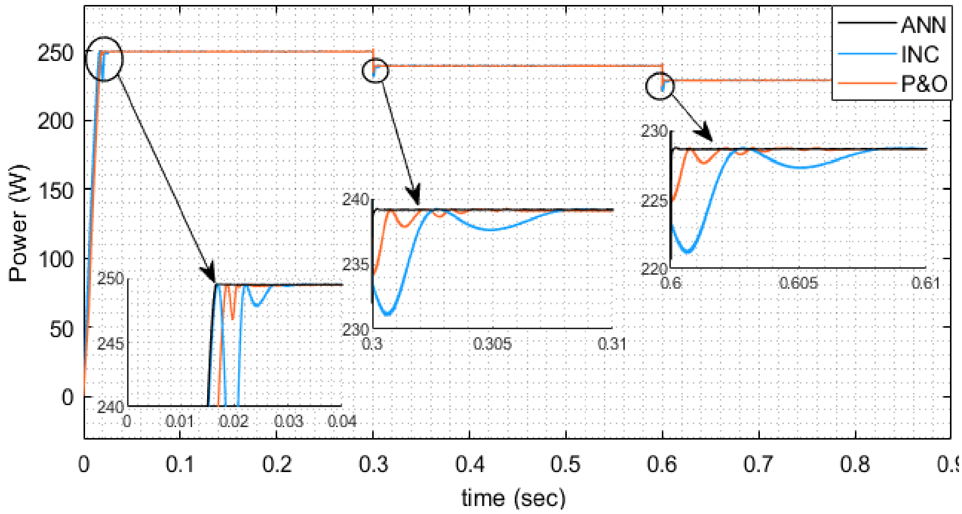

Figure 15. Constant irradiance and variable temperature

4. Conclusions

The most important disadvantage of PV panels is that their efficiency is limited to *5-30%*. In order to ensure the continuity of the energy to be transferred to the load, PV panels must work in MPP. In this study, an ANN algorithm is proposed to provide maximum power to the load. The proposed algorithm uses the irradiance and temperature data of the PV panel as input. Panel irradiance and temperature data are trained with the proposed algorithm, and a reference voltage value is generated at the output. By comparing this reference voltage value and PV panel output voltage, the duty period is determined and the system is enabled to operate in MPP. The proposed algorithm is compared with traditional P&O and INC algorithms for three different irradiance and temperature conditions. It is observed that ANN-based MPPT algorithm gives better results than P&O and INC algorithms in performance criteria such as settling time and overshoot values for all situations. As a future research, ANN-based MPPT of the PV panel may be performed in real time under PSC.

Ethics in Publishing

There are no ethical issues regarding the publication of this study.

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