ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

**MSc THESIS**

**Asan ALI RAOF**

# A COMPARATIVE STUDY OF MPPT METHODS FOR PV ARRAY UNDER PARTIAL SHADING CONDITION IN MATLAB/SIMULINK

**DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING**

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## ABSTRACT

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Supervisor : Assoc. Prof. Dr. Murat AKSOY
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Jury : Assoc. Prof. Dr. Murat AKSOY
: Asst. Prof. Dr. Oğuzhan TİMUR
: Asst. Prof. Dr. Zehan KESİLMİŞ

Photovoltaic solar power is considered as the most important renewable energy sources which use solar radiation to generate electricity. The main aim remains to get the maximum power from the photovoltaic (PV) system at different weather cases. The efficiency of the PV array is affected by shading conditions as in partially cloudy, neighboring buildings, towers, and trees. At partially shaded cases, characteristics of PV array become more complex, multiple peaks appear on the PV characteristics curve then, it becomes difficult to track the maximum power point. This is lead to significant power losses. To solve this problem, bypass diode is connected to the PV arrays, which provides an alternative electrical path for the current to flow through the diode as it cannot flow through the shaded cell. However, used bypassing diodes cause high power losses due to the forward voltage drop. To overcome this drawback, used bypass diodes are replaced by Smart bypass, which has a low forward voltage drop. Maximum power point tracking (MPPT) is a technique employed with photovoltaic (PV) applications to increases the output power of the photovoltaic array by tracking the maximum power point (MPP), which depends on atmospheric conditions such as temperature and insolation. Many MPPT methods have been proposed in the literature. In this thesis work, four MPPT methods are used the Perturb and Observe (P&O) method, the Incremental Conductance (IC) method, the neural network method, and the hybrid MPPT method. The studied methods are compared with each other in terms of performance-based properties like percentage tracking efficiency, speed, and time response by using MATLAB /Simulink.

**Key Words**: Maximum power point tracking (MPPT), renewable energy, Photovoltaic (PV), Smart Bypass, Incremental Conductance (IC), Perturb and Observe (P&O), Neural Network, Hybrid MPPT.

# ÖZ

## YÜKSEK LİSANS TEZİ

**MATLAB/SIMULINK'DE KISMİ GÖLGELEME KOŞULLARINDA, PV PANELLERİ İÇİN MPPT METODLARININ KARŞILAŞTIRMALI İNCELENMESİ**

**Asan ALI RAOF**

**ÇUKUROVA ÜNİVERSİTESİ**
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Danışman : Doç. Dr. Murat AKSOY
Yıl: 2020, Sayfa: 73
Jüri : Doç. Dr. Murat AKSOY
: Dr. Öğr. Üyesi. Oğuzhan TİMUR
: Dr. Öğr. Üyesi. Zehan KESİLMİŞ

Fotovoltaik güneş enerjisi, enerji üretmek için güneş ışınımını kullanan yenilenebilir enerji kaynaklarının en önemlisi olarak kabul edilir. Ana amaç, farklı hava şartlarında, fotovoltaik sistemden maksimum gücü elde etmektir. PV panellerinin verimi, parçalı bulutlu hava, yakındaki komşu binalar, kuleler ve ağaçlar gibi gölge oluşturan durumlarından etkilenir. Kısmen gölgeli durumlarda PV panellerinin karakteristiksel özellikleri daha karmaşık hale gelir, PV karakteristik eğrisinde birden çok tepe görünür ardından maksimum güç noktasını izlemek zorlaşır. Bu durum büyük güç kayıplarına yol açar. Bu sorunu çözmek için PV panellerine bypass(geçiş) diyotları bağlanır. Bypass diyotu, gölgeli hücreden akım akamadığından dolayı, akımın diyot üzerinden akması için alternatif bir yol sağlar. Ancak, kullanılan bypass diyotlar, ileri yönde gerilim düşümü nedeniyle, yüksek güç kayıplarına sebep olurlar. Bu dezavantajın üstesinden gelmek için, kullanılan bypass diyotları daha düşük ileri yönde gerilim düşümüne sahip, akıllı diyotlarla değiştirilirler.Maksimum güç noktası izleme (MGNİ), sıcaklık ve güneşlenme gibi atmosferik koşullara bağlı olan maksimum güç noktasını (MGN) izleyerek fotovoltaik dizinin çıkış gücünü artırmak için fotovoltaik uygulamalarında kullanılan bir tekniktir. Literatürde birçok MPPT yöntemi önerilmiştir. Bu tez çalışmasında, "Değiştir ve Gözlemle" metodu, "Artırımlı İletkenlik" metodu, "Sinir Ağları" metodu ve "Hibrit MGNI" metodu olmak üzere dört tane MGNİ metodu kullanılmıştır. Çalışılan metotlar MATLAB/SIMULİNK kullanılarak, izleme verimliliği yüzdesi, hız ve zaman tepkisi gibi performansa dayalı özellikler açısından, birbirleriyle karşılaştırılmıştır.



**Anahtar Kelimeler:** Maksimum Güç Noktası İzleme (MGNİ), Yenilenebilir Enerji, Fotovoltaik, Akıllı Geçiş, Artırımlı İletkenlik, Değiştir ve Gözleme Sinir Ağları, Hibrit MGNİ

## EXTENDED SUMMARY

Renewable energy applications have become very important mainly because of their features such as requiring little maintenance, incurring no fuel costs, emitting no noise, not being polluting and also problems of using traditional energy sources. Solar energy is the most popular renewable energy sources, which is converted into electrical energy by solar PV cells. When a number of cells are connected in parallel or series, we get a solar photovoltaic module. When a number of PV modules are connected into series or parallel circuits, we get a PV array, which is appropriate for obtaining higher output power.

If the PV array is partially shaded, the characteristics become more complex and multiple peaks appear. This leads to reduces the power of the photovoltaic application. To solve this issue bypass diode is used, Bypass diode is placed with PV panel in reverse parallel with a PV panel to provide an alternative electrical path for the current to flow through the diode as it can not flow through the shaded panel. However, those bypassing diodes causing loss in the power because of those diodes have high forward voltage drop. To overcome this drawback, the bypass diodes are replaced by Smart Bypass, which has a low forward voltage drop.

Maximum power point tracking (MPPT) is a technique employed with photovoltaic system to increases the output power of the solar photovoltaic array by observing the maximum power point (MPP). Several MPPT methods have been proposed in the literature. Examples are the Perturb and Observe (P&O) method, the Incremental Conductance (IC) method, Neural Network Control, Fuzzy Control etc. Among all the methods Incremental Conductance (IC) and Perturb and Observe (P&O) are most commonly utilized due to their simple implementation and several other economic reasons. However, these techniques have several drawbacks such as fail performance because of partially shaded conditions.

To maximize the extracted energy from the PV modules, a converter is placed between the module and load. A duty cycle of the dc-dc converter is set such that the energy flow from the module is maximize. The characteristic of solar module relies on the temperature of cell and solar irradiance. So, under different weather cases the maximum power point change also the duty cycle needs to be changed accordingly

In this thesis, the photovoltaic system modeling and simulation at partial shading cases is presented. Four MPPT methods will be compared. A comparative study of four MPPT methods are analyzed under three different partial shading cases, this comparison is based on the performance of these MPPTs. Also, model of the dc-dc boost converter is designed which is set up the PV's terminal voltage to the suitable voltage to observe maximum power.

Simulation results shows that the hybrid technique is the best among the other methods, it is a good solution giving an excellent efficiency and response time in steady state.

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## LIST OF SYMBOLS AND ABBREVIATIONS

PV : Photovoltaic

D : Duty Cycle

MPPT : Maximum Power Point Tracking

$I_{ph}$ : Photo Generated Current

$V_t$ : Thermal Voltage

ANN : Artificial Neural Network

et al. : And Others

MPP : Maximum Power Point

P&O : Perturb and Observation

K : Boltzmann' constant

$\lambda$ : Wave length of photon

$Eg_0$ : Energy band gap

q : Charge of an electron

I : Current

$I_{SC}$ : Short circuit current

$R_S$ : Serial resistance

$R_{sh}$ : Shunt resistance

n : Diode quality factor

F : Frequency

CCM : Continuous Conduction Mode

NS : Number of cells connected in series

NP : Number of cells (or panels) connected in parallel

T : Temperature in $^{\circ}C$

STC : Standard Test Condition

GMPP : Global Maximum Power Point

# 1. INTRODUCTION

## 1.1. Background

Solar photovoltaic energy has become more popular because of many factors: minimal wear, low maintenance, sustainable energy, shortage of audible noise and easy to install. Small-scale photovoltaic structure is very common like water pumping and lighting solutions in developing countries, distant villages, and small civil and rural societies (Baba et al., 2014).

A photovoltaic solar cell is an electrical instrument based on a semiconductor material which converts a solar energy into useful electricity. When solar power had been dealing with PV system some problems appears such as initial cost, reliability and efficiency of power generation. Therefore, simulation and modeling are an important part in the development and investigate the performances of photovoltaic itself as well to design PV applications (Crocker, 2017).

Photovoltaic solar cell has low power so, many cells are linked into parallel or into series, forming a photovoltaic module and PV modules are linked in parallel or into series with the desired values of voltage and current in order to form a PV array (Neupane and Kumar, 2017). Photvoltaic cell has nonlinear characteristics, which changes with the temperature and level of the radiation. If photovoltaic array is partially shaded the PV characteristics curve become more complex and more than one peak appears. So, photovoltaic efficiency is decrease (Satyendra, 2017).

There have many causes leads to the PV array get shadowed. For example, neighboring building, trees, chimneys, and the dust on the surface of the panels (Mahammad et al, 2013). To overcome this issue, the maximum power point tracking (MPPT) algorithms is employed to get best efficiency for the photovoltaic at various load operating points. MPPT method is done by a controller for the photovoltaic module’s power converter.

Figure 1.1. illustrates this operating point on the current-voltage and power-voltage curves (Al-Soeida et al., 2016).

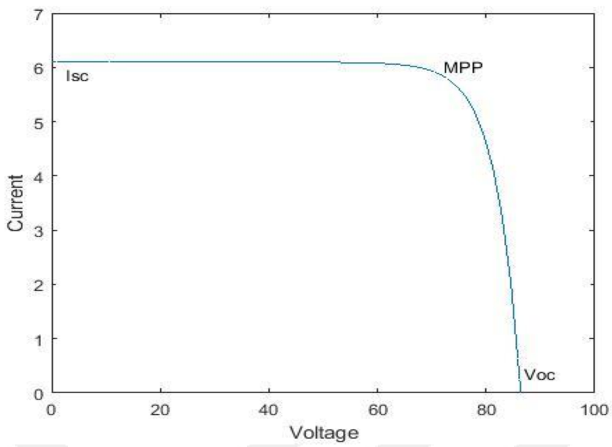


Figure 1.1 (a) Current-voltage Characteristic curves of solar PV array

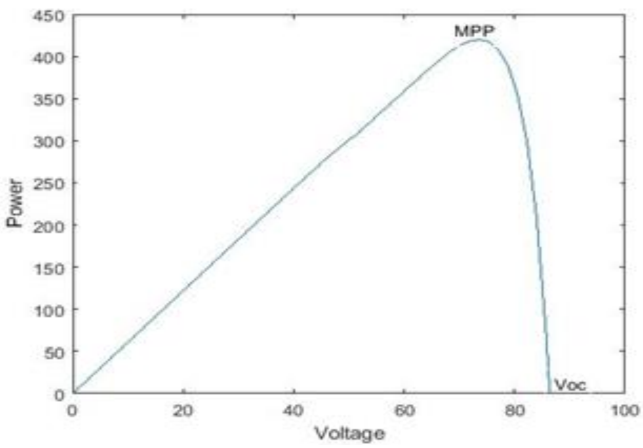


Figure 1.1. (b) Power-voltage Characteristic curves of solar PV array

The solar PV Characteristic is nonlinear and various with temperature and irradiation. generally, there is two various parameters have to be introduced:

- Short Circuit Current ($I_{Sc}$), is the PV cell current when the voltage through the PV cell is zero.

- Open Circuit Voltage ($V_{OC}$), is the PV cell voltage when the current through the PV cell is zero.

There is also a unique point (maximum power point (MPP)) on the I-V curve at which the photovoltaic array works at maximum efficiency.

But under partial shading conditions, these characteristic curves become more complex and more than one peak appear, as seen in Figure 1.2.

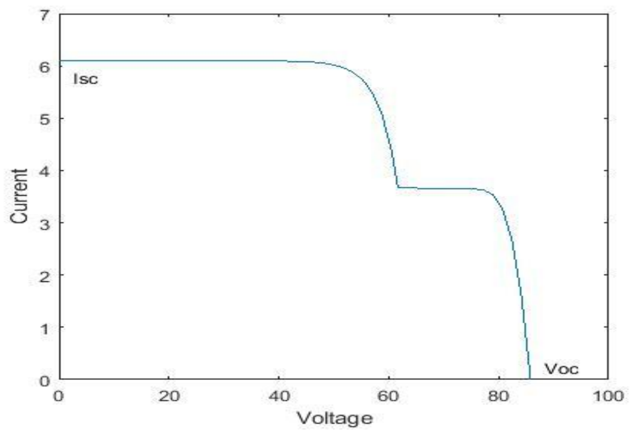


Figure 1.2 (a) Current-voltage characteristic curves during partial shading conditions

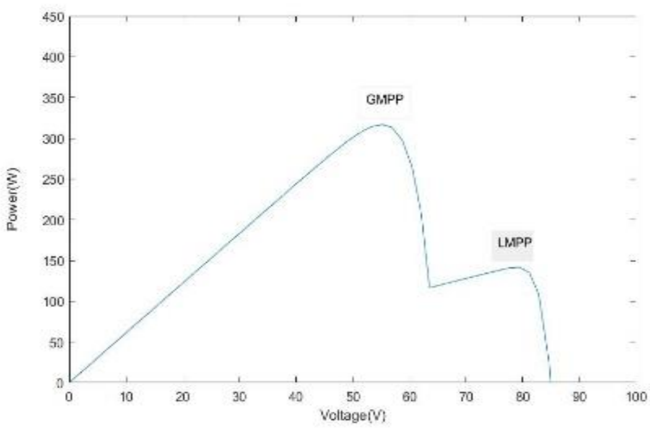


Figure 1.2 (b)Power-voltage characteristic curves during partial shading conditions

In the literature, MPPT techniques have been proposed and plenty of research has been executed to optimize the different algorithms (Baba et al., 2014). However, some of these methods has some disadvantages such as oscillations about MPP and slow tracking speed, this makes it less suitable for rapidly changing weather conditions (Jain, and Agarwal, 2004).

To overcome this issue Veligorskyi et al., (2015) proposes a new MPP tracker with control scheme based on ANN for detection global maximum power for partial shading case of photovoltaic panels.

DC-DC converters are utilized in the photovoltaic applications as a link between the PV module and the load, for extraction maximum power the load must adapt to match the current and voltage of a PV panel. It must be connected directly to the photovoltaic panel and perform operation to get the maximum power point (MPPT) (Kotak, and Tyagi,2013).

## 1.2. Literature Review

The detrimental influences of partial shading on the efficiency of photovoltaic panel still keep on despite recent evolutions in technology. It changes the output power of a PV panel due to multiple peaks appearance in PV curve which reduces the efficiency of solar module cause power loss (Seyedmahmoudian et al., 2014). To avoid this issue bypass diode have to be connected with a PV module. However, those bypassing diodes causing additional loss in the power because of those diodes have high forward voltage drop. To solve this issue, the bypass diodes are replaced by Smart Bypasses which has a low forward voltage drop (Bauwens and Doutreloigne, 2016).

For improving the efficiency of solar photovoltaic application maximum power point tracking techniques is utilized. Many MPPT methods have been proposed. These methods vary in terms of efficiencies, requiring sensors, complexity, and in convergence speed.

. Conventional methods, like P & O, fail to differentiate between the global and local maximum power of the photovoltaic application during partial shading cases due to fixed step size (Allataifeh et al., 2015). Figure 1.3. illustrates the reason of the conventional MPPTs failure for tracking maximum power at partial shading cases. In Figure 1.3., it is supposed that the photovoltaic array operating points is on point A before partial shading conditions has happened. After partial shading conditions has happened, the operating point is moved to point B. The real MPP in this condition is existed onto point C. Due to the traditional techniques change the operating point because of the predetermined voltage reference step (ΔV), the operating point is oscillated near of point B. Due to this MPPT failure the difference in power between $P_C$ and $P_B$ has been lost. To avoid power loss, maximum power point techniques must to move operating point towards point C at partial shading conditions PSC (Ji et al., 2010).

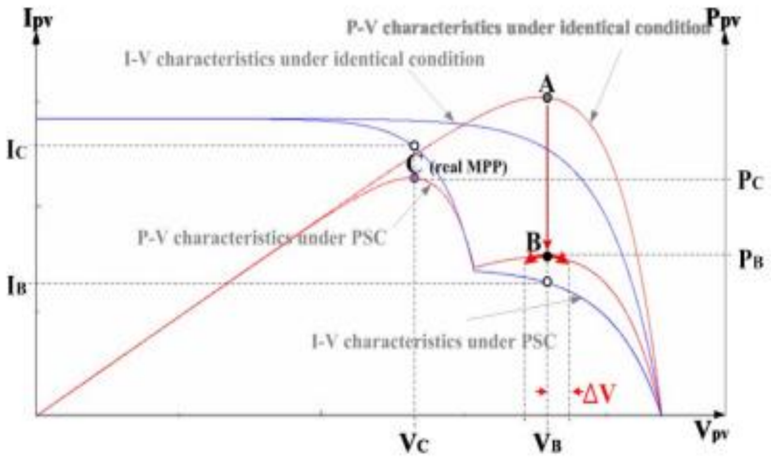

Figure 1.3. Failure of conventional MPPT method under PSC

Whenever conventional technique fails in a partial shading condition. Sivaraman and Sakthi, (2018) proposes artificial neural network MPPT technique is utilized to analyze partial shading effect in Central and Micro-Inverter based PV applications. Further, the NN based MPPT technique is simulated using Simulink and compared with IC and P&O method.

Jiang and Maskell, (2014) proposes a hybrid MPPT for photovoltaic applications to track the maximum power. The proposed technique combines an ANN-based method with a P&O traditional technique.

A MPPT technique that uses offline calculation of the open circuit voltage and online, classic perturbation and observation (P&O) technique is proposed by Moradi et al (Moradi et al., 2013).

Messalti, et al., (2017) proposes the ANN technique to provide the power converter duty cycle at various weather cases.

### 1.3. Objectives

As PV system are the most important renewable energy sources and have the biggest contribution to electric power generation so, the main aims of this thesis are:

1 The wide literature survey for PV application has been accomplished.
2 A complete model of Solar PV array has been simulated by using Matlab/Simulink.
3 Study the influence of partial shading conditions on the solar photovoltaic array.
4 Different MPPT methods are used for making a comparison among them to know which ones are the best and able to observe global maximum power by using Simulink.
5 DC-DC boost converter is designed and simulated to regulate the output voltage of the photovoltaic array.

# 2. INTRODUCTION OF THE PHOTOVOLTAIC SYSTEMS

## 2.1. Solar Energy

The Sun sends amount of energy towards Planet Earth about $10^{17}$ W. In electrical supply terms this is amounting to the output of around one hundred million newfangled fossil fuel or nuclear power stations. To illustrate it another way, the Sun supplies in about an hour the current energy requirement of the all human population for a whole year. It appears that all we need do to convert society from carbon to solar is to tap into a negligible proportion of this great potential (Lynn, 2010). The rate solar power received at atmosphere of Earth is about 342 W/m$^2$.

Figure 2.1. describes the yearly average intensity of solar irradiation upon the earth surface. (Kabir et al., 2018).

Generating electricity by using photovoltaic panels is one of the most promising markets in the field of renewable energy. For its fast growing and high levels investment associating, now the photovoltaic market becomes one of the most predominant over the world (Sampaio and González,2017).

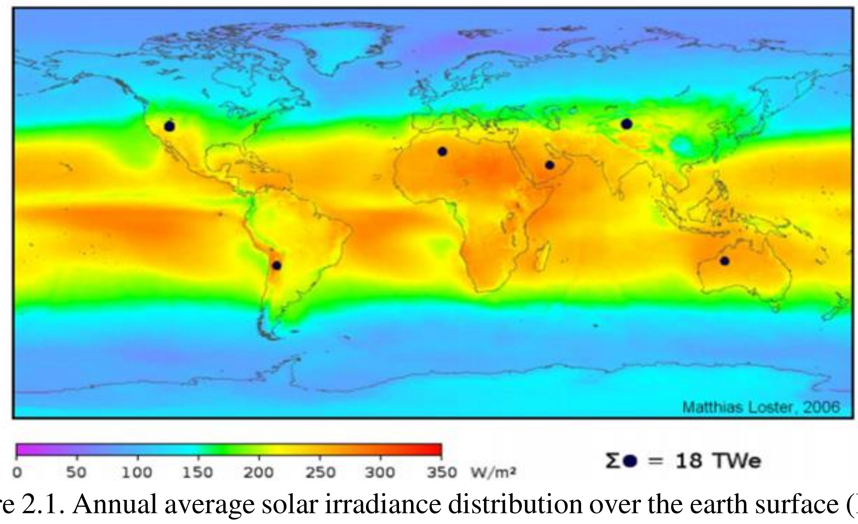


Figure 2.1. Annual average solar irradiance distribution over the earth surface (Kabir et al., 2018)

## 2.2. Physical Structure of a Photovoltaic Cell

Photovoltaic cell is essentially a semiconductor diode whose p–n junction is exposed to light. Photovoltaic cells are made of numerous kinds of semiconductors utilizing various manufacturing operation. Figure 2.2 shows a PV cell's physical structure.

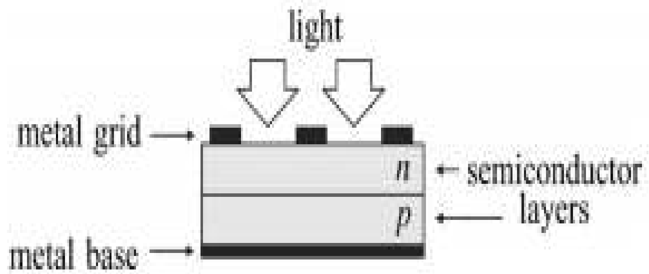


Figure 2.2. PV cell's physical demonstration (Rasool, and Samaneh, 2013).

Essentially, a phenomenon of photovoltaic is defined as the sucking of the solar insolation, the generation and transport of free carriers at the p–n junction, and the combination of these electric charges in the terminals of the photovoltaic system. The electric carrier's generation rate rely on the capacity of absorption of the semiconductor. The ability of absorption depends mainly on the semiconductor bandgap, on the intrinsic concentration of carriers of the semiconductor, on the temperature, and many other factors (Villalva et al., 2009).

The modern photovoltaic solar industry came to contain three separate sectors. a wafer cell and panel production are the first, the construction of these solar cells is the second. The third is polysilicon industry, the primary raw material used to industry photovoltaic cell. Polysilicon was the effective component for the new electronics manufacture that appeared after the invention of the transistor, due to Polysilicon was a semiconductor whose electrical characteristics could be accurately adjusted (Jones and Bouamane, 2012).

**2.3. Photovoltaic Cell Types**

A photovoltaic cell relying on the nature and materials characteristics used. The most common material used for construct solar panel is silicon which has semiconducting properties.

**2.3.1. Monocrystalline Photovoltaic Cell**

Monocrystalline solar cell is manufactured from so-called crystalline solar photovoltaic cells and facilely is known by its color which refer to a purity of silicon and its standardized appearance. It is manufactured of silicon ingots and has a cylindrical figure. To improve its performance and decrease the cost, every sides of its cells are cut to create cylindrical ingots from which Single-crystal wafer can be made, which differentiate it from others. They have a dark black color (Roy et al., 2014).

Figure 2.3. Monocrystalline silicon solar PV cell (Roy et al., 2014)

**2.3.2. Polycrystalline Photovoltaic Cell**

Poly-crystalline solar cells are containing many small silicon crystals. Poly-crystalline solar cells are melted into square template, that is cut to completely square wafers. these solar cells have a lower price than monocrystalline solar cells, but they are less efficient (Dobrzański et al., 2013; Roy et al., 2014).

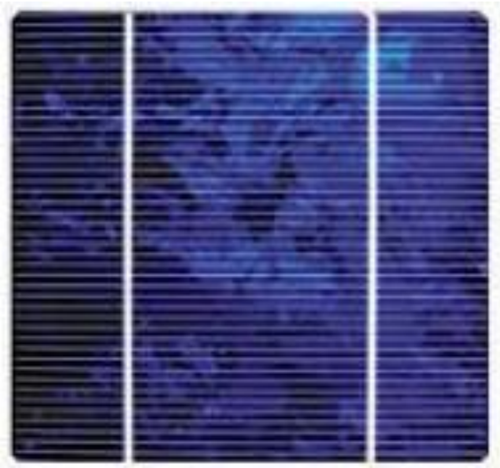

Figure 2.4. Polycrystalline silicon solar PV cell (Roy et al., 2014)

### 2.3.3. Thin-film Photovoltaic Cell

Photovoltaic thin-film is essentially thin layer of semiconductor material applied to a stiff backing material. It extremely decreases quantity of semiconductor material demanded for every cell if compare it with silicon wafers. Titanium dioxide (TiO2), copper, cadmium telluride (CdTe) and Gallium arsenide (GaAs), these materials were used for thin-film solar cells. (Parida et al., 2011). They are more flexible and cheaper than conventional solar cells.

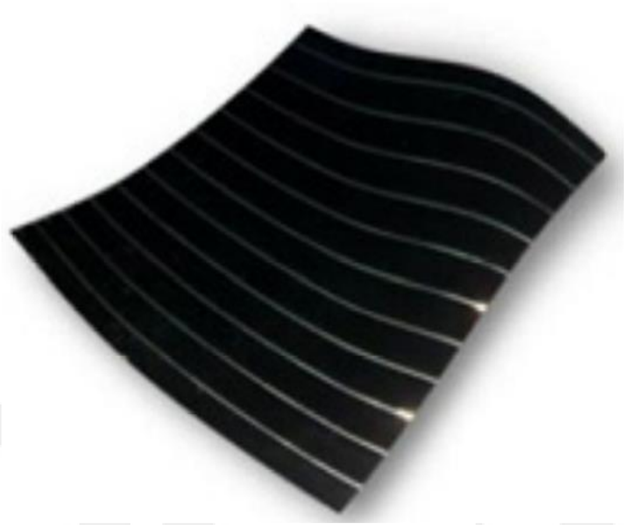

Figure 2.5. Thin-film solar PV cell (Bojic et al 2016)

### 2.4. Characteristics of Photovoltaic Array

The photovoltaic application uses more than one photovoltaic panel to convert sunlight energy into useful electrical energy. mainly, photovoltaic system consists of solar modules, electrical connections and a tool for adapting the electrical output.

#### 2.4.1. Photovoltaic Cell

Photovoltaic cells convert sun light into electricity by using semiconductor materials such as silicon, which is an extract from pure sand. There are different kinds of solar cells which all utilize semiconductors to interact with photons that are coming from the Sun for generating an electric current. The performance of solar cells is based on their maximum direct current power output (watts) at Standard Test Conditions which are a radiation of 1 kW/ $m^2$, a cell temperature of 25°C.

### 2.4.2. Photovoltaic Module

An individual solar cell is produced extremely low voltage, about 0.5V. So, multiple solar cells are connected together in parallel or in series circuits to get a required voltage and current. A junction box exists in the back of the module to produces a protected position for electrical connections and bypass diode.

a bypass diode used to avoid reverse current through a photovoltaic device hence, preventing power loss and overheating.

### 2.4.3. Photovoltaic Array

An individual panel is produced low power that is not enough to fulfill the power requirements for most practical applications. Most Industrial companies produce standard photovoltaic modules with 12V or 24V output voltage. A Photovoltaic array contains multiple single PV modules which linked in series-parallel to get the needed output power for the photovoltaic system.

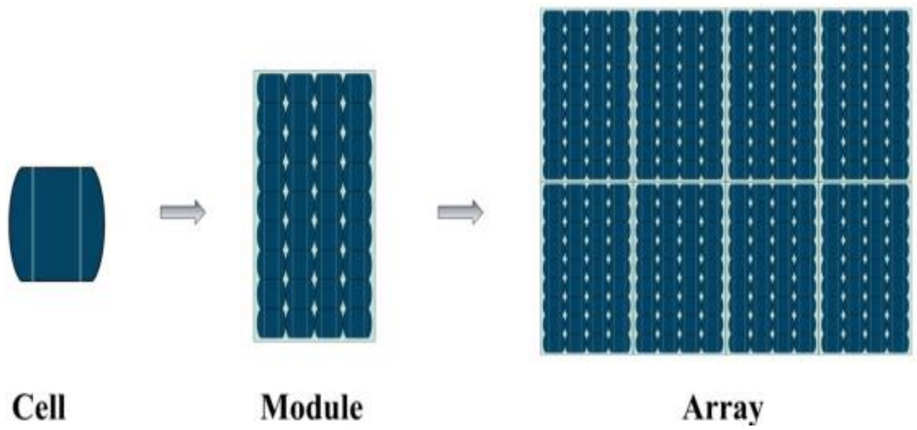


Figure 2.6. PV cell, module and array (Dutta,2014)

## 2.5. Equivalent Circuit of a PV Cell and Mathematical Model

Figure 2.7 shows equivalent circuit of a photovoltaic cell. It constrains of a photo current, a diode, a parallel resistor ($R_{SH}$ ) and a series resistor ($R_S$).

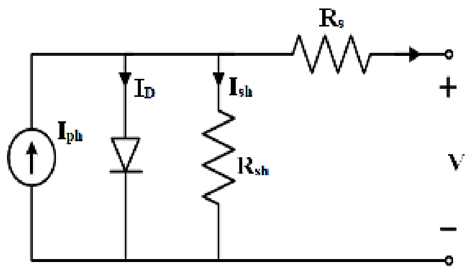


Figure 2.7. The equivalent circuit of a photovoltaic cell (Nasir and Husaini, 2018)

The general equations that describe the I-V characteristic of the photovoltaic module are (Francis et al., 2014; Nguyen, 2015).

$$I = Np * I_{Ph} - Np * I_O * \left[\exp\left(\frac{V/Ns + I * \frac{Rs}{Np}}{n * V_t}\right) - 1\right] - I_{sh} \tag{2.1}$$

with

$$V_t = \frac{k * T}{q} \tag{2.2}$$

and

$$I_{sh} = \frac{V * Np/Ns + I * Rs}{Rsh} \tag{2.3}$$

Where $N_P$ is the number of parallel cells, $N_S$ is the number of series cells, n is the diode ideality factor, $V_t$ is the thermal voltage, $R_{sh}$ and $R_S$ are shant and series resistors of the PV cell, respectively.

Photocurrent $I_{Ph}$: The photocurrent $I_{Ph}$ depends linearly on the temperature and is also affected by the irradiation which is given by Equation (2.4).

$$I_{ph} = I_{sc} + Ki(T_k - T_{Ref}) * \frac{\lambda}{1000} \tag{2.4}$$

Where $I_{Ph}$ is the photocurrent current, $T_K$ is the actual temperatures and $T_{Ref}$ is the reference temperatures in K, $\lambda$ is the irradiation on the device surface (W/m$^2$).

The module saturation current changes with the cell temperature $I_0$ is given by Equation (2.5).

$$I_o = I_{rs}[\frac{T}{Tr}]^3 \exp\left[\frac{q*Eg_o}{nk}\left(\frac{1}{T_r}-\frac{1}{T}\right)\right] \quad (2.5)$$

Module Reverse Saturation Current at reference temperature, is presented by Equation (2.6).

$$I_{rs} = I_{sc}/[\exp\left(\frac{qVoc}{NsknT}\right)-1] \quad (2.6)$$

Where $q$ is the electron charge, $V_{OC}$ is the open circuit voltage, $n$ is diode ideality factor, $T$ is the operating temperature and $K$ is the Boltzmann constant

Photovoltaic modules are connected in parallel or in series to form PV array to get the desired voltage and current. The equivalent circuit for a photovoltaic array is seen in Figure 2.8

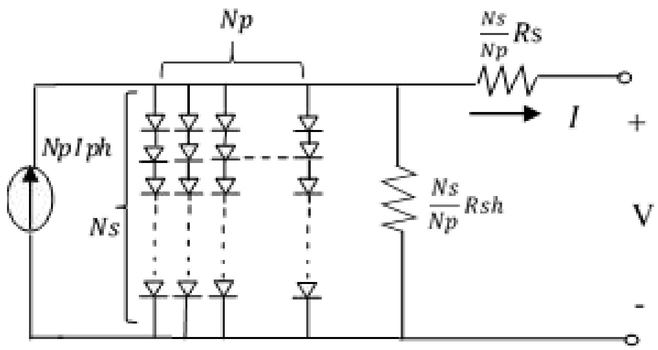


Figure 2.8. Equivalent circuit of a solar array

**2.6. Irradiance and Temperature Effects**

The PV array's power which depend on the atmospheric cases like that level of the irradiance and the temperature. Figure 2.9. Shows the voltage and current dependence on temperature and radiation.

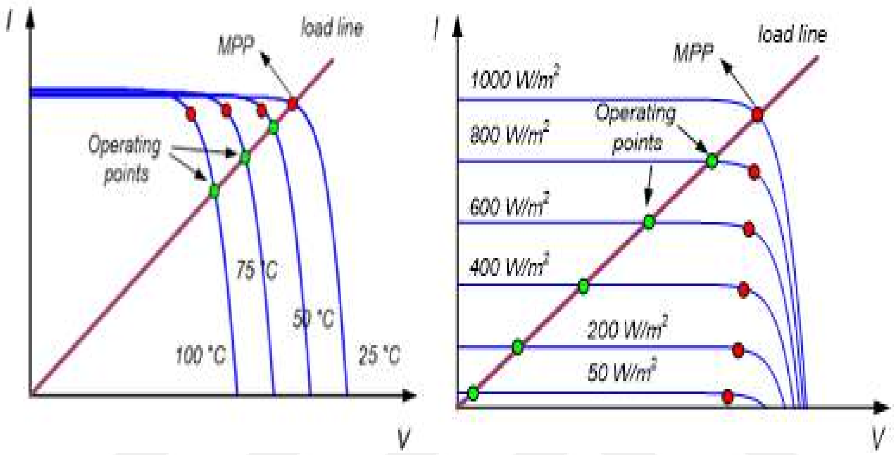


Figure 2.9. I-V characteristics with dependence on irradiance and temperature

Current ($I_{PV}$) of a PV is affected by irradiation and the voltage ($V_{PV}$) of PV related with the temperature. So, the extraction of maximum power point from photovoltaic panels is also affected by irradiance level and temperature.

Open circuit voltage ($V_{OC}$) of the photovoltaic panel is affected by temperature. It is necessary to put into consideration the hot and cold temperatures during design photovoltaic system, If the temperature of the panel is minimum than the standard test condition value of 25°C, the panel's open-circuited voltage, $V_{OC}$ rate will actually be more than the rate listed on the panel's listing label (Massawe, 2013). Short circuit current ($I_{SC}$) of the PV panel is affected by level of irradiance. higher levels of irradiance lead to more electrons to flow off the photovoltaic cells to the load attached.

**2.7. Partial Shading Effects**

Partial shading is one of the issues that reduces the efficiency of the PV panel, it happens because of the shadow buildings, atmosphere fluctuation, daily sun angle changes, electric poles and trees. Shaded PV cells cannot give the same quantity of the current of unshaded PV cells. Since each cell is wired in series in a panel, the same amount of the current should be flow across each cell. Unshaded cell will compel shaded cell to pass a higher current than their new short circuit current (Abdulazeez and Iskender, 2011). Besides, a hot spot issue happens because of the large quantity of electric power which produced by the unshaded panels has been taken in by shaded modules. When such a case happens, the influenced cell is forced into reverse bias and causing a loss in power (Deng et al., 2017). thus, this will damage the photovoltaic cells. As a method to reduce a hot spot problem, bypass diode is used with each photovoltaic panel to prepare a substitutional path for the current to flow (Kamarzaman et al., 2015).

Figure 2.10 shows a series-parallel configuration of the photovoltaic array. When the whole photovoltaic array is fully illuminated and there is no shade, as seen in Figure. 2.10(a), the curve of P–V demonstrates the typical unique maximum power point (MPP). Under partial shading condition the third PV panel becomes less illuminated, the change in solar radiation between two PV modules activates the bypass diode of PV module 3. As a result, two stairs current waveform is appeared on the current–voltage curve. Thus, the power–voltage curve is characterized by one global peak, and multiple local peaks (Ishaque and Salam, 2013)

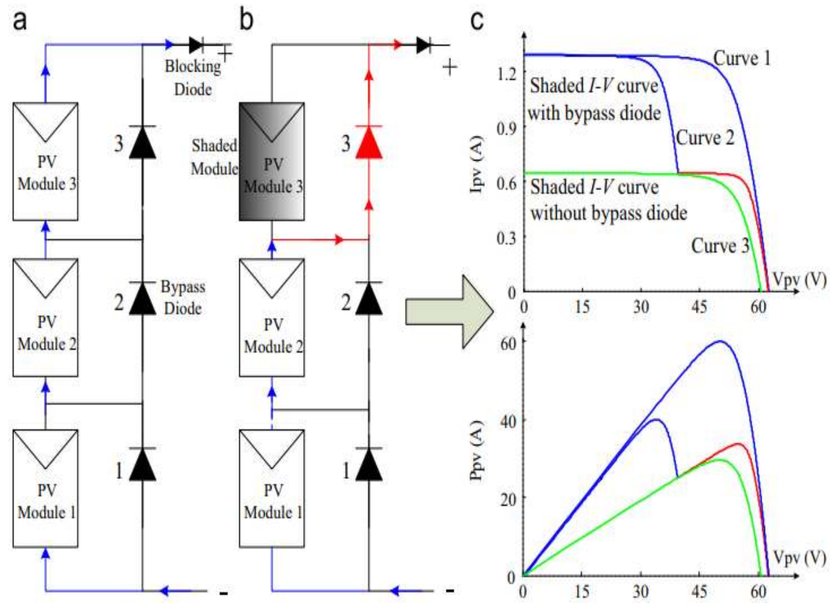


Figure 2.10. PV array operations (a) at uniform radiation (b) at partial shading (c) the resulting I–V and P–V curve for (a) and (b) (Ishaque and Salam, 2013).

### 2.8. Smart Bypass Diode

Bypass diode is used to reduce the loss in the power of solar module due to shading. It is placed in parallel with every PV panel in a string. If the photocurrent of cells in such a substring are decreased, the overflowing current produced by the other substrings passes through this bypass diode. In the other substrings, the cells are not influenced and can still produce entire power, but shaded cells with the substring is bypassed and does not participate in generating the power (Bauwens and Doutreloigne, 2016).

Figure 2.11 shows a power-voltage PV curves with multiple peaks. a global MPP is found when a PV array operates at a lower voltage and higher current, and a local MPP is found when a PV array operates at a higher voltage and lower current the former happens when bypass diode of the shaded panel is “activated” and the latter happens when bypass diode of the shaded panel is not carrying any current.

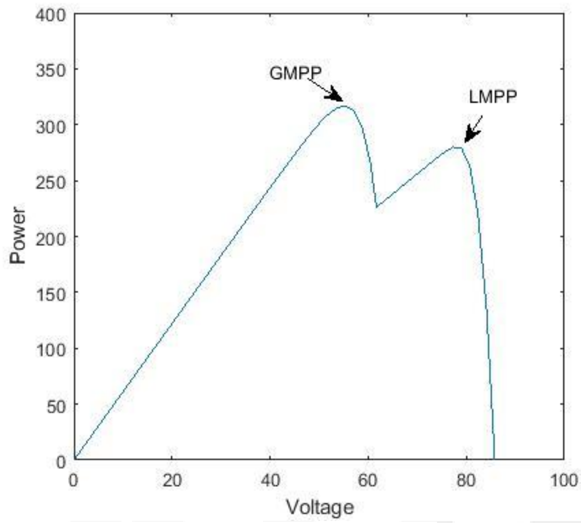


Figure 2.11. PV curve of a solar array with shading

Bypass diode characteristics depending on two factors: forward voltage and turn-on resistance. These factors affect the PV arrays output power during shadow cases. When forward voltage of diode and on resistance is low, a power loss reduces and we get the better PV curves.

Normal bypassing diodes causing power reduction due to those diodes have high forward voltage drop (approximately for normal diodes 0.6 V and for Schottky 0.4 V). Ordinarily, by increasing the forward voltage of the bypassed diode, output power decreases due to a voltage drop on the load (Ziar et al., 2012). To overcome this drawback, normal bypass diodes are replaced by smart bypasses. Which has a low forward voltage drop approximately (26mV at 8A, ideally 0 V) voltage drop.

Figure 2.12 shows the smart bypass block diagram. When solar cells are shaded, the FET Q1 is off and the current of bypass flows across the body diode of the FET. This current produces a voltage drop through ANODE and CATHODE terminal of the bypass diode, at the same time, the charge pump circuitry is active. When cells in the photovoltaic modules fully illuminated and there is no shade the FET is on, it produces a low resistive path for the bypass current to flow thus reducing the power losses through ANODE and CATHODE. Due to FET is active, very low voltage through the ANODE and CATHODE to work charge pump. at the same time, charge stored on C1 is employed to supply the controller as well as drive the FET (TI, 2012).

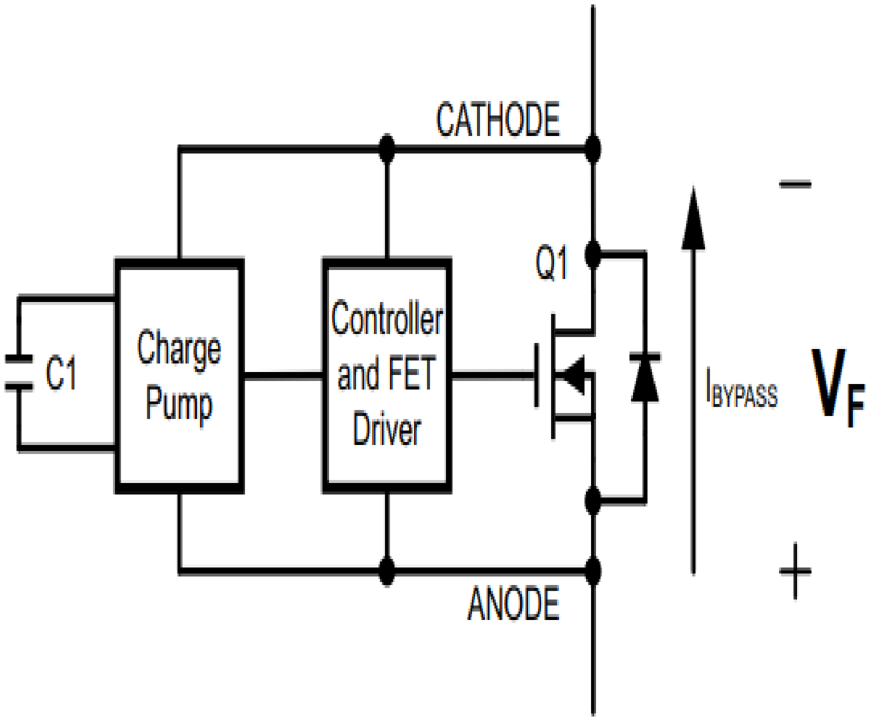


Figure 2.12. Block diagram of the Smart Bypass (TI, 2012).

# 3. MPPT CONTROLLERS AND DC-DC CONVERTERS

## 3.1. Maximum Power Point Tracking

Maximum power point tracking is the main part of a photovoltaic applications due to the MPP of a PV panel various with the temperature and level of radiation as shown in Figure 3.1.

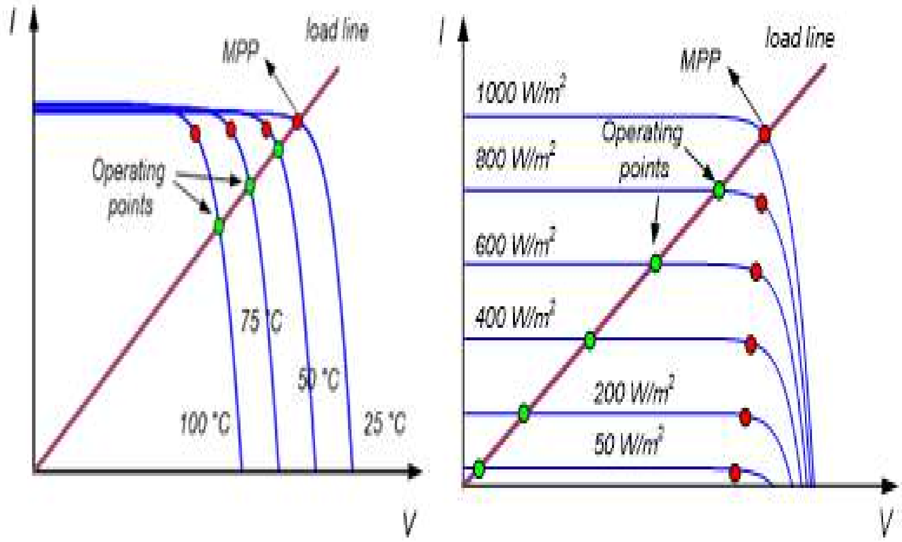


Figure 3.1. PV I-V curve at various temperature and irradiance with load line

Figure 3.2 shows a simple resistive load. It could be clearly seen that the operating point changes with changing load resistance $R_L$. The maximum power point (MPP) may be attained through appropriate selection of the load $R_L$. In most actual cases, loads resort to become less than optimal. It can be extracted maximum power from the photovoltaic module by merging an intelligent mechanism can be changing the load resistance of a photovoltaic module. Power converters are utilized to adapt the PV system operating points to maximize the obtained power from the system (Shiau and Chen, 2015).

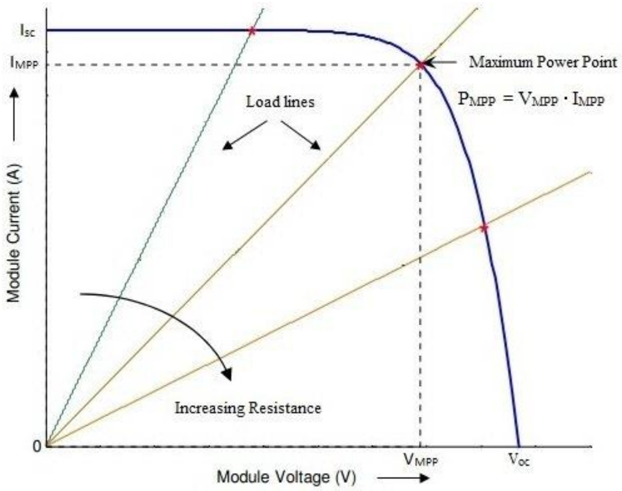


Figure 3.2. I-V curve of PV panel with different resistive loads (Ferdous et al.2012)

Figure3.3 shows the block diagram of a PV application contain of (MPPT) system equipped with DC to DC converter and load (Shiau and Chen, 2015).

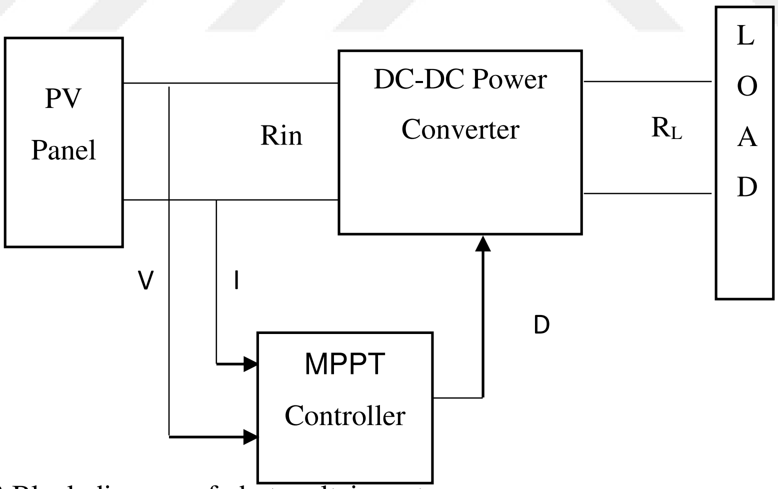


Figure 3.3 Block diagram of photovoltaic system

The maximum power point tracking technique tracks the power of the PV panels and controls the input voltage or the input current of a dc-dc converter, to get the MPP. Relying on the converter topology can select the current or voltage as the control variable. Inductor current of the converter and a PV array output current are the same, thus the MPPT techniques can observe the photovoltaic arrays output power and optionally use the inductor current of a dc to dc converters as the control variable (Villalva et al.,2009).

### 3.2. MPPT Methods

Several MPPT methods have been proposed in the literature to increase a solar panels efficiency. Many of proposed algorithms can make it hard to find the best method to take on when implementing a Photovoltaic application (Babaa et al., 2014). The role or aim of different proposed methods is to control the duty cycle of the converter employed (Husain et al., 2017). These algorithms can be included three categories: offline methods, the PV module physical values are utilized to generate the control signals. It needs to one (or) two of the solar module values. Online methods, the instantaneous values of photovoltaic output current or voltage are employed to generate the control signals. Hybrid methods, is a method which combines the online and offline methods, observing the maximum power point needs in two steps: accurate regulation of maximum power point (Reisi et al, 2013) as shown in Table 3.1.

Table 3.1. Classification of MPPT algorithms (Reisi et al, 2013).

<table>
<tr><th>Offline MPPT algorithms</th><th>Online MPPT algorithms</th><th>Hybrid MPPT algorithms</th></tr>
<tr><td>Open Circuit Voltage algorithm</td><td>Extremum seeking control algorithm</td><td rowspan="2">Incremental Conductance and Artificial Neural Network MPPT algorithm</td></tr>
<tr><td>Fuzzy Logic algorithm</td><td>Perturb and observe algorithm</td></tr>
<tr><td>Short Circuit Current algorithm</td><td>Incremental - conductance algorithm</td><td rowspan="2">Perturb & Observation and Artificial Neural Network MPPT algorithm</td></tr>
<tr><td>Artificial Neural Network algorithm</td><td>Ripple Correlation Control MPPT algorithm</td></tr>
<tr><td>Evolutionary Algorithms</td><td>Current Sweep MPPT algorithm</td><td rowspan="2">Genetic Algorithm Optimized & Fuzzy Based MPPT algorithm</td></tr>
<tr><td></td><td>Differentiation Based MPPT algorithm</td></tr>
</table>

All of the techniques vary in implementation complexity in hardware, cost of effectiveness, number of sensors wanted, and convergence speed, traceability during partial shading condition and involved economics (Pallavee Bhatnagar and Nema, 2013) as shown in Table 3.2.

Table 3.2. A comparison of different MPPT methods (Harjai et al., 2011; Karami et al., 2017)

| MPPT methods | Sensors | Speed | Analog or Digital | complexity |
|---|---|---|---|---|
| P&O MPPT method | Voltage, current | Low-Medium | Both | Low |
| INC MPPT method | Voltage, current | Low-Medium | Digital | Medium |
| ANN MPPT method | Varies | Very fast | Digital | High |
| Hybrid MPPT method | Varies | Very fast | Digital | High |

### 3.2.1. Perturb and Observe (P & O) Method

The photovoltaic panel produces the characteristic of current-voltage curve with a unique point (Maximum Power Point) (Mamatha, 2015). Perturb and Observe algorithm is largely employed in MPPT due to their easy structure and reliability. It is based on the sign of the last increment in the power and the sign of the last perturbation are utilized to decide what should be the next perturbation. At left of the maximum power point increasing voltage of the PV panel leads to power increases while at right of the maximum power decreasing the voltage increases power of a PV panel. Perturbation must be remaining in the same direction, when the power decreases, next perturbation should move into the opposite direction (Patel et al., 2013). These can be summarized using the table 3.3.

The control flow chart of this technique is shown in Figure 3.4. The drawback of this technique is it oscillates around MPP and the voltage variation is high. This method also takes a long time for tracking and it has a slow response during rapidly changing conditions (Putri et al., 2015).

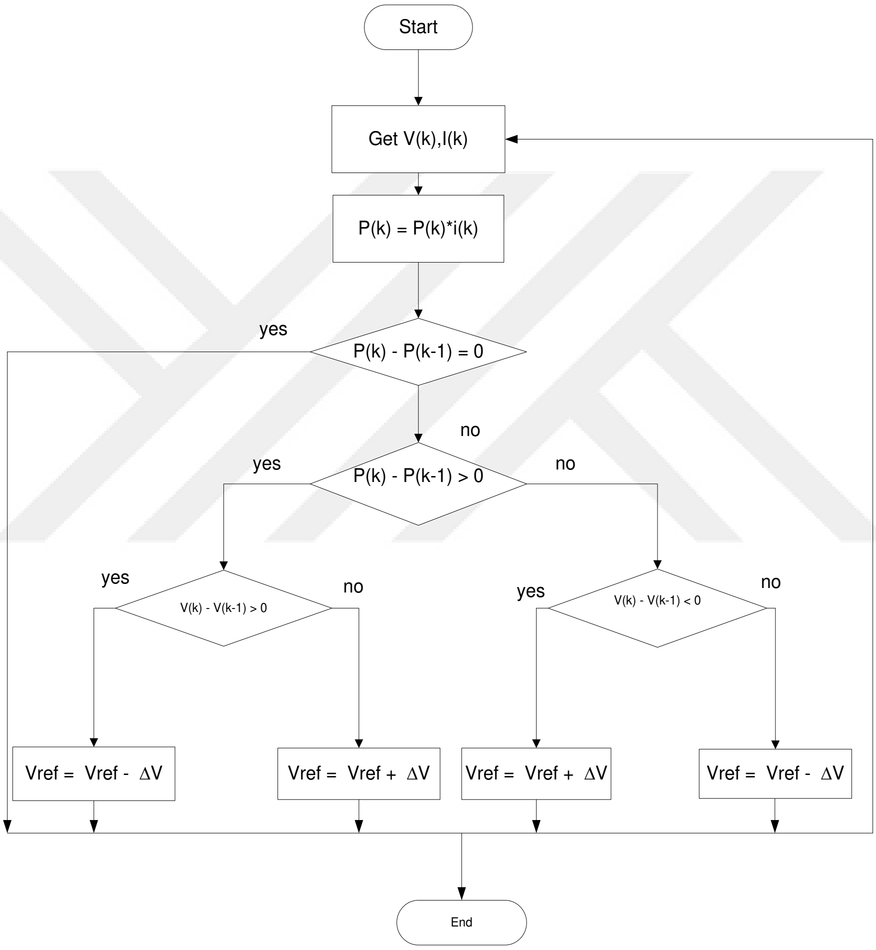


Figure 3.4. Flowchart of (P & O) Method (Nigam and Sharma, 2016)

Table 3.3. Summary of P&O Method (Roncero-Clemente et al., 2013)

| Perturbation | Change in power | Next Perturbation |
|---|---|---|
| Positive | Positive | Positive |
| Positive | Negative | Negative |
| Negative | Positive | Negative |
| Negative | Negative | Positive |

### 3.2.2. Incremental Conductance Method

The incremental conductance technique is based on the truth which the derivative power of the photovoltaic with its voltage equals to zero (Sharma and Purohit, 2014). This technique varying conditions more speedily than the Perturb and observes algorithm. It is producing oscillations in the output power.

This algorithm utilizes the slope of the photovoltaic module power curves to observe a maximum power point. The slope at the maximum power point (MPP) is zero, negative at the left of the MPP, and positive at the right of the MPP. The derivative of power PV panel is given as in Equation (3.1), and the error $e$ is given by Equation (3.2) (Subudhi, and Pradhan, 2012; Rezk, and Eltamaly, 2015).

$$\frac{dP}{dV} = \frac{d(V \times I)}{dV} = I + V\frac{dI}{dV} = 0 \tag{3.1}$$

$\Delta I / \Delta V = -I/V$ , at MPP

$\Delta I / \Delta V > -I/V$ , left of MPP

$\Delta I / \Delta V < -I/V$ , right of MPP

Also, $\frac{dI}{dV} + \frac{I}{V} = \frac{I(i)-I(i-1)}{V(i)-V(i-1)} + \frac{I(i)}{V(i)} = 0$

$$e = \frac{I(i)-I(i-1)}{V(i)-V(i-1)} + \frac{I(i)}{V(i)} \tag{3.2}$$

The flowchart of this method as illustrated in Figure 3.5. It can be achieved by discrete integrator with a scaling factor k, and the error signal *e* as the input. The error signal is adjusted by the scaling factor before the integral compensator. When operating point close to a maximum power point, the error signal becomes smaller Thus, it produces better tracking (Sivachandran et al., 2015; Rezk and Eltamaly, 2015).

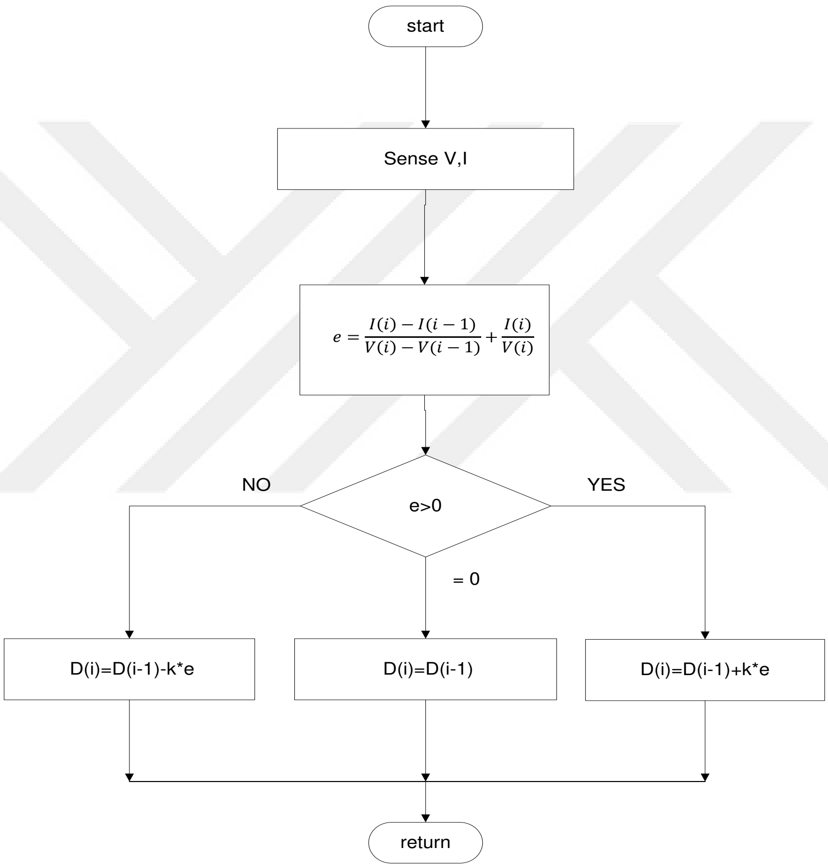


Figure 3.5. Flow chart of INC MPPT method

In both INC and P&O algorithms, how fast the maximum power point is attained relies on size of the increment of the reference voltage. Disadvantages of these methods are that they can lose observe of maximum power point in state of step changes if solar radiation changes rapidly, both methods are tracking the MPP well. However, when the change in insolation following a slope, methods depend on the curve which is changing continuously with the solar radiation, so the current and voltage changes are not only because of the perturbation of the voltage. thus, the methods are unable to determine whether the power changes because of its change in level of insolation. or because of own voltage increment (Patel et al., 2013).

### 3.2.3. Artificial Neural Network MPPT Method

Artificial neural networks are densely interconnected processing units that employ parallel computation algorithms. Neural networks are contained of easy elements working in parallel (Chekired et al., 2013). This method is similar to biological nervous in human brain (Lippmann, 1987). The ANN structure contains of an input layer, weight-bias, activation function, summing junction and layer outputs as seen in Figure 3.6.

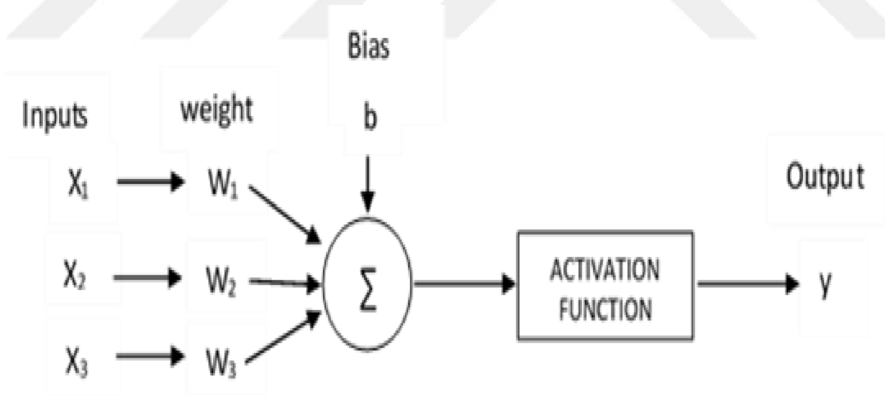


Figure 3.6. The structure of an artificial neuron

ANNs, which utilized to find a suitable solution for the non-linear, consisting of three layers as shown in Figure 3.7.

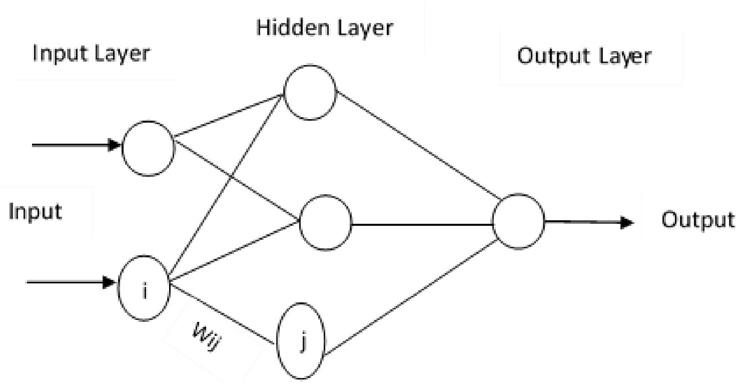


Figure 3.7. Illustration of a neural network

The input layer is the first layer which receives an external data, the second layer is the hidden layer which receive a data from the input layer and send it to the output layer (Elgharbi et al., 2012). In each layer, number of nodes, Number of inputs and initial values of weights are depending on the user. The input parameters can be parameters of photovoltaic panel such as voltage and current or atmospheric conditions such as solar radiation and temperature. Parameters of the output can be duty cycle or reference voltage which employed to adjust converters power to work at a maximum power point. (Esram and Chapman, 2007).

The accuracy this method relies on the number of neurons, the learning algorithm used in training data set and hidden layer. The features of ANN are improving efficiency of photovoltaic panels at partial shading conditions and uniform irradiance. However, PV panels have various characteristics, so the artificial neural network must be specially trained for every PV panels used. Also, the PV panel characteristics change with passage of time, needing periodic training of the artificial neural network used. (Husain et al., 2017).

The benefits of this MPPT method are their capability to handle big and complex applications with many interrelated parameters (Veerachary and Yadaiah, 2000).

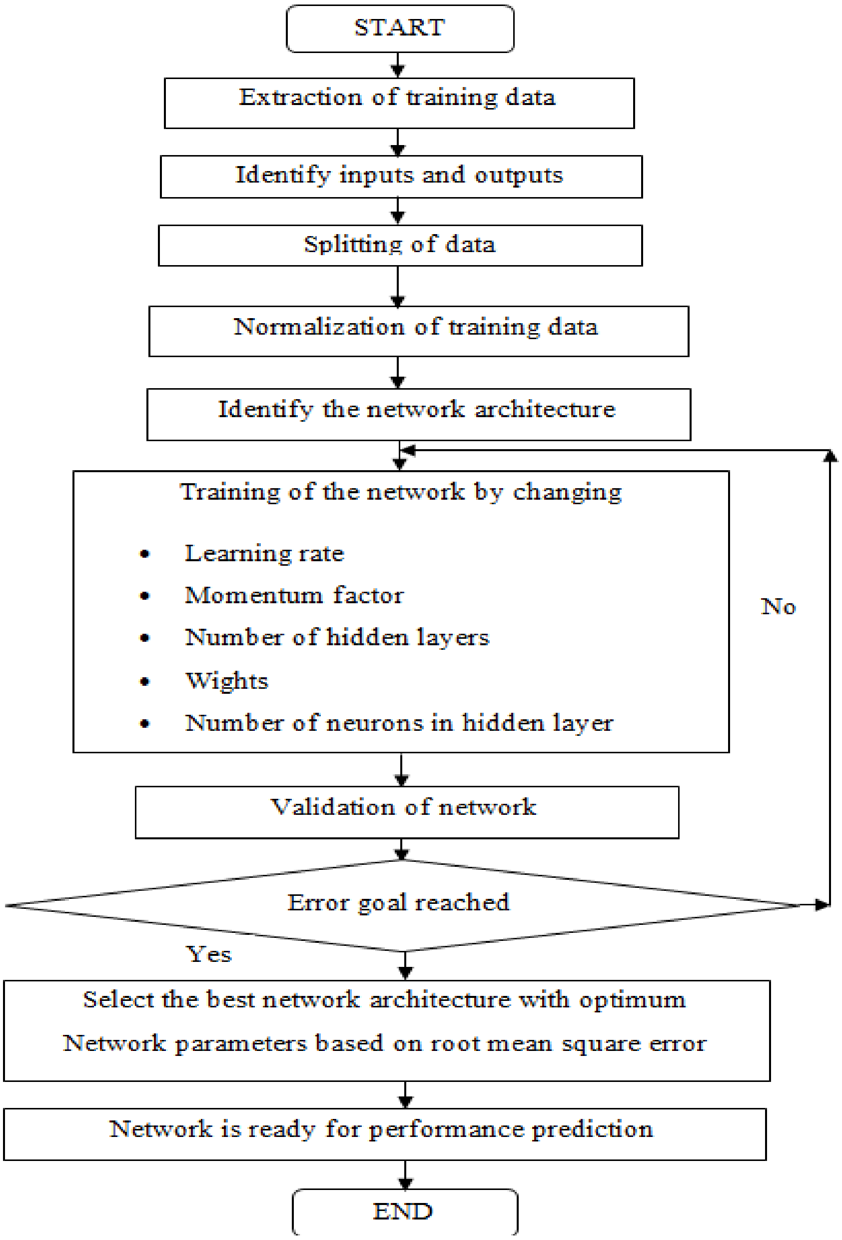


Figure 3.8. Training procedure of proposed ANN based MPPT algorithm

### 3.2.4. Hybrid MPPT Method

Traditional maximum power point tracking methods are unable to extract maximum power because of global maximum power point (GMPP) occurring at partial shading cases and overall system efficiency is decreased. To overcome this drawback many researchers proposed a hybrid method. The method adjusts the duty cycle to provide load matching and to regulate an input voltage at a maximum power point (MPP) (Rabi, and Kanimozhi, 2016)

A hybrid MPPT is formed by a combination of two MPPT methods or more to improve tracking performance. Jiang and Maskell (2014) proposed a hybrid MPPT method for photovoltaic applications operating during non-uniform insolation cases. This technique combines the artificial neural network algorithm with traditional P&O algorithm for tracking a maximum power. Rather than of iteratively disturbing the operating point at the search area, firstly employ an ANN to find the global maximum power point utilizing the combination of the successively estimated current values onto every stair of the current-voltage curve when partial shading happens, and then utilize Perturb and Observe, or some another efficient optimization technique for unimodal functions, at the local region to get the global maximum power.

The P&O method begins searching from an initial value of the boost converter duty cycles for reach to the optimum voltage which corresponds to the maximum power point. Once a sudden variation in irradiance occurs, the ANN technique is then triggered to recognize a new global peak region for a new case of the irradiance (El-Helw et al.2017).

Figure 3.9 describe a hybrid MPPT method. When the change in power value in two succeeding perturbations is greater than the critical specified power difference, the ANN based predictor is used to set initial operating point for Perturb and Observe technique. This is utilized for adapting the operating point of P&O technique to a new MPP. The critical power difference value, Psudden, can be adapted according to the photovoltaic application and its environment. Till other sudden variation in the irradiance level happens, the system stays at the current maximum power point by continuously executing the Perturb and Observe technique (Jiang et al.,2015).

This method has a faster convergence speed and a good performance during partial shading condition. However, the hybrid method makes the application more complex and cost of the application may be increased.

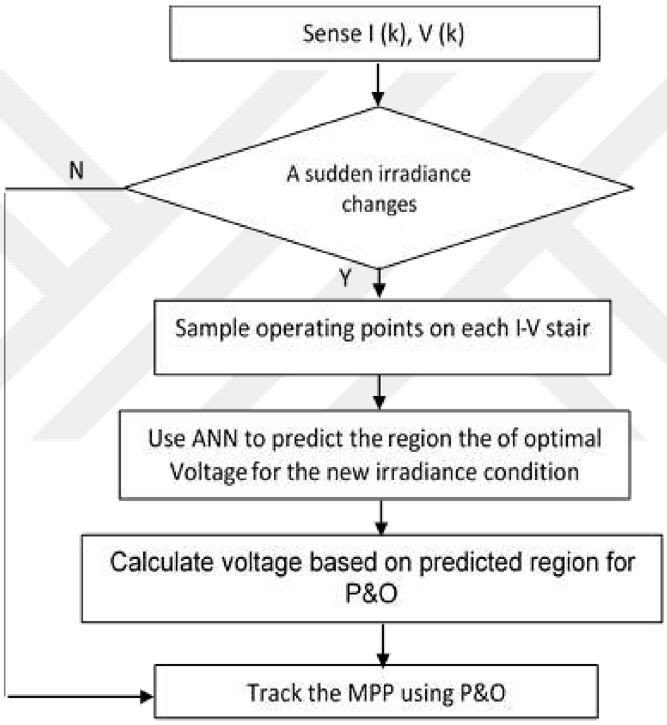


Figure 3.9. The tracking process of the hybrid method (ANN and P&O)

Yang et al (2012) proposed hybrid MPPT method which combines the online P&O MPPT techniques and the $V_{OC}$ offline MPPT techniques. In this technique $V_{OC}$, that was measured directly, is utilized as the elementary estimate of the maximum power point. P&O technique is utilized in order measuring the slope of the characteristic curves to get maximum power point carefully.

### 3.3. DC-DC Converters

A dc to dc converter is essential part of a maximum power point tracking application. Without it, no maximum power point tracking system is designed. It has wide applications in photovoltaic systems. Whether it is boost converter which the output voltage is upper than input voltage, buck converter which has a less output voltage than the input voltage or buck-boost converter which the output voltage is either less or greater than the input voltage (Chaudhari, 2005).

The input resistance of the converter also, the photovoltaic load resistance is dependent on $R_L$ and duty cycle. the input resistance ratio to load resistance is illustrate in Table 3.4. (Coelho et al., 2009)

Table 3.4. Variation range of the *Rin*

| **Converter Topology** | $R_{in}$ | **Interval of the Rin** |
|---|---|---|
| Buck | $R_L/D^2$ | $R_L < R_{in} < \infty$ |
| Boost | $(1 - D^2)R_L$ | $0 < R_{in} < R_L$ |
| Buck-Boost | $(1 - D^2)R_L/D^2$ | $0 < R_{in} < \infty$ |

### 3.3.1. Boost Converter

The boost converter is a switch mode dc-dc converter which rises voltage from its input (supply) to its output (load). Figure 3.10 shows the simple boost converter.

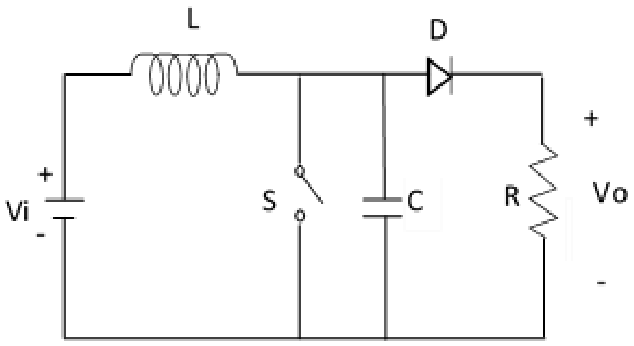


Figure 3.10. boost converter topology

The boost converter design is given as following (Saibabu et al., 2011; Kotak, Tyagi, 2013):

$$V_{in} \times t_{on} - (V_o - V_{in}) \times t_{off} = 0 \tag{3.3}$$

$$V_{in} \times \mathrm{D} \times \mathrm{T} = (V_o - V_{in})\,(1 - \mathrm{D})\,\mathrm{T} \tag{3.4}$$

Assuming that the ideal converter in which the input power and the output power are equal, Pin = Pout,

$$V_{in}\, I_{in=} V_o\, I_o \tag{3.5}$$

$$\frac{V_o}{V_{in}} = \frac{I_{in}}{I_O} = \frac{1}{1-\mathrm{D}} \tag{3.6}$$

$$Vin = Vo(1 - D) \tag{3.7}$$

$$I_{in} = \frac{I_o}{1-D} \tag{3.8}$$

$$\mathrm{R}_{in} = \frac{V_{in}}{I_{in}} = \frac{V_o(1-D)}{\frac{I_o}{1-D}} = \frac{V_o}{I_o}(1-D)^2 \quad \text{so, we get}$$

$$R_{in} = R_L\,(1 - D)^2 \tag{3.9}$$

The maximum load for photovoltaic is described as:

$$R_{MPP} = \frac{V_{MPP}}{I_{MPP}} \tag{3.10}$$

D : the duty cycle, D= $t_{on}$/T and T= 1/Fs.

Vo: is the output voltage.

Vin: is the input voltage.

Iin: is the input current.

Io: is the output current.

Rin: is the input resistance

$R_L$: is the load resistance.

$R_{MPP}$: is the maximum load resistance

ton: is the switching on time

T: is the switching period.

Fs: is the switching frequency.

The MPPT method will adjusts the range of Rin until to get $R_{in} = R_{MPP}$. But this will not be possible if $R_{MPP}$ was not within the group of values allowed for Rin, that is, the method will not find the MPP if $R_L < R_{MMP}$. It will only be possible for $RL \geq R_{MPP}$ values. A boost regulator has a high efficiency because of a single switch so, it can rise the voltage without the transformer.

The value of inductance L is given by Equation (3.9) such that the current of inductor $I_L$ flows continuously and never drops to zero (Ayop and Tan, 2018).

$$L = \frac{\mathrm{Vi}\ D}{\Delta \mathrm{i_L}\ f_s} \tag{3.11}$$

Vi: the input voltage

$\Delta i_L$: ripple current of the inductor

The output capacitance given by Equation (3.10) (TI, 2013):

$$C_O \geq \frac{I_O\ D}{f_s\ \Delta V_O} \tag{3.12}$$

$C_O$: the output capacitance

I: the output current

D: the duty cycle

$\Delta V_O$: the output voltage ripple

The basic principle of the boost converter consists of two states

- ON-State

If the switch is turned on the inductor gets charged across the battery and stocks the power. At this state, the current of inductor exponentially increases for ease we assume that the inductor charging and discharging are linear. The diode restricts the flux of current and so the load current stays constant (Dutta, 2014).

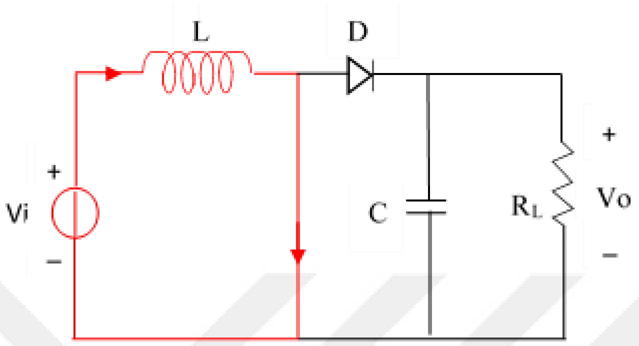

Figure 3.1. ON-state of boost converter

- OFF-State

If the switch is turned off the diode becomes short circuited. Stocks power in the inductor discharging across opposite polarities that charge the capacitor. The current through inductor decreases, but the load current stays constant throughout the process. The waveform of the boost converter is shown in Figure 3.13 (Pradhan, and Panda, 2018)

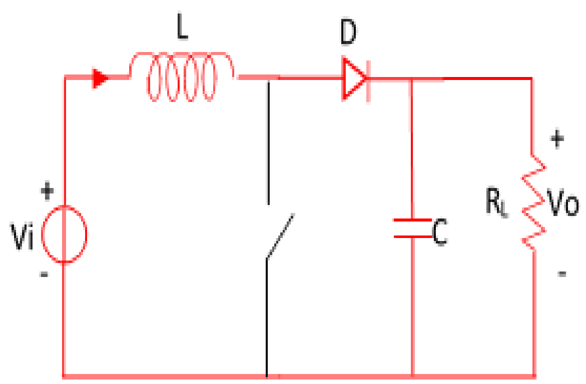

Figure 3.12. OFF-state of boost converter

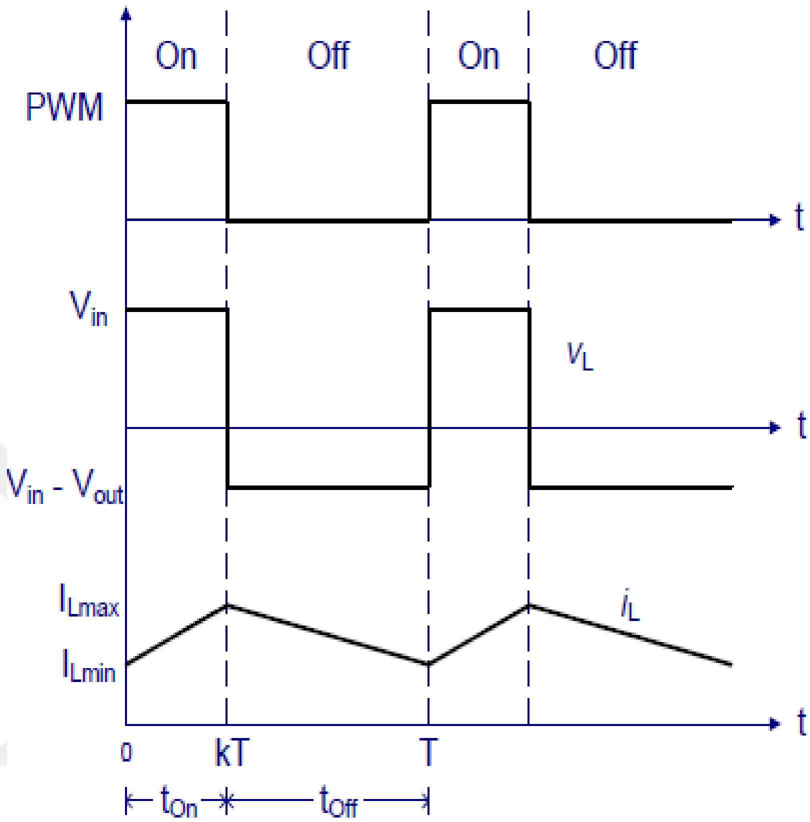


Figure 3.13. Waveforms for a Boost Converter (Pradhan, and Panda, 2018)

# 4. SIMULINK MODELING

In this section, the photovoltaic system modeling and simulation at partial shading cases is presented using MATLAB/Simulink and the case of shading is generated by providing various insolation levels to the panels. Four MPPT methods will be compared.

The normal bypass diode is replaced by smart bypass to decrease the loss in the power at partial shading conditions.

PV panel is simulated based on the mathematical equations of the solar panels, every module contains of 36 cells connected in series, then four- module connected into series to form the PV array. The aim of the simulation study is to make a comparison between various MPPT techniques based on performance to determine which ones are optimized and can capable of tracking the global MPP during partial shading cases.

## 4.1. Simulink Model of Photovoltaic Array in Matlab

A complete model of photovoltaic panel has been developed and simulated by MATLAB/Simulink based. A 100 W photovoltaic panel is taken as reference panel for the simulation and module key parameters is given in Table 4.1.

This model is based on the mathematical equations of the PV array as mentioned before in section (2.5). Figure 4.1(a) shows the photocurrent $I_{Ph}$ of the photovoltaic panel, Figure 4.1(b) shows saturation current $I_{0,}$ Figure 4.1(c) shows the reverse saturation current of PV panel at reference temperature, Figure 4.1(d) shows diode current, Figure 4.1(e) shows the shunt current and Figure 4.1 (f) shows output current of panel

Four modules connect together to form a photovoltaic array as shown in Figure 4.2

Table 4.1. Key parameters of DS-100 PV panel (Nguyen, 2015)

| Parameter | Value |
|---|---|
| $I_{sc}$ | 6.11 A |
| IMPP | 5.55 A |
| $V_{oc}$ | 21.6 V |
| $V_{MPP}$ | 18 V |
| n (quality factor) | 1.2 |
| Ns | 36 |
| NP | 1 |

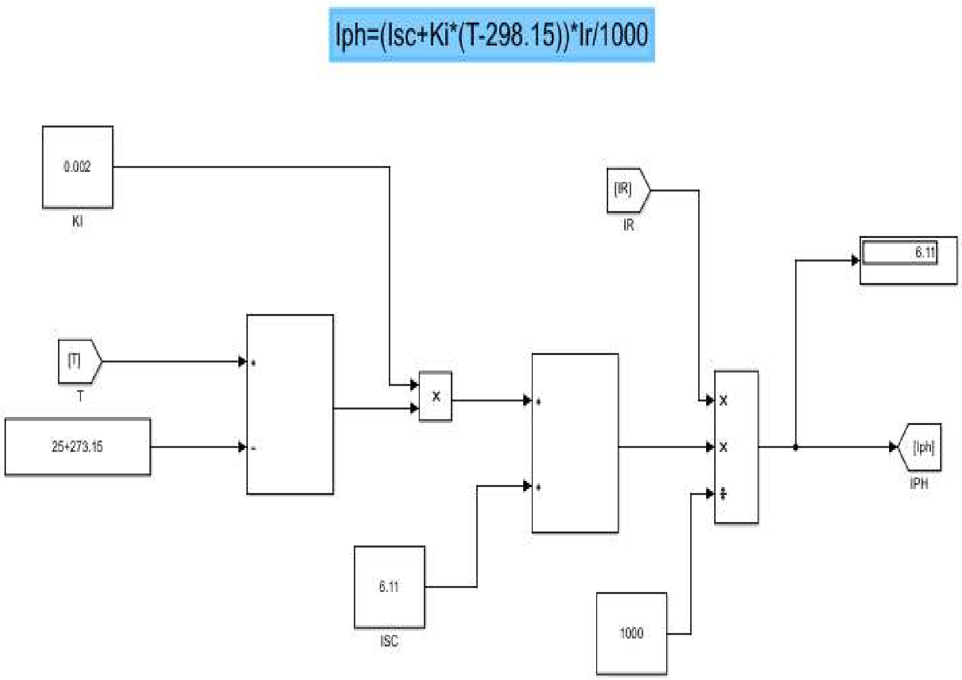


Figure 4.1(a) Photocurrent of PV module

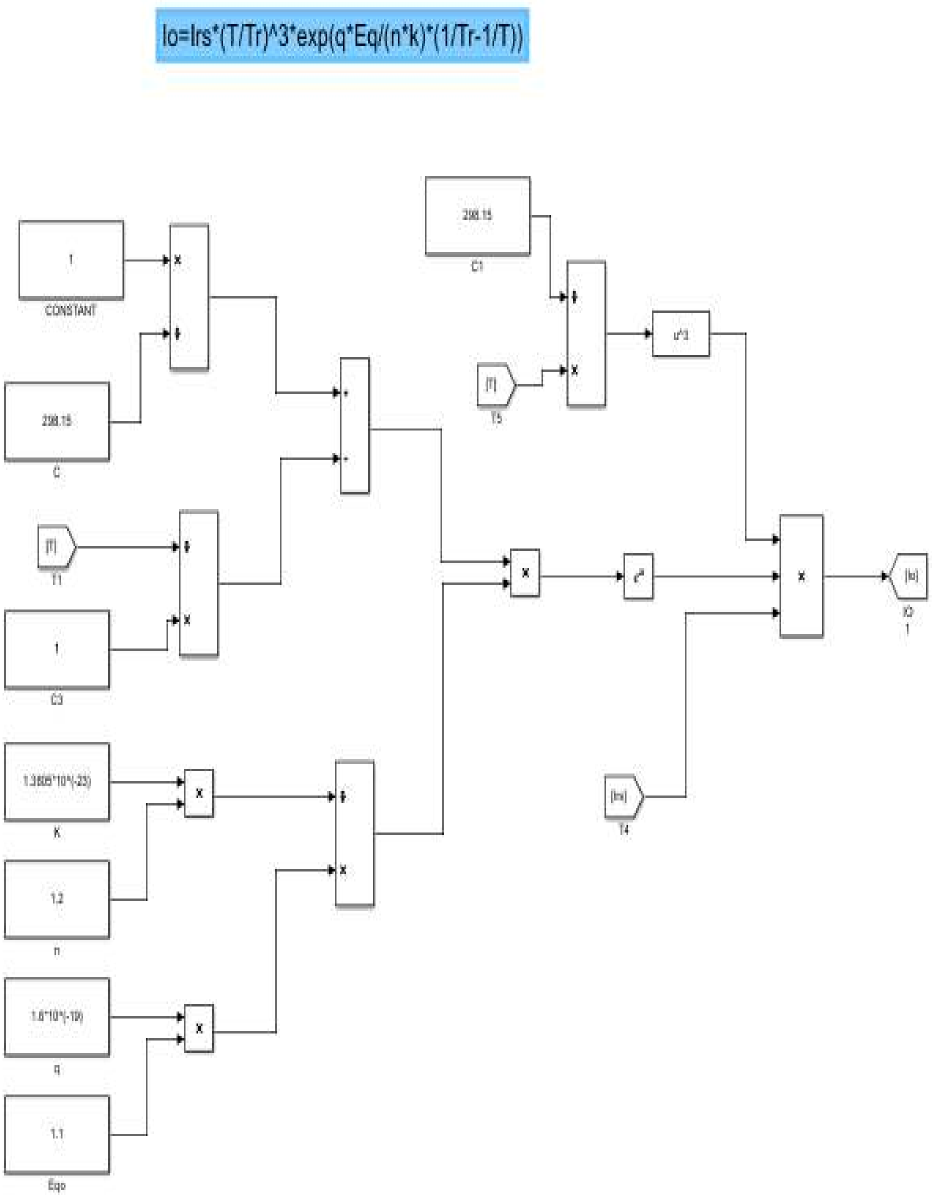


Figure 4.1 (b) Saturation current of PV module

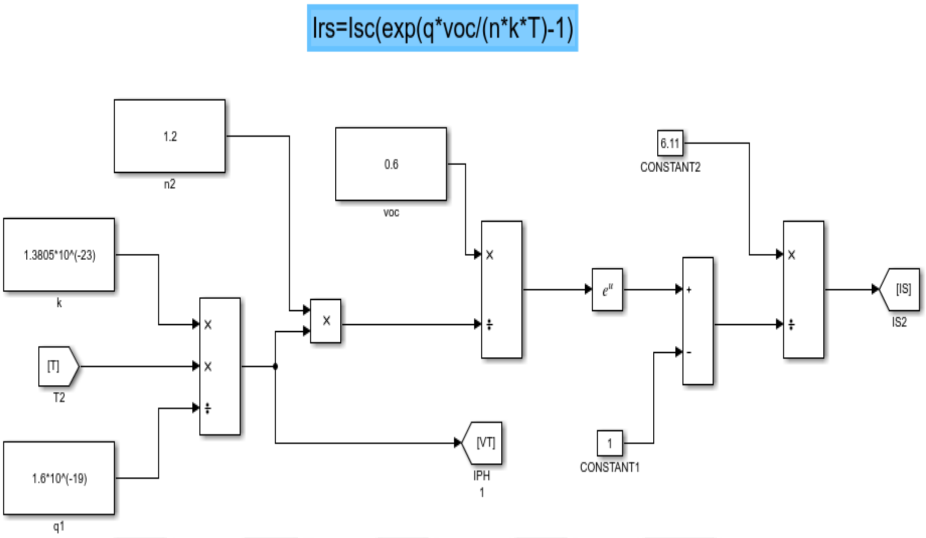


Figure 4.1 (c) Reverse saturation current of PV module

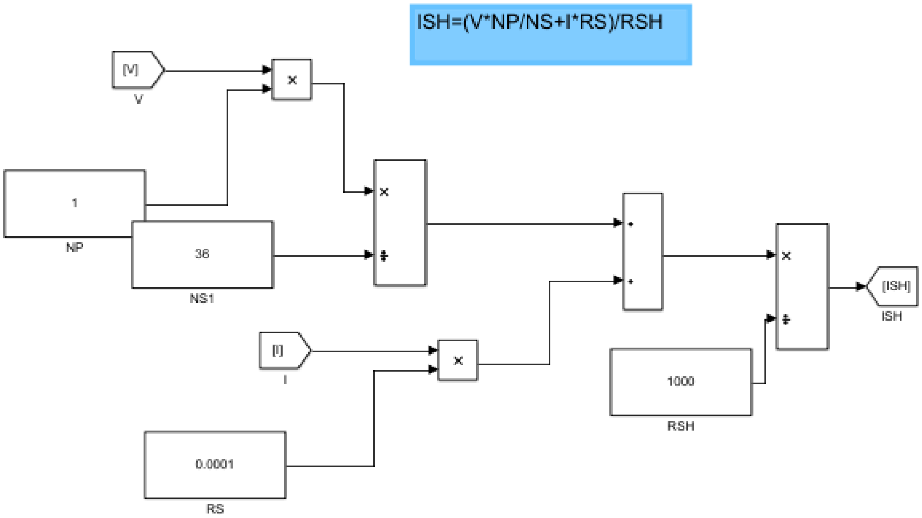


Figure 4.1 (d) Shunt current of PV module

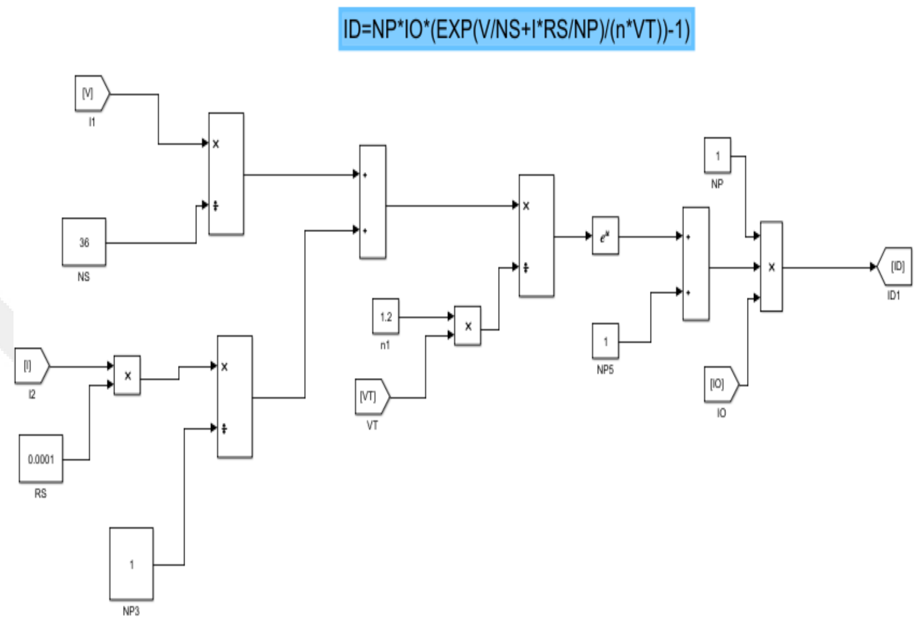


Figure 4.1 (e) Diode current

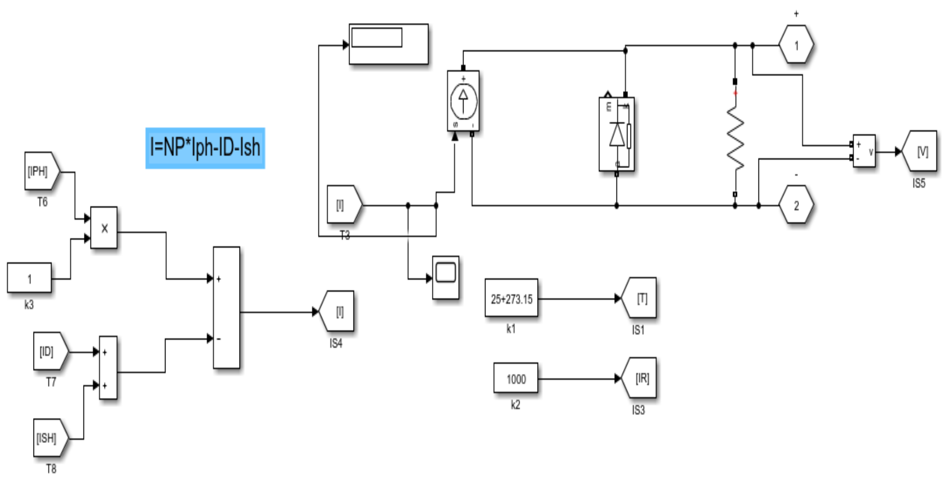


Figure 4.1 (f) Output current of PV module

Four photovoltaic modules connected in series to form a photovoltaic array. Figure 4.2 shows the PV array.

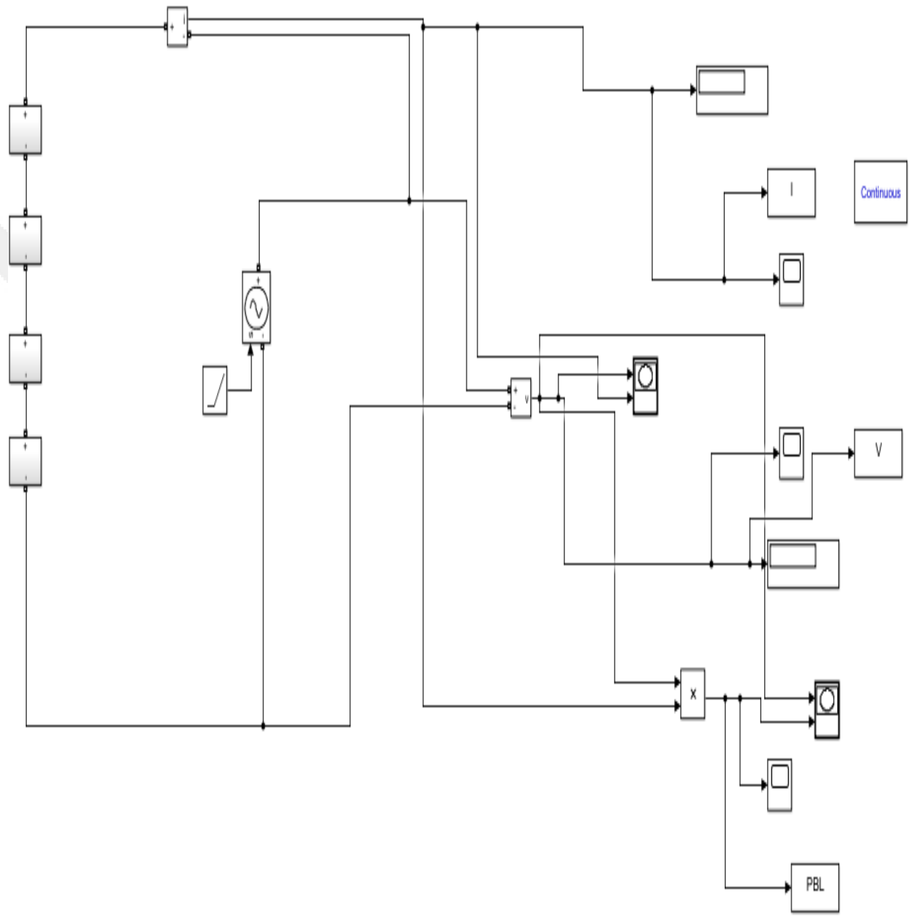


Figure 4.2. Simulation model of PV array

## 4.2. Simulink Model for Smart Bypass

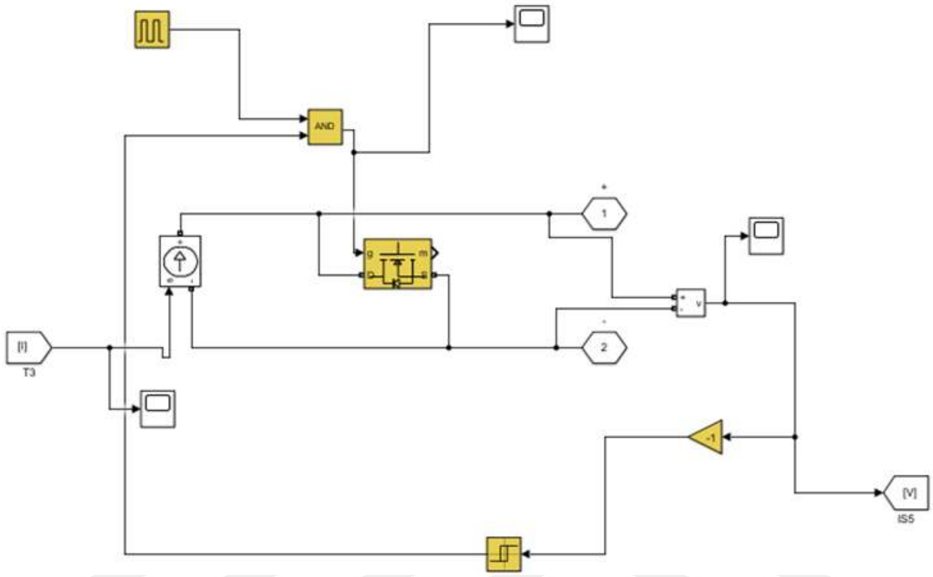


Figure 4.3. Smart bypass simulink model

## 4.3. Simulink Model for Boost Converter

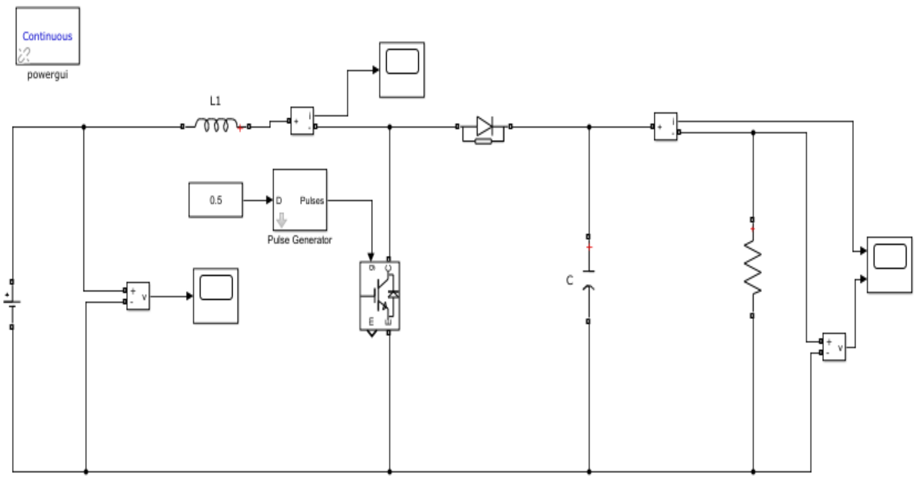


Figure 4.4. Boost converter simulink model

For the duty cycle $D_{min}$ is 0.2 and $D_{max}$ is 0.6 at fs=10000, the value of inductance L is:

$$L = \frac{\mathrm{Vi}\ D}{\Delta \mathrm{i_L}\ f_s}$$

A good estimation for the inductor ripple current is 20% to 40% of the input current. The input inductor current ($I_L$) is 5.55 A, and the ripple current of the inductor is;

$$\Delta \mathrm{i_L} = 0.3 \times I_L = 0.3 \times 5.55 = 1.665\ A$$

Using this equation;

$$L = \frac{72 \times 0.6}{1.665 \times 10 \times 10^3} = 2.5mH$$

The value of inductance C is:

$$C_O \geq \frac{I_O\ D}{f_s\ \Delta \mathrm{V}_{co}}$$

Capacitors design criterion is that the ripple voltage through coupling capacitor must be from 1% to 5%.

$$\Delta \mathrm{V}_{co} = 0.01 \times 178 = 1.78\ V$$

Using this equation;

$$C_O \geq \frac{2.24 \times 0.6}{1.78 \times 10 \times 10^3} = 75.5\mu\mathrm{f}$$

Standard 100 µf is selected as boost capacitor

The required modeling parameters of the boost converter are given in the Table 4.2.

Table 4.2. Key parameters of boost converter

| Parameter of Converter | Value |
|---|---|
| Input Voltage (Vin) | 72 V |
| Output Voltage (Vout) | 178 V |
| Capacitance(C) | 100 μF |
| Inductance(L) | 2.5 mH |
| Switching Frequency (f) | 10 kHz |

### 4.4. Simulink Model for MPPT Methods

The photovoltaic system simulink model with MPPT method is given in Figure 4.5.

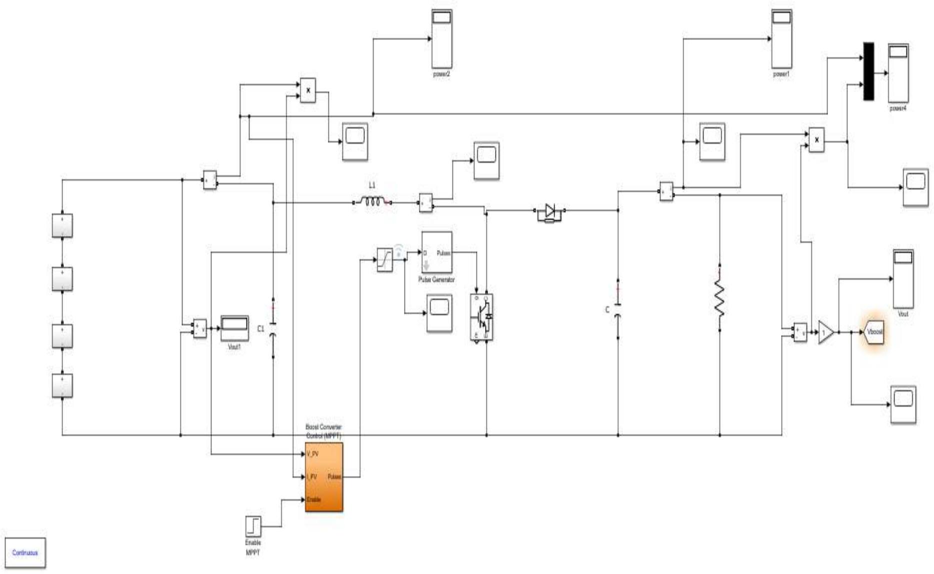

Figure 4.5. Simulation model of the PV System

Simulation model of MPPT method (which is a subsystem given in Figure 4.5) based on INC method is seen in Figure 4.6

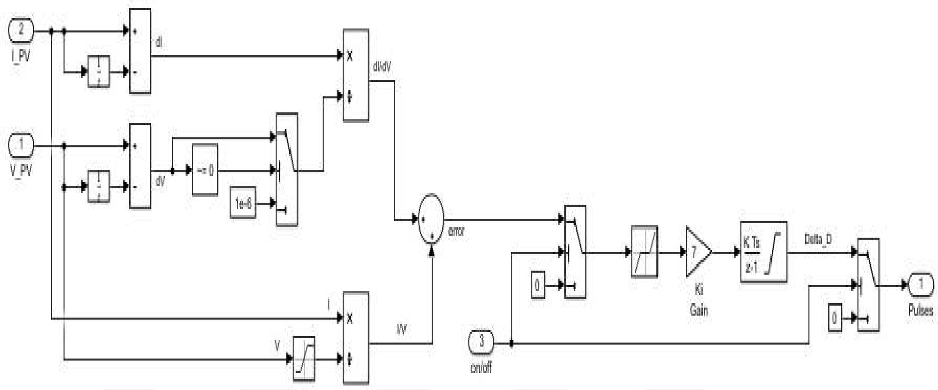


Figure 4.6. Simulation Model of PV System with Incremental Conductance Method

Simulation model of MPPT method (which is a subsystem given in Figure 4.5) based on P&O method is seen in Figure 4.7.

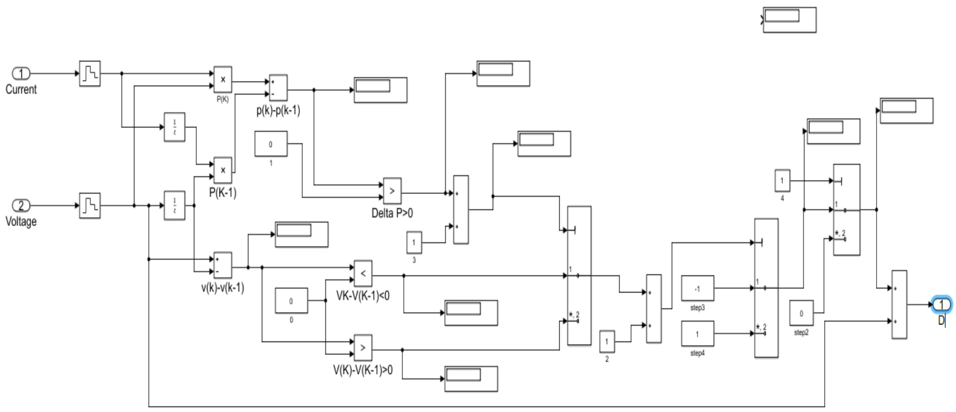


Figure 4.7. Simulation model of PV system with P&O method

The first step of the ANN designing is the chosen of the input parameters and the second step is the definition of the hidden neurons number. The Neural network was defined and designed using 'MATLAB NNET toolbox' as shown in Figure 4.8.

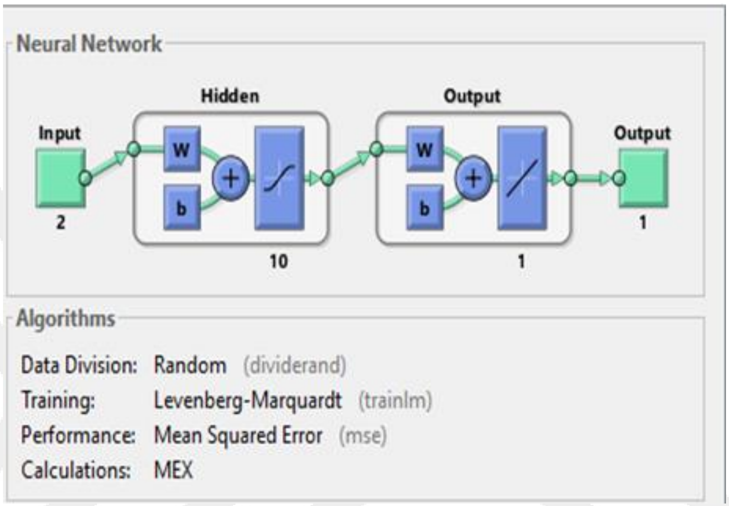

Figure 4.8. MATLAB neural network tool box

The developed ANN has two inputs which are the current and voltage of PV array with two layers which are the hidden and the output layer. The hidden layer has ten neurons and the output layer has one neuron which is the duty cycle. The MATLAB software is used to obtain the datasets, 1000 samples that were used for the testing, training, and validation. The datasets are obtained taking values of current, voltage of the photovoltaic array. Generated datasets were splits randomly to 70% for training, 15% for validation, and 15% for testing.

Performance and regression plots are clarified in Figure 4.9 and 4.10, respectively.

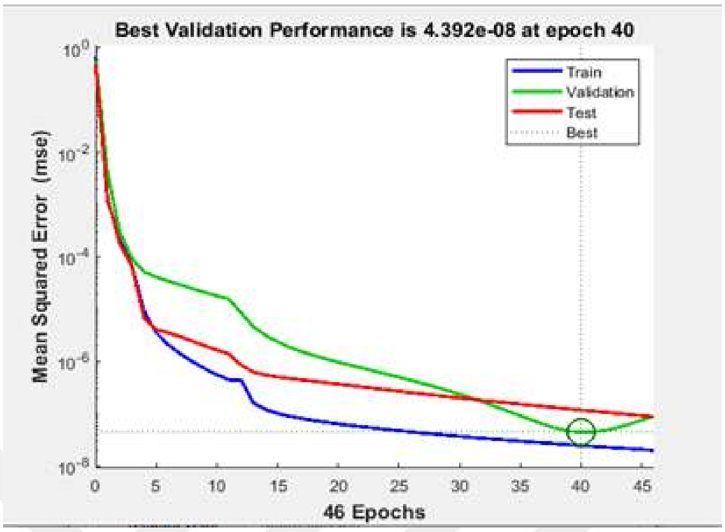


Figure 4.9. Performance plot of network

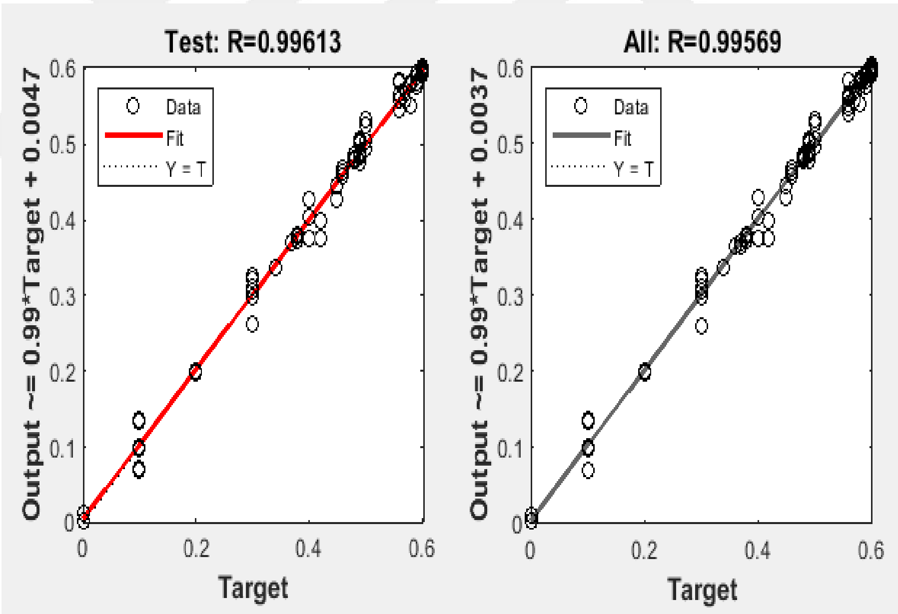


Figure 4.10. Neural network regression plot

Figure 4.11 shows simulation model of the hybrid method which combines an ANN method with the P&O method. Basic idea of this technique is to recognize the global maximum power point region from the values of current measured onto current–voltage curve utilizing the ANN classifier, then employ the traditional MPPT technique to find the maximum power point inside the local area.

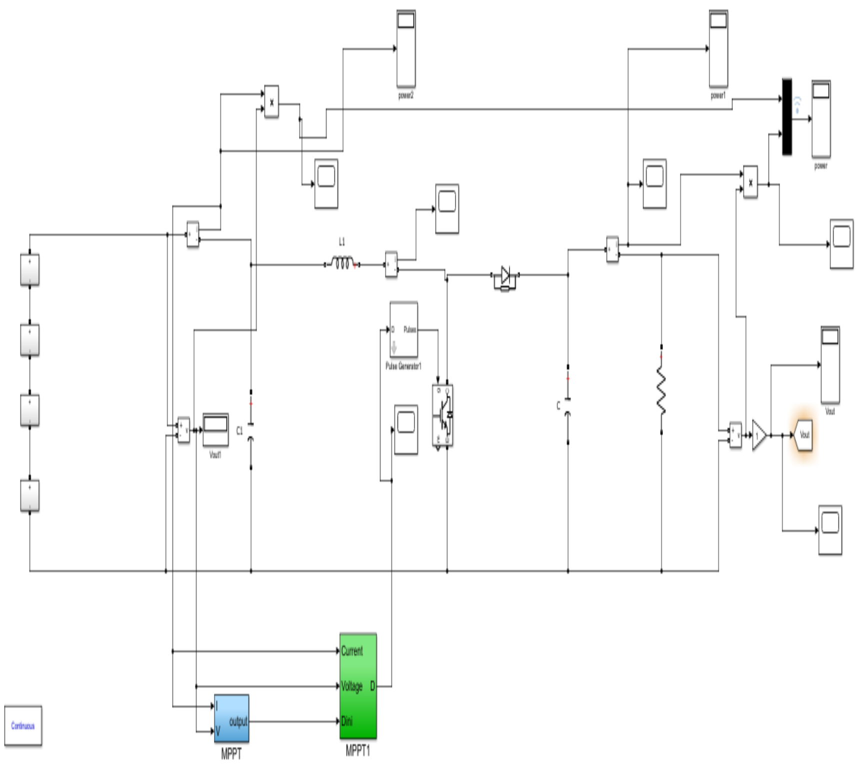


Figure 4.11. simulation model of PV System with Hybrid Method

# 5. RESULTS AND CONCLUSION

## 5.1. Simulation Results

The photovoltaic system was simulated at partial shading conditions, in the simulations the effect of bypass diode characteristic in a PV arrays is presented. Figure 5.1 shows what happens with PV power output where the bypasses are used. the power output when using a normal bypass ($P_{mpp}$ =309.6 W), with a smart bypass ($P_{mpp}$ =314.5 W).

It can be seen clearly the differences in the power of the photovoltaic array when replacing normal bypass diode with smart bypass diode. The smart bypass dissipates a small amount of output power.

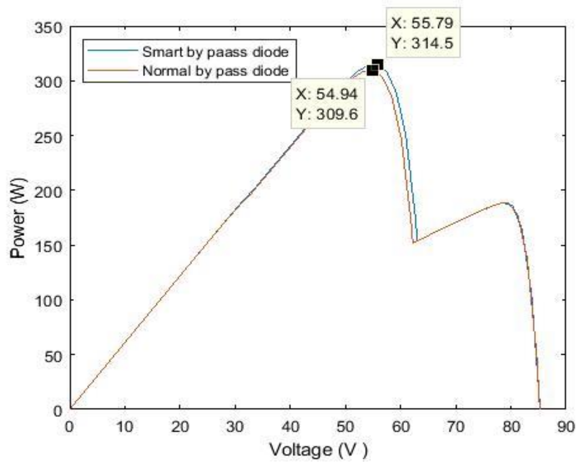


Figure 5.1. P $_{MPP}$ of PV array when the bypasses diode (normal bypass, smart bypass) are used

Observing the global maximum power point (GMPP) by the four MPPT techniques is analyzed under three cases:

Case1- GMPP at the right of power-voltage curve.

Case2- GMPP at the middle of power-voltage curve.

Case3- GMPP at the left of power-voltage curve

Different irradiance level used in this thesis are given in table 5.1

Table 5.1. Different irradiance used in this thesis

| Case | Shading pattern W/m$^2$ | | | |
|---|---|---|---|---|
| | A | B | C | D |
| 1 | 400 | 500 | 800 | 1000 |
| 2 | 1000 | 600 | 600 | 300 |
| 3 | 1000 | 300 | 1000 | 500 |

Figures 5.2–5.4 depict the PV characteristic curves of the PV arrays under three cases.

Table 5.2–5.4 depict the state of bypass diode for PV array.

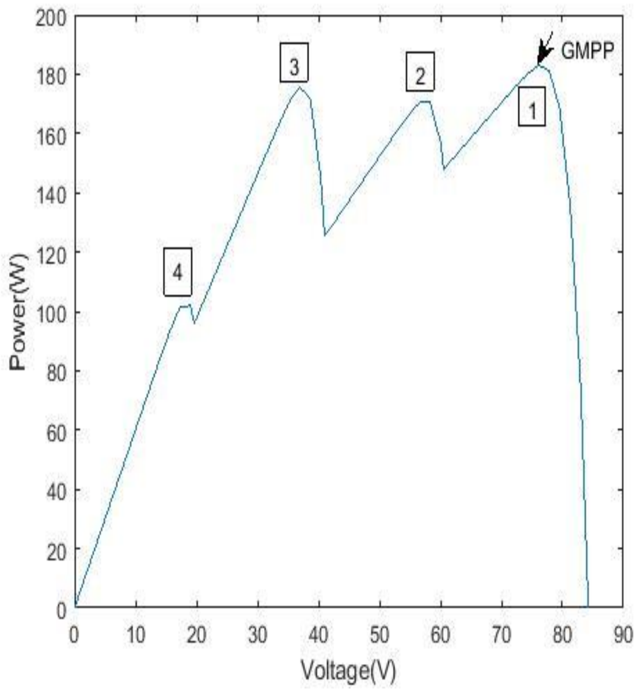


Figure 5.2. Case1- GMPP point located at the right of P-V curve

Table 5.2. State of bypass diode at case1

| State BPD | A | B | C | D |
|---|---|---|---|---|
| 1 | off | off | off | off |
| 2 | on | off | off | off |
| 3 | on | on | off | off |
| 4 | on | on | on | off |

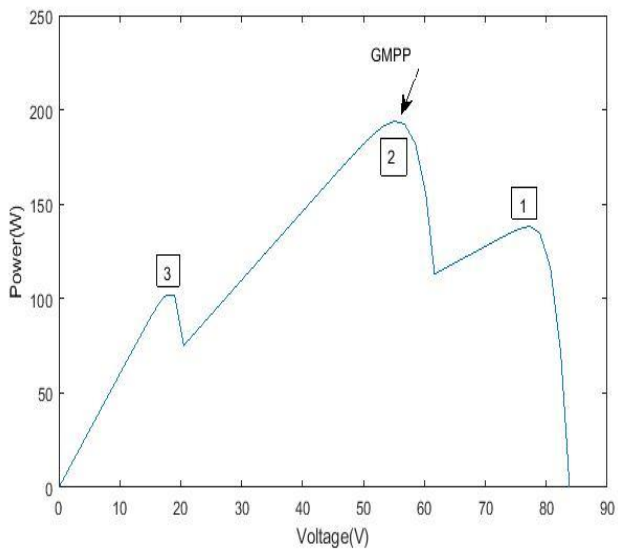


Figure 5.3. Case2- GMPP located at the middle of P-V curve

Table 5.3. State of bypass diode at case2

| State BPD | A | B | C | D |
|---|---|---|---|---|
| 1 | off | off | off | off |
| 2 | off | off | off | on |
| 3 | off | on | on | on |

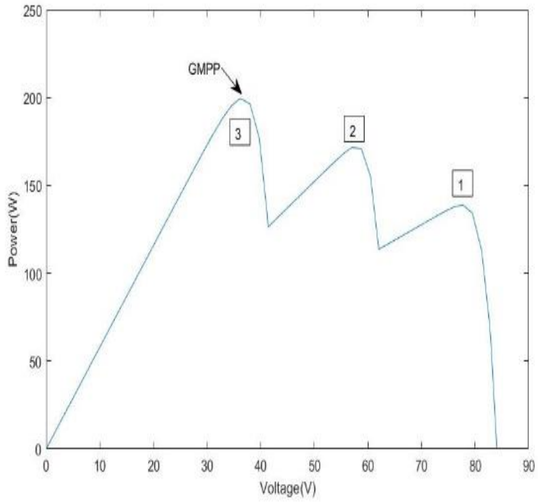

Figure 5.4 Case3- GMPP located at the left of P-V curve

Table 5.4. State of bypass diode at case3

| State BPD | A | B | C | D |
|---|---|---|---|---|
| 1 | off | off | off | off |
| 2 | off | on | off | off |
| 3 | off | on | off | on |

For comparison, the four MPPT methods were employed to track the global MPP, Figure 5.4-5.6 shows the tracking performance by these MPPT methods.

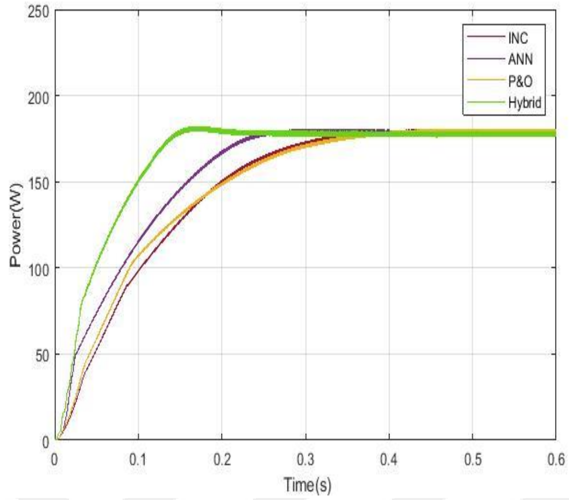


Figure 5.5. Output Power of the PV array with MPPT methods when GMPP at the right of PV curve

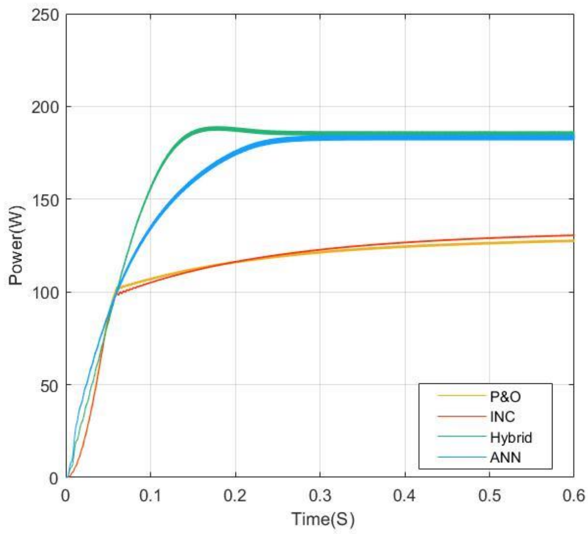


Figure 5.6. Output Power of the PV array with MPPT methods when GMPP at the middle of PV curve

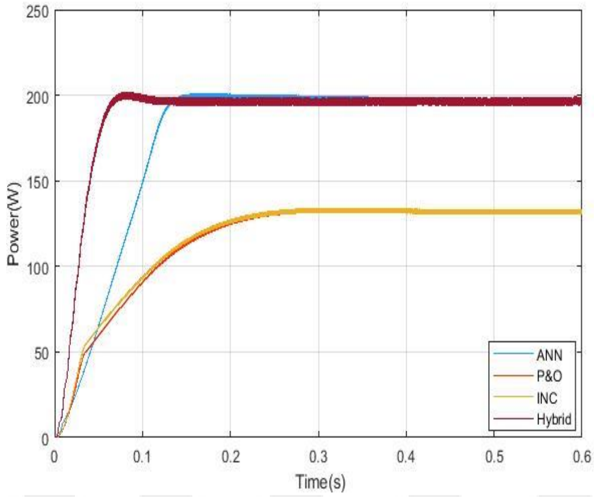


Figure 5.7. Output Power of the PV array with four MPPT methods when GMPP at the left of PV curve

From results of the simulation, it is noticed that in case 1 the all MPPT methods are able to track global maximum power point when global maximum power point at the right of the PV curve.

Case 2 and case 3 show the difference in performance among the MPPT methods, when the global maximum power at the left and middle of the photovoltaic curve. Artificial Neural Network and hybrid methods are able to find the global maximum power point, but the traditional methods Incremental Conductance and Perturb and Observe failed to differentiate between local maximum power and global maximum power point, so always give power around local MPP and in this case a large amount of output power lost. The tracked values of power and time taken to track global maximum power using the four MPPT methods are given in table 5.5.

Table 5.5. Performance comparision of four MPPT method under partial shading conditions

| | | Case1-GMPP at the right of PV curve | Case2-GMPP at the middle of PV curve | Case3-GMPP at the left of PV curve |
|---|---|---|---|---|
| $P_{max}$ (W) | | 182 | 190 | 200 |
| **Hybrid** | $P_{hybrid}$ (W) | 181 | 188.5 | 198 |
| | Time (s) | 0.192 | 0.211 | 0.109 |
| **ANN** | $P_{ann}$ (W) | 180 | 187 | 196.3 |
| | Time (s) | 0.223 | 0.261 | 0.147 |
| **P&O** | $P_{P\&O}$ (W) | 178.1 | 134.1 | 133 |
| | Time (s) | 0.399 | 0.328 | 0.276 |
| **INC** | $P_{INC}$ (W) | 179.2 | 135.3 | 134 |
| | Time (s) | 0.389 | 0.321 | 0.254 |

### 5.2. Conclusion

Photovoltaic energy is one of important sources of renewable energy that uses solar radiation to generate electricity. The main goal remains to get the maximum power from a solar PV system at various environmental condition by using various MPPT methods. Unfortunately, these methods efficiency decrease during partial shading conditions because of occurrence of multiple peaks on PV characteristic curve which makes tracking MPP of the PV arrays more complex.

The smart bypass is employed to reduce the power loss of a PV panel during partial shading conditions.

In this thesis, simulation of four maximum power point tracking (MPPT) methods for solar PV array at partial shading condition are presented. Also, a model of the boost converter is designed which is set up the PV's terminal voltage to the suitable voltage to track MPP. The simulation was performed using MATLAB/Simulink environment.

A comparative study of four MPPT methods are analyzed under three different partial shading conditions, this comparison is based on the performance of these MPPTs.

From the results obtained it is concluded that the ANN and hybrid MPPT methods are able to distinguish between the global maximum power point and local maximum power points with good efficiency and reduces power loss during mismatching conditions, while the conventional methods (P&O and INC) appears worse tracking performance and fails to track the global maximum power point. A comparative study among the four methods has been carried out. The results demonstrate the hybrid method is the best among the other three methods, it is a good solution giving an excellent efficiency and response time in steady state, and under partial shading conditions.

## REFERENCE


Abdulazeez, M., & Iskender, I., 2011. Simulation and experimental study of shading effect on series and parallel connected photovoltaic PV modules. In 2011 7th International Conference on Electrical and Electronics Engineering (ELECO) (pp. I-28). IEEE.

Al-Soeidat, M. R., Cembrano, A., and Lu, D. D., 2016. Comparing effectiveness of hybrid mppt algorithms under partial shading conditions. In 2016 IEEE International Conference on Power System Technology (POWERCON) (pp. 1-6). IEEE.

Allataifeh, A. A., Bataineh, K., and Al-Khedher, M., 2015. Maximum power point tracking using fuzzy logic controller under partial conditions. Smart Grid and Renewable Energy, 6(01), 1.

Asim, M., Tariq, M., Mallick, M. A., Ashraf, I., Kumari, S., and Bhoi, A. K., 2018. Critical evaluation of offline MPPT techniques of solar PV for stand-alone applications. In Advances in Smart Grid and Renewable Energy (pp. 13-21). Springer, Singapore.

Ayop, R., and Tan, C. W., 2018. Design of boost converter based on maximum power point resistance for photovoltaic applications. Solar Energy, 160, 322-335.

Babaa, S. E., Armstrong, M., and Pickert, V., 2014. Overview of maximum powerpoint tracking Control methods for PV systems. Journal of Power and Energy Engineering, 2(08), 59

Bauwens, P., and Doutreloigne, J., 2014. Reducing partial shading power loss with an integrated smart bypass. Solar Energy, 103, 134-142.

Bauwens, P., and Doutreloigne, J., 2016. NMOS-based integrated modular bypass for use in solar Systems (NIMBUS): Intelligent bypass for reducing partial shading power loss in solar panel applications. Energies, 9(6), 450.

Bojic, M., Radulovic, J., Rankovic, V., Nikolic, D., Bojic, L., and Skerlic, J., 2016. Flexible thin-film solar photovoltaics: research and application. Annals of the Faculty of Engineering Hunedoara, 14(1), 37.

Chekired, F., Mahrane, A., Smara, Z., Guenounou, A., and Mellit, A., 2013. Maximum power point tracking using neural networks for stand-alone photovoltaic system. In Proceedings of the first International Conference on Nano electronics, Communications and Renewable Energy.

Coelho, R. F., Concer, F., and Martins, D. C., 2009. A study of the basic DC-DC converters applied in maximum power point tracking. In 2009 Brazilian Power Electronics Conference (pp. 673-678). IEEE.

Crocker, F., 2017. Prediction of photovoltaic (PV) output via artificial neural network (ANN) based on real climate condition (Doctoral dissertation, Universiti Tun Hussein Onn Malaysia).

Chaudhari, V. A.,2005. Automatic peak power tracker for solar pv modules using dspacer software. Maulana Azad National Institute of Technology. Master Thesis of Technology in Energy. Bhopal: Deemed University.

Deng, S., Zhang, Z., Ju, C., Dong, J., Xia, Z., Yan, X., ... and Xing, G.,2017. Research on hot spot risk for high-efficiency solar module. Energy Procedia, 130, 77-86.

Dobrzański, L. A., Szczęsna, M., Szindler, M., and Drygała, A., 2013. Electrical properties mono-and polycrystalline silicon solar cells. solar cells, 59(2), 67-74.

Dutta, T., 2014. Global Maximum Power Point Tracking (MPPT) technique in a solar photovoltaic array under partially shaded condition (Doctoral dissertation).

Elgharbi, A., Mezghani, D., and Mami, A., 2012. A maximum power point tracking method based on artificial neural network for a pv system. International Journal of Advances in Engineering & Technology, 5(1), 130.

El-Helw, H. M., Magdy, A., and Marei, M. I., 2017. A hybrid maximum power point tracking technique for partially shaded photovoltaic arrays. IEEE access, 5, 11900-11908.

Essefi, R. M., Souissi, M., and Abdallah, H. H., 2014. Maximum power point tracking control using neural networks for stand-alone photovoltaic systems. International Journal of Modern Nonlinear Theory and Application, 3(03), 53.

Esram, T., and Chapman, P. L., 2007. Comparison of photovoltaic array maximum power point tracking techniques. IEEE Transactions on energy conversion, 22(2), 439-449.

Francis, W. K., Shanifa, B. S., & Mathew, P. J. (2014). MATLAB/Simulink PV Module Model of P & O and DC Link CDC MPPT Algorithms with Labview Real Time Monitoring and Control Over P & O Technique. Int. J. Adv. Res. Electr. Electron. Instrum. Eng, 5, 92-101.

Ferdous, S. M., Mohammad, M. A., Nasrullah, F., Saleque, A. M., and Muttalib, A. S., 2012. Design and simulation of an open voltage algorithm based maximum power point tracker for battery charging PV system. In 2012 7th International Conference on Electrical and Computer Engineering (pp. 908-911). IEEE.

Gilbert, M., 1998. Renewable and Efficient Electric Power Systems.Wiley Online Library.

Husain, M. A., Tariq, A., Hameed, S., Arif, M. S. B., and Jain, A., 2017. Comparative assessment of maximum power point tracking procedures for photovoltaic systems. Green Energy & Environment, 2(1), 5-17.

Ishaque, K., and Salam, Z., 2013. A review of maximum power point tracking techniques of PV system for uniform insolation and partial shading condition. Renewable and Sustainable Energy Reviews, 19, 475-488.

Jiang, L., and Maskell, D. L., 2014. A simple hybrid MPPT technique for photovoltaic systems under rapidly changing partial shading conditions.

In 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC) (pp. 0782-0787). IEEE.

Jain, S., and Agarwal, V., 2004. A new algorithm for rapid tracking of approximate maximum power point in photovoltaic systems. IEEE power electronics letters, 2(1), 16-19.

Ji, Y. H., Jung, D. Y., Kim, J. G., Kim, J. H., Lee, T. W., and Won, C. Y., 2010. A real maximum power point tracking method for mismatching compensation in PV array under partially shaded conditions. IEEE Transactions on power electronics, 26(4), 1001-1009.

Jones, G. G., & Bouamane, L., 2012. " Power from Sunshine": A Business History of Solar Energy. Harvard Business School Working Paper Series.

Kabir, E., Kumar, P., Kumar, S., Adelodun, A. A., and Kim, K. H., 2018. Solar energy: Potential and future prospects. Renewable and Sustainable Energy Reviews, 82, 894-900.

Karami, N., Moubayed, N., and Outbib, R., 2017. General review and classification of different MPPT Techniques. Renewable and Sustainable Energy Reviews, 68, 1-18.

Kotak, V. C., and Tyagi, P., 2013. DC to DC Converter in maximum power point tracker. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, 2(12), 6115-6125.Kundu, S., Gupta, N., and Kumar, P., 2016, November. Review of solar photovoltaic maximum power point tracking techniques. In Power Electronics (IICPE), 2016 7th India International Conference on (pp. 1-6). IEEE.

Lippmann, R. P., 1987. An introduction to computing with neural nets. IEEE ASSP magazine, 4(2), 4-22.

Jiang, L. L., Nayanasiri, D. R., Maskell, D. L., and Vilathgamuwa, D. M., 2015. A hybrid maximum power point tracking for partially shaded photovoltaic systems in the tropics. Renewable Energy, 76, 53-65.

Lynn, P. A., 2010. Electricity From Sunlight. John Wiley

Mahammad, A. K., Saon, S., and Chee, W. S., 2013. Development of optimum controller based on MPPT for photovoltaic system during shading condition. Procedia Engineering, 53, 337-346.

Massawe, H. B., 2013. Grid Connected Photovoltaic Systems with SmartGrid functionality (Master's thesis, Institutt for elkraftteknikk).

Mamatha, G., 2015. Perturb and observe MPPT algorithm implementation for PV applications. International Journal of Computer Science and Information Technologies, 6(2), 1884-1887.

Messalti, S., Harrag, A., and Loukriz, A., 2017. A new variable step size neural networks MPPT controller: Review, simulation and hardware implementation. Renewable and Sustainable Energy Reviews, 68, 221-233.

Moradi, M. H., Tousi, S. R., Nemati, M., Basir, N. S., and Shalavi, N., 2013. A robust hybrid method for maximum power point tracking in photovoltaic systems. Solar Energy, 94, 266-276.

Murtaza, A., Chiaberge, M., De Giuseppe, M., and Boero, D., 2014. A duty cycle optimization-based hybrid maximum power point tracking technique for photovoltaic systems. International Journal of Electrical Power & Energy Systems, 59, 141-154.

Nasir, F. H., and Husaini, Y., 2018, March. MATLAB Simulation of Photovoltaic and Photovoltaic/Thermal Systems Performance. In IOP Conference Series: Materials Science and Engineering (Vol. 341, p. 012019).

Neupane, S., and Kumar, A., 2017. Modeling and Simulation of PV array in Matlab/Simulink for comparison of perturb and observe & incremental conductance algorithms using buck converter. International Research Journal of Engineering and Technology (IRJET), 4(7), 2479-2486.

Nguyen, X. H., 2015. Matlab/Simulink based modeling to study effect of partial shadow on solar photovoltaic array. Environmental Systems Research, 4(1), 20.

Nigam, A., and Sharma, A. K. G. S., 2016. Simulation of modified P&O MPPT technique for solar PV cell using MATLAB/SIMULINK. International Research Journal of Engineering & Technology, 3(4).

Parida, B., Iniyan, S., and Goic, R., 2011. A review of solar photovoltaic technologies. Renewable and sustainable energy reviews, 15(3), 1625-1636.

Pallavee Bhatnagar, A., & Nema, B. R. K., 2013. Conventional and global maximum power point tracking techniques in photovoltaic applications: A review. Journal of Renewable and Sustainable Energy, 5(3), 032701.

Patel, U., Sahu, M. D., and Tirkey, D., 2013. Maximum power point tracking using perturb & observe algorithm and compare with another algorithm. International Journal of Digital Application & Contemporary research, 2(2).

Pradhan, A., and Panda, B., 2018. A simplified design and modeling of boost converter for photovoltaic sytem. International Journal of Electrical and Computer Engineering, 8(1), 141.

Putri, R. I., Wibowo, S., and Rifa'i, M., 2015. Maximum power point tracking for photovoltaic using incremental conductance method. Energy Procedia, 68, 22-30.

Rabi, B. R. M., and Kanimozhi, K., 2016. Development of Hybrid MPPT Algorithm under Partial Shading Conditions for Low Power Applications. Journal of Electrical Engineering.

Rasool, F. K., and Samaneh, P., 2013. Photovoltaic device modeling and effect of its parameters. Research Journal of Recent Sciences.

Reisi, A. R., Moradi, M. H., & Jamasb, S., 2013. Classification and comparison of maximum power point tracking techniques for photovoltaic system: A review. Renewable and sustainable energy reviews, 19, 433-443.

Rezk, H., and Eltamaly, A. M., 2015. A comprehensive comparison of different MPPT techniques for photovoltaic systems. Solar energy, 112, 1-11.

Roy, S., Sharmin, R. S., and Ferdous, T., 2014. Performance analysis of mono-crystalline and poly-crystalline silicon solar cells under different climatic conditions: a comparative study (Doctoral dissertation, BRAC University).

Roncero-Clemente, C., Husev, O., Minambres-Marcos, V., Romero-Cadaval, E., Stepenko, S., and Vinnikov, D., 2013. Tracking of MPP for three-level neutral-point-clamped qZ-source off-grid inverter in solar applications. Journal of Microelectronics, Electronic Components and Materials, 43(4), 212-221.

Satyendra, V., 2017. Study of Partial shading effect on Solar Module Using MATLAB. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE), 2(7), 5303-5308.

Sampaio, P. G. V., and González, M. O. A., 2017. Photovoltaic solar energy: Conceptual framework. Renewable and Sustainable Energy Reviews, 74, 590-601.

Saadsaoud, M., 2016. Study of partial shading effects on photovoltaic arrays with comprehensive simulator for global MPPT control. International Journal of Renewable Energy Research (IJRER), 6(2), 413-420.

Saibabu, T. C. C., and Kumari, J. S., 2011. Modeling and simulation of PV array and its performance enhancement using MPPT (P&O) technique. Int. J. Comput. Sci. Commun. Netw, 1(1), 9-16.

Seyedmahmoudian, M., Mekhilef, S., Rahmani, R., Yusof, R., and Asghar Shojaei, A., 2014. Maximum power point tracking of partial shaded photovoltaic array using an evolutionary algorithm: A particle swarm optimization technique. Journal of Renewable and Sustainable Energy, 6(2), 023102.

Sharma, D. K., and Purohit, G., 2014. Maximum Power Angle (MPA) Based Maximum Power Point Tracking (MPPT) Technique for Efficiency Optimization of Solar PV System. International Journal of Renewable Energy Research (IJRER), 4(3), 810-815.

Shiau, J. K., Wei, Y. C., and Chen, B. C., 2015. A study on the fuzzy-logic-based solar power MPPT algorithms using different fuzzy input variables. Algorithms, 8(2), 100-127.

Sivaraman, p., and Sakthi, J. S., 2018. Performance Enhancement of Solar PV System under Partial Shading Environment. International Journal of Engineering and Advanced Technology (IJEAT), 8 (25).

Sivachandran, P., Lakshmi, D., and Janani, R., 2015. Survey of maximum power point tracking techniques in solar pv system under partial shading conditions. ARPN Journal of Engineering and Applied Sciences, 10(1), 256-264.

Subudhi, B., & Pradhan, R., 2012. A comparative study on maximum power point tracking techniques for photovoltaic power systems. IEEE transactions on Sustainable Energy, 4(1), 89-98.

Texas Instrument, (TI) SM74611 Smart Bypass Diode, 2012. Available https://www.ti.com/lit/ds/symlink/sm74611.pdf.

Texas Instrument, (TI) Basic Calculation of a Boost Converter's Power Stage, 2014. Available at http://www.ti.com/lit/an/slva372c/slva372c.pdf.

Veligorskyi, O., Chakirov, R., and Vagapov, Y., 2015. Artificial neural network-based maximum power point tracker for the photovoltaic application. In 2015 1st International Conference on Industrial Networks and Intelligent Systems (INISCom) (pp. 133-138). IEEE.

Veerachary, M., and Yadaiah, N., 2000. ANN based peak power tracking for PV supplied DC motors. Solar Energy, 69(4), 343-350.

Villalva, M. G., Gazoli, J. R., and Ruppert Filho, E., 2009. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Transactions on power electronics, 24(5), 1198-1208.

Yang, C. Y., Hsieh, C. Y., Feng, F. K., and Chen, K. H., 2012. Highly efficient analog maximum power point tracking (AMPPT) in a photovoltaic system. IEEE Transactions on Circuits and Systems I: Regular Papers, 59(7), 1546-1556.

Ziar, H., Mansourpour, S., Afjei, E., and Kazemi, M., 2012. Bypass diode characteristic effect on the behavior of solar PV array at shadow condition. In 2012 3rd Power Electronics and Drive Systems Technology (PEDSTC) (pp. 229-233). IEEE.

## CURRICULUM VITAE

Born on 07-11-1990 in Kirkuk, Iraq. Completed secondary school in 2008. received BSc degree in Electrical and Electronics Engineering from Kirkuk University in 2012. In 2018 she started her MSc education in Electrical and Electronics Engineering in Çukurova University.