M.S. AHMAD

COMPARATIVE ANALYSIS OF MPPT TECHNIQUES FOR SOLAR AND WIND SYSTEMS UNDER DIFFERENT OPERATING CONDITIONS

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
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MUHAMMAD SAEED AHMAD

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Approval of the Graduate School of Natural and Applied Sciences, Atilim University.

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Prof. Dr. Ender KESKİNKILIÇ
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I certify that this thesis satisfies all the requirements as a thesis for the degree of **Master of Science in Electrical and Electronics Engineering Atilim University.**

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This is to certify that we have read the thesis " COMPARATIVE ANALYSIS OF MPPT TECHNIQUES FOR SOLAR AND WIND SYSTEMS UNDER DIFFERENT OPERATING CONDITIONS” and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

COMPARATIVE ANALYSIS OF MPPT TECHNIQUES FOR SOLAR AND WIND SYSTEMS UNDER DIFFERENT OPERATING CONDITIONS

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Renewable energy technologies have gained a lot of traction in the last few decades as a means of reducing reliance on fossil fuels and mitigating the impact of climate change. Renewable sources such as sunlight, wind, and water are clean and sustainable. These technologies have gained significant attention in recent years. While renewable energy technologies have many advantages, one of the main challenges is their relatively low efficiency compared to fossil fuels. As a result, renewable energy systems typically require more land and resources to produce the same amount of energy as fossil fuel-based systems.

Additionally, the efficiency of renewable energy systems can vary depending on the weather and other environmental conditions. For example, solar panels are less effective on cloudy days and wind turbines are less effective in calm weather. This can make it difficult to predict and control the amount of energy that renewable systems will produce, which can create challenges for integrating them into the grid.

The problem with efficiency can be dealt with the use of maximum power point tracking (MPPT) techniques. These techniques are used to optimize the performance of renewable energy systems by ensuring that they operate at the maximum power point, or the point at which they can generate the most power. There are several types of maximum power point tracking (MPPT) techniques, but they can be broadly classified into three categories: simple, artificial intelligence (AI), and hybrid.

Simple MPPT techniques such as PO and IC are the most basic and widely used type of MPPT. These techniques use relatively simple algorithms to continuously adjust the operating conditions of the system to maintain the maximum power point.

AI-based MPPT techniques like PSO and ANN use advanced algorithms and machine learning techniques to optimize the performance of renewable energy systems. These techniques can adapt to changing environmental conditions and can continuously adjust the operating conditions of the system in real-time.

Hybrid MPPT techniques like ANFIS and PSO&PO are a combination of simple and AI-based techniques. These techniques use simple algorithms to quickly track the maximum power point, and then use AI-based techniques to fine-tune the operating conditions of the system in real-time.

A comparative analysis of simple, AI, ML, and hybrid MPPT techniques for hybrid energy (Solar and Wind) systems is discussed in this thesis. The MPPT algorithms were ranked based on different metrics such as efficiency, settling time, oscillations at MPPT and algorithm complexity. For PV system, AI based techniques performed best as compared to Hybrid and conventional techniques. For Wind system, hybrid techniques yield the best results as they combine the benefits of conventional and AI techniques.

Keywords: Maximum power point tracking, Efficiency, Renewable Energy, Solar and Wind Energy

ÖZ

FARKLI ÇALIŞMA KOŞULLARI ALTINDA GÜNEŞ VE RÜZGAR SİSTEMLERİ İÇİN MPPT TEKNİKLERİNİN KARŞILAŞTIRMALI ANALİZİ

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Yenilenebilir enerji teknolojileri, fosil yakıtlara güvenin azalması, iklim değişimlerinin etkisini azaltması gibi sebeplerden dolayı son birkaç 10 yıldır önem kazanmıştır. Güneş, rüzgar ve su gibi yenilenebilir kaynaklar temiz ve sürdürülebilirdir. Bu teknolojiler son yıllarda önemli derecede dikkatleri üzerine çekmiştir. Yenilenebilir enerji teknolojileri birçok avantajlara sahip olmalarına rağmen fosil yakıtlarına göre oldukça düşük verimlere sahip olmaları önemli bir dezavantajdır. Sonuç olarak, yenilenebilir enerji sistemleri, fosil-yakıt temelli sistemlerin ürettiği miktardaki bir enerjiyi üretmek için daha fazla yere ve kaynağa ihtiyaç duyarlar.

İlave olarak, yenilenebilir enerji sistemlerinin verimi hava ve diğer çevresel koşullara bağlı olarak değişebilir. Örnek olarak, güneş panelleri bulutlu günlerde daha az etkiliyken rüzgar türbinleri de sakin (rüzgarsız) havada daha az etkilidir. Bu durumlar yenilenebilir enerji sistemlerinin üreteceği enerji miktarını tahmin ve kontrol etmeyi zorlaştırabilir. Bu durum yenilenebilir enerji sistemlerinin şebekeye entegrasyonunu zorlaştırabilecektir.

Maksimum güç noktası takip (MPPT) tekniklerinin kullanılmasıyla verimle ilgili problemlerin üstesinden gelinebilir. Bu teknikler, maksimum güç noktasında veya en çok gücü üreteceği noktada çalışmayı sağlayarak yenilenebilir enerji sistemlerinin

performansını optimize etmek için kullanılır. Birkaç çeşit maksimum güç noktası izleme (MPPT) tekniği vardır, fakat genel olarak üç kategoride sınıflandırılırlar. : Basit, Yapay zeka (AI) ve hibrit.

PO ve IC gibi basit MPPT teknikleri en temel olanlardır ve MPPT'de oldukça fazla kullanılır. Bu teknikler, maksimum güç noktasını sağlamada sistemin çalışma koşullarını sürekli olarak ayarlamak için oldukça basit algoritmalar kullanırlar.

PSO ve ANN gibi AI-temelli MPPT teknikleri, yenilenebilir enerji sistemlerinin performansını optimize etmek için ileri algoritmalar ve makine öğrenme teknikleri kullanır. Bu teknikler çevresel koşulların değişimine kendilerini uyarlayabilir ve gerçek zamanda sistemin çalışma koşullarını sürekli olarak ayarlayabilirler.

ANFIS ve PSO&PO gibi hibrit MPPT teknikleri, basit ve AI-temelli tekniklerinin bir birleşimidir. Bu teknikler maksimum güç noktasını hızlıca takip etmek için basit algoritmalar kullanır ve daha sonra gerçek zamanda sistemin çalışma koşullarının ince ayarı için AI-temelli teknikler kullanırlar.

Hibrit enerji (güneş ve rüzgar) sistemleri için basit, AI, ML ve hibrit MPPT tekniklerinin karşılaştırmalı analizi bu tezde sunulmuştur. MPPT algoritmaları, verim, yerleşme zamanı, MPPT noktasında salınım ve algoritma karmaşıklığı gibi farklı metriklere dayanan verilere göre sıralanmıştır. PV sistem için, hibrit ve konvansiyonel tekniklere göre AI-temelli teknikler en iyi performansı göstermiştir. Rüzgar sistemi için ise, konvansiyonel ve AI tekniklerinin faydalarını birleştiren hibrit teknikler en iyi sonucu göstermiştir.

Anahtar Kelimeler: Maksimum güç noktası takibi, Verim, Yenilenebilir enerji, Yapay zeka, Güneş ve Rüzgar enerjisi.

To My Parents, Family, and Friends

you will always be my source of strength.

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LIST OF ABBREVIATIONS

MPPT	Maximum Power Point Tracking
AI	Artificial Intelligence
ML	Machine Learning
P&O	Perturb and Observe
IC	Incremental Conductance
PSO	Particle Swarm Optimization
ANN	Artificial Neural Network
ANFIS	Adaptive Neuro Fuzzy Inference System
PID	Proportional Integral Derivative
MPP	Maximum Power Point
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine

CHAPTER 1

INTRODUCTION

Energy consumption is increasing constantly and with that the energy sources such as fossil fuels are depleting. One way to tackle this the growing consumption is by using renewable energy sources such as solar and wind energy. Conventional energy sources are exhaustible and affect the global environment and climate. On the other hand, renewable energy sources are clean, inexhaustible, and environmentally friendly. Due to this reason along with many other, the interest in renewable energy sources has been increasing rapidly over the last few years.

One challenge of renewable energy sources is their efficiency, which refers to the amount of energy that is converted into usable electricity. The efficiency of renewable energy sources can vary significantly and is often lower than that of fossil fuels.

For example, solar panels have an average efficiency of around 15-20%, which means that only 15-20% of the energy from the sun that they absorb is converted into electricity. The efficiency of wind turbines is also relatively low, typically ranging from 30-45% [3]. In comparison, fossil fuel power plants, such as coal and natural gas, have efficiencies of around 40-60%.

There are several factors that can impact the efficiency of renewable energy sources. For example, the efficiency of solar panels can be affected by the angle at which they are installed, the amount of dust and debris on their surface, and the temperature of the environment in which they are operating. Similarly, the efficiency of wind turbines can be affected by the strength and consistency of the wind, as well as the size and design of the turbines.

Also at nighttime, the solar panel does not provide any power and at times with zero or low wind speed the power from wind turbine is also negligible. Considering that, it is very hard to provide reliable power supply by just using Solar or Wind system. This can be improved by using a hybrid system which consists of both solar and wind sources. The hybrid system can be used with or without a battery backup. According to previous research [1- 2], using hybrid energy system along with battery backup is more efficient and energy effective.

To overcome the low efficiency issue, a control system is used. The control system consists of a maximum power point tracking-based on DC-DC converter. This control system makes sure that both solar and wind systems are always operating at maximum power.

Traditional, AI, ML and hybrid algorithms are applied using DC-DC boost converter. Several parameters such as output power at different conditions, settling time, MPP accuracy and steady state oscillations are measured for each MPPT to find out the best and most compatible algorithm for the system.

1.1. Primary research objective

- A comparative study of conventional, hybrid, artificial intelligence and machine learning based MPPT algorithms
- Performance analysis of MPPT techniques based on different metrics such as efficiency, speed, complexity, time and accuracy.
- Battery backed energy management system
- Creating an adaptive Hybrid MPPT for Solar and Wind that can perform efficiently under all operating conditions

CHAPTER 2

LITERATURE REVIEW

The literature review section is divided into 5 main parts.

1. Energy Source – Wind and Sun
2. DC-DC boost converter
3. MPPT algorithms
4. Battery storage system
5. Load side control

In the sections below each part is discussed in detail.

2.1. Solar Energy

Solar energy is a form of renewable energy that is generated by converting sunlight into electricity using photovoltaic cells or concentrated solar power. Solar panels, which are made up of photovoltaic cells, are used to convert sunlight into electricity. Solar energy has many benefits. It is a clean and renewable energy source that does not produce greenhouse gases or other pollutants. It can also help to reduce reliance on fossil fuels, which are a limited resource.

Solar panels have an average efficiency of 15%-20% and several other factors can further reduce their efficiency such as dust, shading, panel quality, and panel temperature. There are some methods to increase the solar efficiency including Sun tracking. In the sun tracking method, the panel follows the sun as it moves across the sky, ensuring that the panels are always facing directly at the sun.

Using a reflective surface can also increase solar panel efficiency. In this method a reflective surface is placed under the solar panel that can help increase the amount of sunlight that is absorbed by the panel.

2.2. Wind Energy

Wind energy is a form of renewable energy that is generated by using the wind to turn turbines, which results in generating electricity. The efficiency of a wind energy system is typically measured by its capacity factor, which is the amount of electricity that the system generates compared to its maximum potential output. The capacity factor of a wind energy system can vary depending on the location, wind speed, and other factors. In general, wind energy systems have a capacity factor of around 30-40%.

Wind energy is a clean energy source, and it does not produce greenhouse gases or other pollutants. Also, it is widely available and reduces reliance on fossil fuels.

The main types of wind turbines are Horizontal axis wind turbines (HAWT) and Vertical axis wind turbines (VAWT). HAWTs are the most common type of wind turbine and are characterized by their three blades that are mounted on a horizontal axis. The rotor of a HAWT is mounted on a tower and faces into the wind. VAWTs are characterized by their vertical axis of rotation. The rotor of a VAWT is mounted on a tower and faces into the wind.

2.3. Boost Converter

A boost converter is a type of DC-to-DC converter that is used to increase the voltage of a DC power source. It works by using an inductor to store energy and a switch (usually a MOSFET) to control the flow of current. The switch is turned on and off at a high frequency, and the inductor stores energy during the on-time and releases it during the off-time. This results in an increase in the voltage at the output of the converter. Figure 2.1 shows the configuration of the boost converter [5].

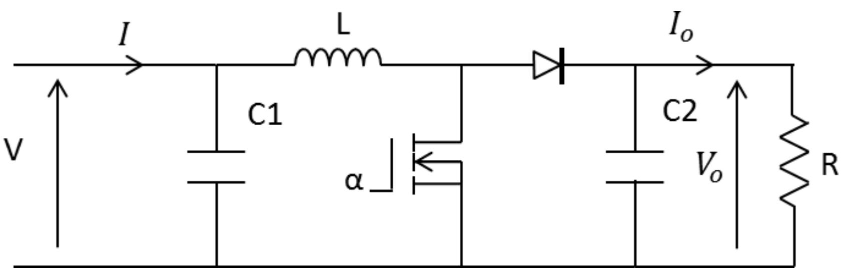

Figure 2.1: Boost converter diagram [5]

The boost converter consists of four main components: An input capacitor C1, an inductor L, a switch, and an output capacitor C2. The basic equation of a boost converter is given in Eq[2.1]. [5]

$$\frac{Vo}{Vin} = \frac{1}{1-D} \tag{2.1}$$

Where Vo is the output power, V_{in} is the input power and D is the duty cycle. The boost converter operates in two modes: Continuous conduction mode (CCM) and discontinuous conduction mode (DCM). In CCM, the inductor current never stays at zero, and the switches always conduct. In DCM, the inductor current reaches zero at some point during each switching cycle, and the switch does not always conduct[4].

2.4. Maximum Power Point Tracking

MPPT techniques are crucial for maximizing the efficiency and effectiveness of renewable energy systems. Overall, the use of renewable energy technologies and MPPT techniques is an important step in the transition towards a more sustainable and equitable energy future. By increasing the efficiency and effectiveness of renewable energy systems, these technologies can help to reduce greenhouse gas emissions, improve air quality, and provide clean and reliable energy for communities around the world.

MPPT allows renewable energy systems to operate more consistently and predictably. By maintaining the system at the maximum power point, MPPT helps to minimize fluctuations in output and ensure that the system produces a steady flow of electricity. This is important for integrating renewable energy into the grid, as it helps to ensure that there is a stable and reliable source of clean energy available.

Multiple maximum power point tracking (MPPT) techniques are available to optimize the performance of renewable energy systems. These techniques can be categorized as: Simple, artificial intelligence (AI), and hybrid.

Simple MPPT techniques are designed to be easy to implement and require minimal hardware and software resources. These techniques may not be as accurate or adaptable as more complex MPPT algorithms but can be a good option for small-scale renewable energy systems or for applications where cost and complexity are a concern.

One example of a simple MPPT technique is the fixed switching frequency MPPT algorithm, which uses a fixed switching frequency to control the output power of the renewable energy system. This technique is simple to implement but may not be as accurate as other MPPT algorithms, particularly under changing conditions.

AI-based MPPT techniques use advanced algorithms to track MPP. These techniques can be more accurate and adaptable than traditional MPPT algorithms, as they are able to learn and adapt to changing conditions.

One example of an AI MPPT technique is the fuzzy logic MPPT algorithm, which uses fuzzy logic principles to determine the maximum power point. Fuzzy logic is a type of AI that allows for the representation of uncertainty and imprecision in a system. In the context of MPPT, fuzzy logic can be used to adjust the voltage of the renewable energy system based on the uncertainty in the power-voltage curve.

Hybrid MPPT techniques are a combination of simple and AI-based techniques such as neural networks and genetic algorithms.

One of the main advantages of AI-based MPPT techniques is their ability to adapt to rapidly changing conditions. [22] Traditional MPPT techniques, such as perturb and observe and incremental conductance, are effective at tracking the maximum power point, but they may not be able to respond quickly to changes in the environment. AI-based

MPPT techniques, on the other hand, can continuously monitor the performance of the system and make rapid adjustments to maintain the maximum power point. By combining the benefits of simple and AI-based MPPT techniques, hybrid MPPT techniques can help increase the efficiency and reliability of renewable energy systems, making them more competitive with fossil fuels and supporting the transition towards a more sustainable and equitable energy future.

2.5. MPPT Techniques

The MPPT techniques used in the comparative study are given in Fig 2.2.

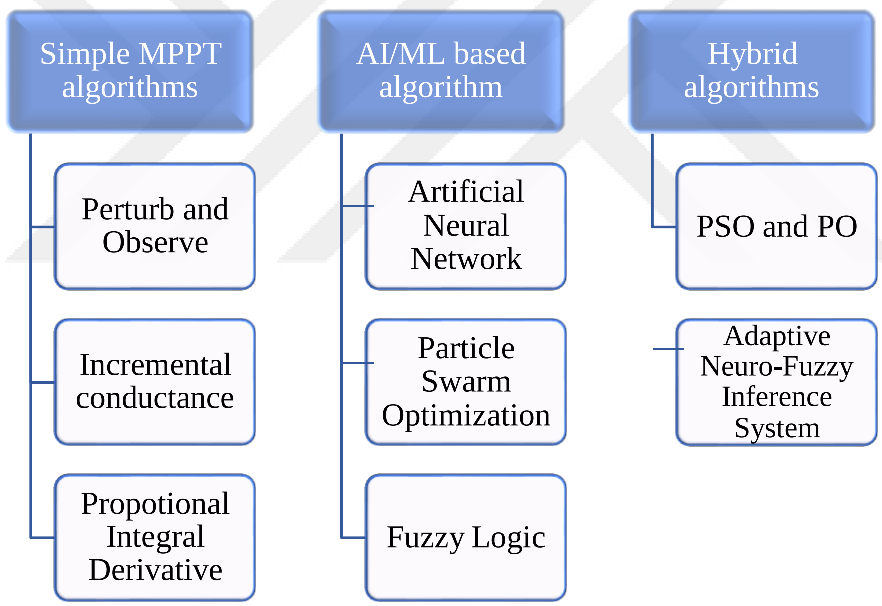

Figure 2.2: MPPT categories

2.5.1. Perturb and Observe Method

The perturb and observe (P&O) is a traditional MPPT technique. The P&O algorithm works by periodically perturbing the duty cycle of the inverter and observing the change at the output power. If the change at the output power is positive, the duty cycle is increased; if the change is negative, the duty cycle is decreased [7]. This process is repeated until the output power is maximized. The flow chat in Fig 2.3 shows the operation of PO method [6].

The P&O algorithm is simple and easy to implement and does not require any special hardware or sensors. However, the P&O algorithm has some limitations. It is not as accurate as other algorithms and can produce oscillations at the output power. It is also sensitive to the load on the system and may not work well with nonlinear loads.

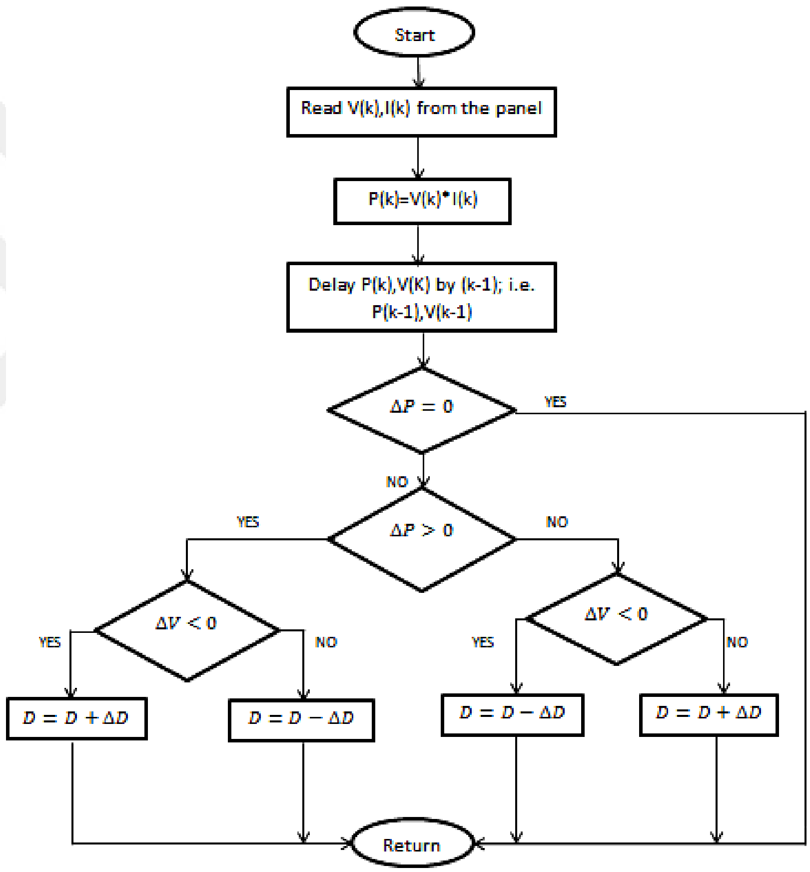

Figure 2.3: PO algorithm flowchart [6]

2.5.2. Incremental Conductance

Incremental conductance is another traditional MPPT method. The IC MPPT algorithm operates by continuously measuring the current and voltage of the PV cells and calculating the output power. The algorithm then adjusts the duty cycle of the inverter to maximize the output power. It does this by calculating the incremental conductance, which is the derivative of the power curve with respect to the voltage. The incremental conductance is used to predict the change in the output power for a given change in the voltage. Fig. 2.4 shows the operation of IC algorithm [8].

The IC algorithm is slightly more accurate than PO method and produces less oscillations at the output. However, it requires more computational resources and may not be suitable for small-scale PV systems.

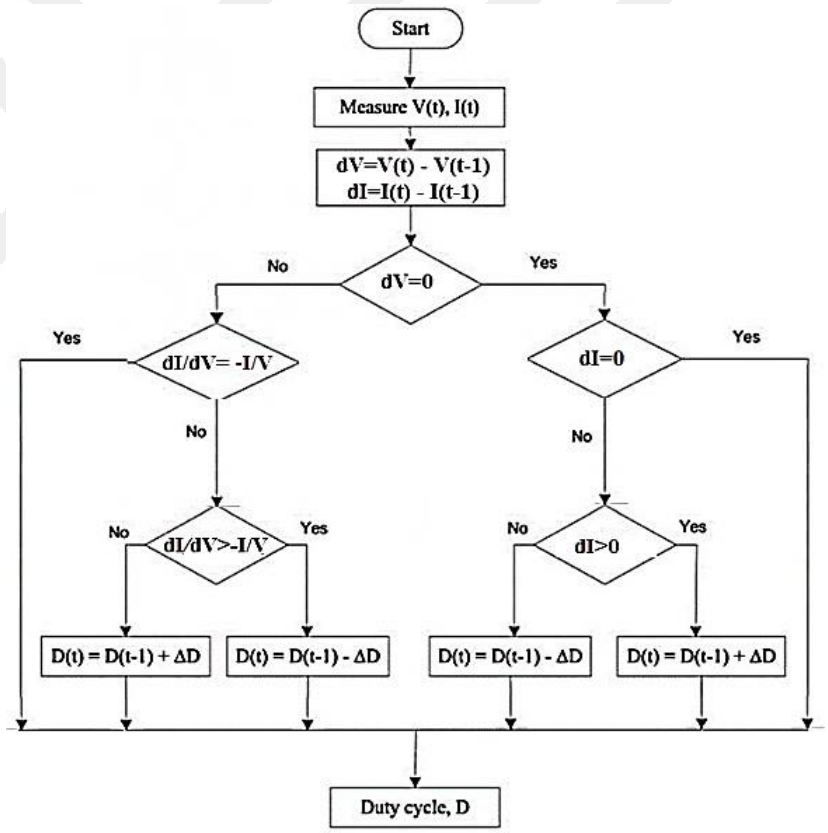

Figure 2.4: Incremental Conductance flowchart [8]

2.5.3. Fuzzy Logic Method

Fuzzy logic is an AI based MPPT technique. The use of the FL method has increased rapidly in the last few years due to its efficiency and simplicity. Fuzzy logic MPPT can handle nonlinear conditions to obtain MPP from the solar or wind source. Another benefit of fuzzy logic-based system is that it does not need any accurate mathematical model for the controller, and it can find MPP under any value of wind speed, solar irradiation, and temperature.

There are four stages involved in Fuzzy logic method [9-10].

- Data collection: The system gathers data on the voltage and current output of the PV panels.
- Fuzzification: The data is "fuzzified" by assigning membership values to each input variable based on their relationship to predetermined membership functions.
- Inference: The fuzzy rules are applied to the fuzzified input data to determine the appropriate control action.
- Defuzzification: The output of the inference stage is "defuzzied" to a crisp value that can be used to control the system.

The use of fuzzy logic in MPPT allows more precise control of the operating point and better utilization of the available solar energy, resulting in increased efficiency of the PV and wind systems. The operation of FL MPPT is shown in Fig.2.5.

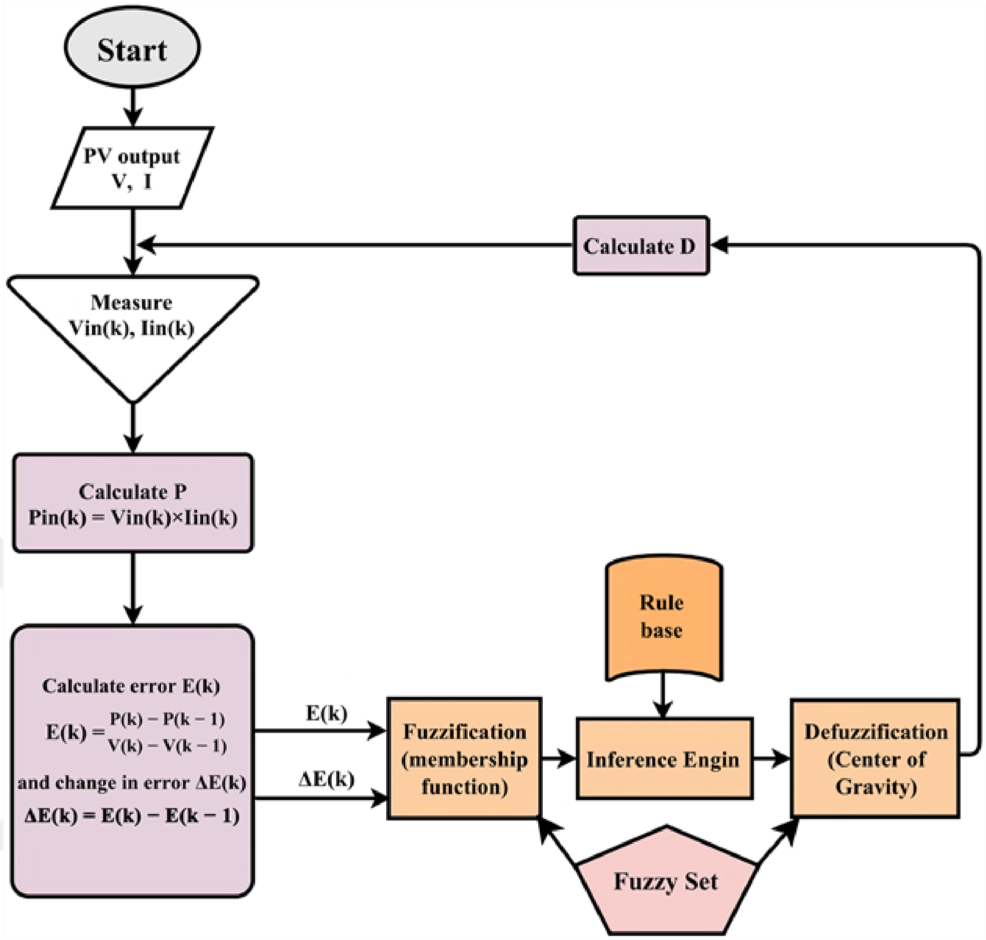

Figure 2.5: Fuzzy logic MPPT flow chart [23]

2.5.4. Artificial Neural Network

Artificial neural networks (ANNs) are computational models inspired by the structure and function of the human brain. ANNs can be used in MPPT by training them to recognize patterns in the voltage and current output of the wind and PV panels and predict the appropriate control action to take in order to maximize output power. This can be done using a supervised learning approach, in which the ANN is trained on a dataset of input-output pairs that represent different operating points and control actions [12].

Figure 2.6 shows the operation of ANN algorithm [11].

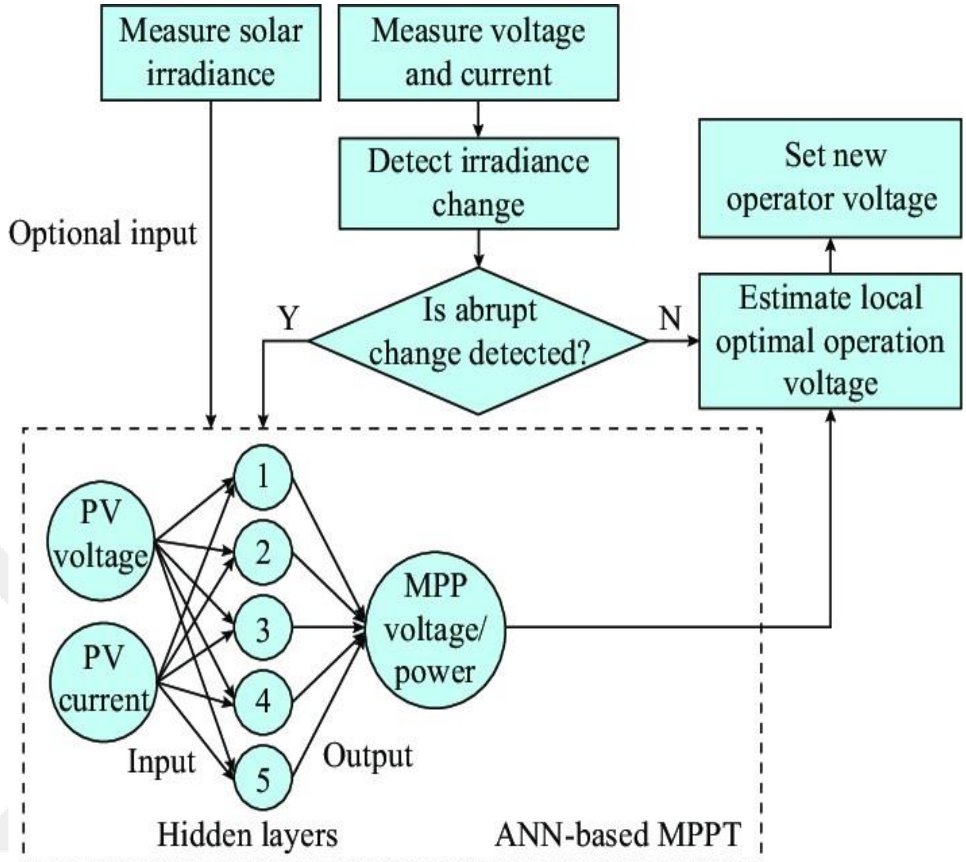

Figure 2.6: ANN algorithm working [11]

The use of ANNs in MPPT can result in increased efficiency of PV systems, as they allow for more precise control of the operating point and better utilization of the available wind and solar energies. However, ANNs can be more complex and computationally intensive to implement than other control algorithms, such as fuzzy logic, PO, and IC.

2.5.5. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a heuristic optimization algorithm that is inspired by the social behavior of animals such as birds and ants. In the PSO method a swarm of particles are initialized, where each particle represents a potential operating point for the PV panel or array. The operating point is represented by a set of variables such as voltage and current, and each particle has a corresponding position in the search space. The output power of the PV panel or array for each particle's position is measured and the best particle in this case the best voltage/current value is selected [13-14].

PSO is a computationally efficient algorithm that can quickly find the global optimum of a non-linear optimization problem, and it has been shown to be effective for MPPT in PV systems. Fig.2.7 shows the flowchart of PSO algorithm for a PV system [24].

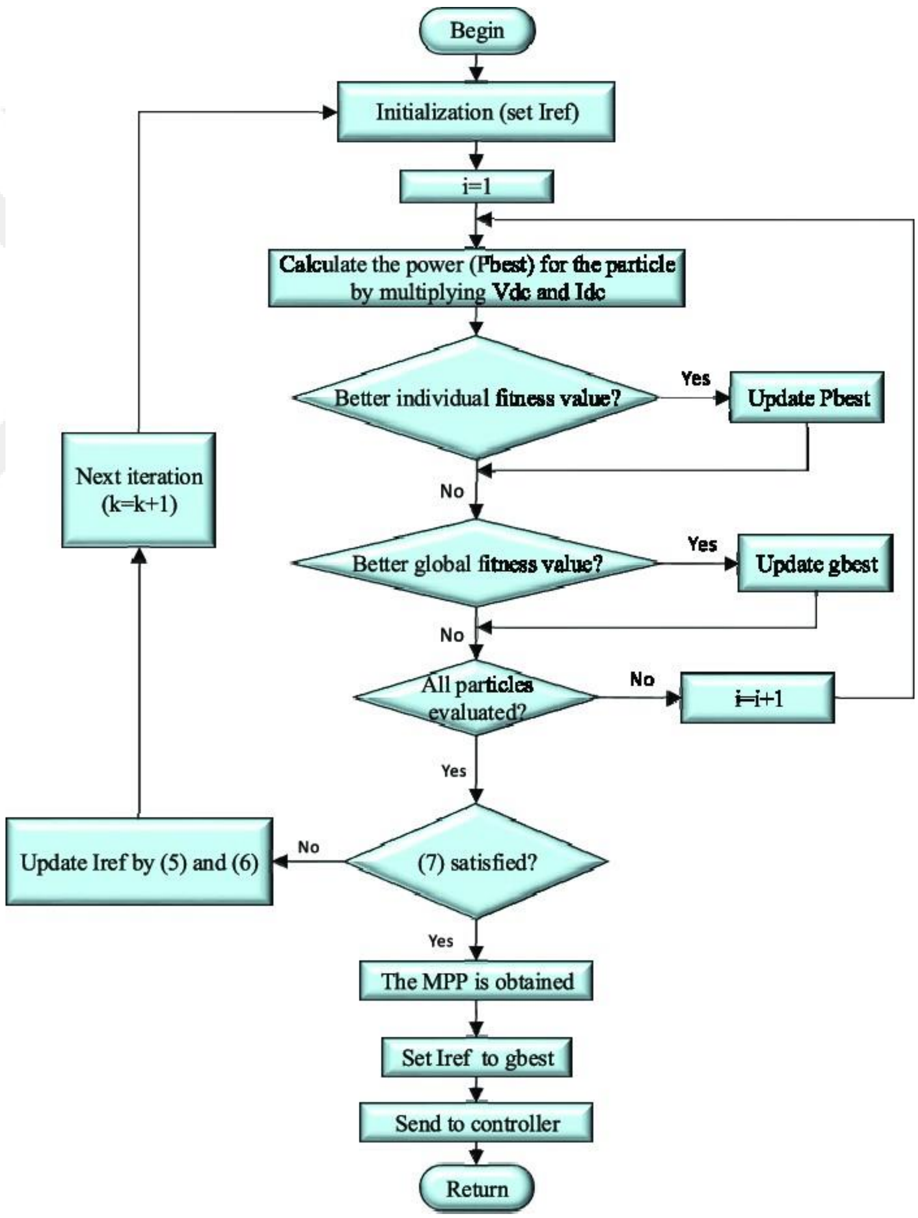

Figure 2.7: PSO algorithm flowchart [24]

2.5.6. Proportional-Integral-Derivative

Proportional-Integral-Derivative (PID) control is a type of feedback control algorithm that is commonly used to control systems with dynamic behavior. The PV panel or wind turbine is connected to a DC-DC converter, which adjusts the voltage and current of the PV panel's output to match the voltage and current requirements of the load. The controller continuously measures the voltage and current of the PV panel's output and calculates the power.

The controller compares the current output power with the desired output power, which is set to the maximum power point (MPP) of the PV panel or wind turbine. The difference between the current output power and the desired output power is known as the error. The microcontroller adjusts the DC-DC converter's duty cycle based on the error until MPP is achieved [15].

It is important to properly tune the PID parameters to achieve good performance. PID MPPT is a more complex algorithm than some other MPPT methods, but it has the advantage of being able to accurately track the MPP and maintain stable operation even in the presence of rapid changes in environmental conditions or load.

2.5.7. Adaptive Neuro-Fuzzy Inference System (ANFIS)

Adaptive Neuro-Fuzzy Inference System (ANFIS) is a type of fuzzy logic system that combines the learning capabilities of neural networks with the interpretability and flexibility of fuzzy logic. ANFIS can be used for a variety of control and optimization tasks, including Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems.

The ANFIS algorithm consists of a set of fuzzy rules that define the relationship between the input variables like voltage and current and the output variable which is the duty cycle of the DC-DC converter. The ANFIS algorithm uses a training process to optimize the parameters of the fuzzy rules and the membership functions. Once the ANFIS model has been trained, it can be used to predict the duty cycle of the DC-DC converter for a given set of input values (voltage and current). The predicted duty cycle is then used to control the DC-DC converter and adjust the operating point of the PV panel or array. This process of measuring, calculating, and adjusting is repeated continuously to ensure that the PV panel or array is always operating at the maximum power point [16].

The performance of the ANFIS model may depend on the quality of the training data and the choice of hyperparameters such as the number of fuzzy rules and the learning rate [17].

2.5.8. Hybrid MPPT method - PSO & PO

A hybrid algorithm combining P&O MPPT with PSO could potentially take advantage of the simplicity and robustness of P&O MPPT, while also incorporating the optimization capabilities of PSO. This could result in improved performance compared to either algorithm alone, particularly for PV systems with complex or non-linear power-voltage characteristics [18].

It is important to note that the specific implementation of a hybrid P&O-PSO MPPT algorithm may vary depending on the specific needs and constraints of the PV system, and the performance of the algorithm may depend on the choice of hyperparameters and other design factors.

CHAPTER 3

METHODOLOGY

3.1. System Configuration

The control system consists of 5 main parts. Energy source, MPPT algorithm, DC-DC converter, and Load and Battery storage system. Fig.3.1 shows the system configuration [19].

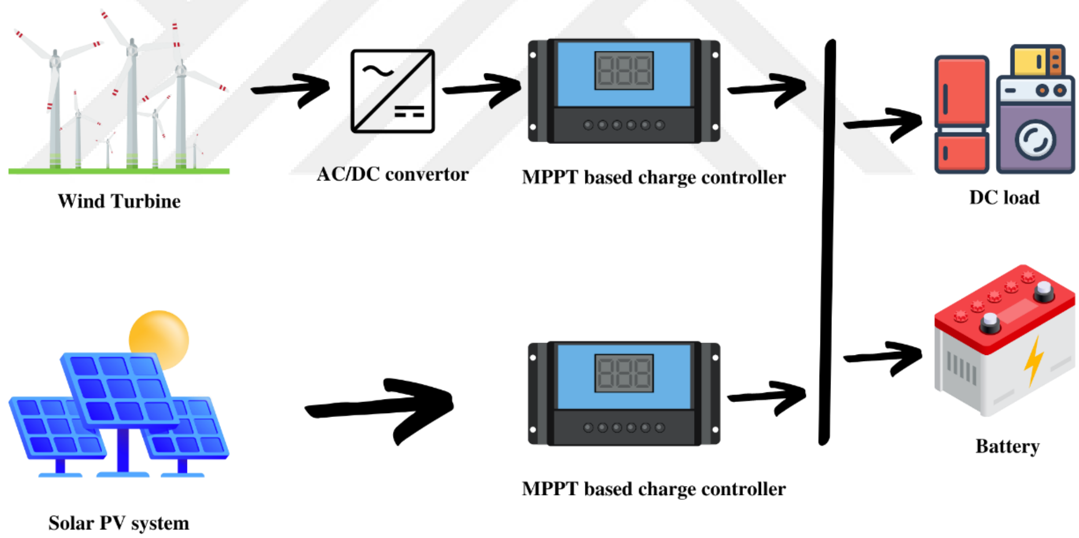

Figure 3.1: System Configuration

For this comparative study, the output results of 8 different algorithms under different environmental conditions were measured. For the wind system the wind speed varied from 8 m/s to 14 m/s. The pitch angle was kept constant. For solar system, the irradiation was varied from 400W/m^2 to 1000W/m^2 and the panel's temperature was kept constant.

Each MPPT was tested under different conditions. Some MPPTs have shown better performance in normal shading and wind speed, and some performed better performance under partial shading and low wind speed.

The Simulink configuration of the system is given in Fig.3.2. Each block will be discussed in detail as a separate section.

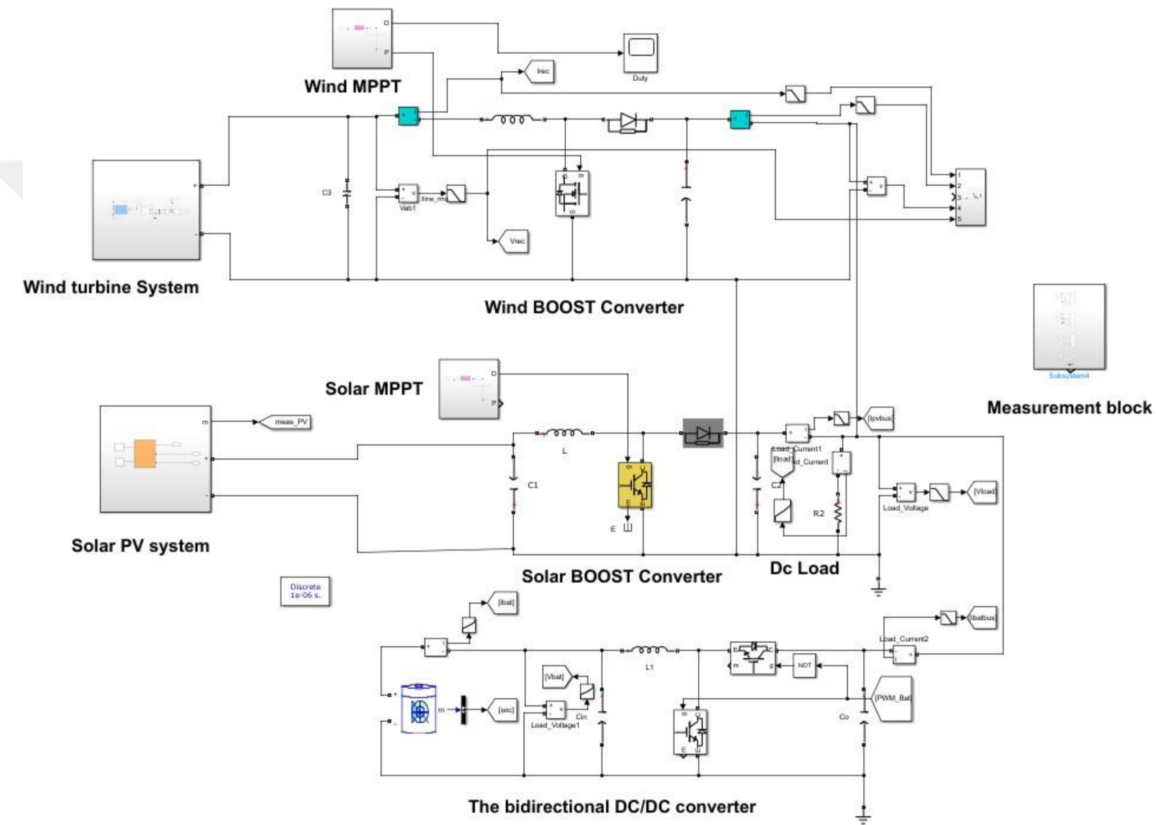

Figure 3.2: Simulink Diagram of whole system

3.2. Wind Turbine System

Wind turbines convert the kinetic energy of wind into electricity using a generator. The generator is typically an alternating current (AC) generator, which produces an AC voltage. Since DC input is required for DC-DC converter, the AC output of the generator must be converted to DC before it can be used.

This conversion is done using a rectifier, which is a device that converts AC to DC. A rectifier consists of diodes, which are electronic components that allow current to flow in only one direction. When the AC voltage from the generator is applied to the diodes in the rectifier, the diodes only allow the positive half of the AC voltage to pass through, effectively converting the AC voltage to a pulsating DC voltage.

The pulsating DC voltage is then typically smoothed out using a device called a filter, which can be a simple capacitor or a more complex circuit. The resulting smooth DC voltage can then be used to power electrical loads or be stored in a battery for later use.

It is worth noting that some wind turbines use permanent magnet generators, which produce a DC voltage directly, eliminating the need for a rectifier. However, these types of generators are less common in large power wind turbines.

The Simulink diagram of wind turbine system is shown in Fig.3.3. The permanent magnet synchronous machine is used to convert kinetic energy into electrical energy. Later universal bridge is used to convert pulsating AC voltage to DC voltage. Here, a simple capacitor can also be added to further smooth the DC voltage.

The pitch angle is set at zero and a signal generator is used to generate variable speed ranging from 8 m/s to 14 m/s. The maximum power of the wind turbine at 14m/s is around 8850 W.

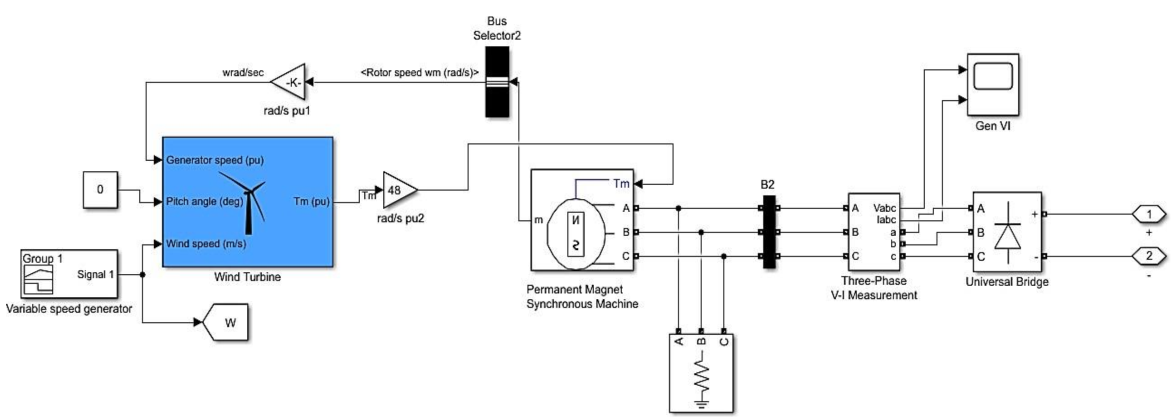

Figure 3.3: Wind Turbine configuration

3.3. Solar System

Photovoltaic (PV) solar panels are devices that are used to convert sunlight into electricity. They are made up of photovoltaic cells, which are made of semiconductor materials such as silicon. When sunlight hits a PV cell, it excites the electrons in the semiconductor material, causing them to flow and creating an electric current.

PV cells are connected in a PV panel, and multiple PV panels can be connected to form a PV system. The electricity generated by a PV panel is direct current (DC) electricity, which means it flows in only one direction and does not require PMSG or rectifiers to operate. A total of 24 panels were used, each with 250 W maximum power. There are 8 panels in series and a total of 3 parallel strings. The total output power is 6000 W @ 1000 irradiations. The temperature is set at constant 25^{o}C, and signal generator is used to provide different irradiation ranging from 400 W/m^2 to 1000 W/m^2 . The solar system configuration is given in Fig.3.4.

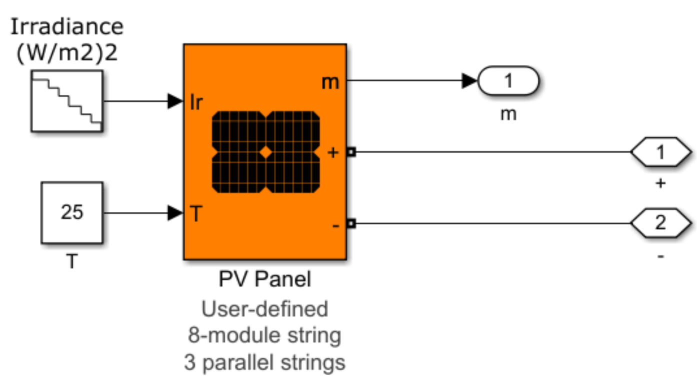

Figure 3.4: PV Panel configuration

Table 3.1 shows the parameters of the solar panel.

Table 3.1: PV panel parameters

Maximum Power	250.2 Watt
Open Circuit Voltage	37.3 Volts
Short Circuit Current	8.66 Amp
Voltage at MPP	30.7 Volts
Current at MPP	8.15 Amp
Modules in series	8
Parallel Strings	3
Total Power @ 1000W/m^2	6000.4 Watts

The PV output power with respect to irradiation is given in Fig.3.5. Fig.3.5 also shows maximum current and voltage value for each irradiation level.

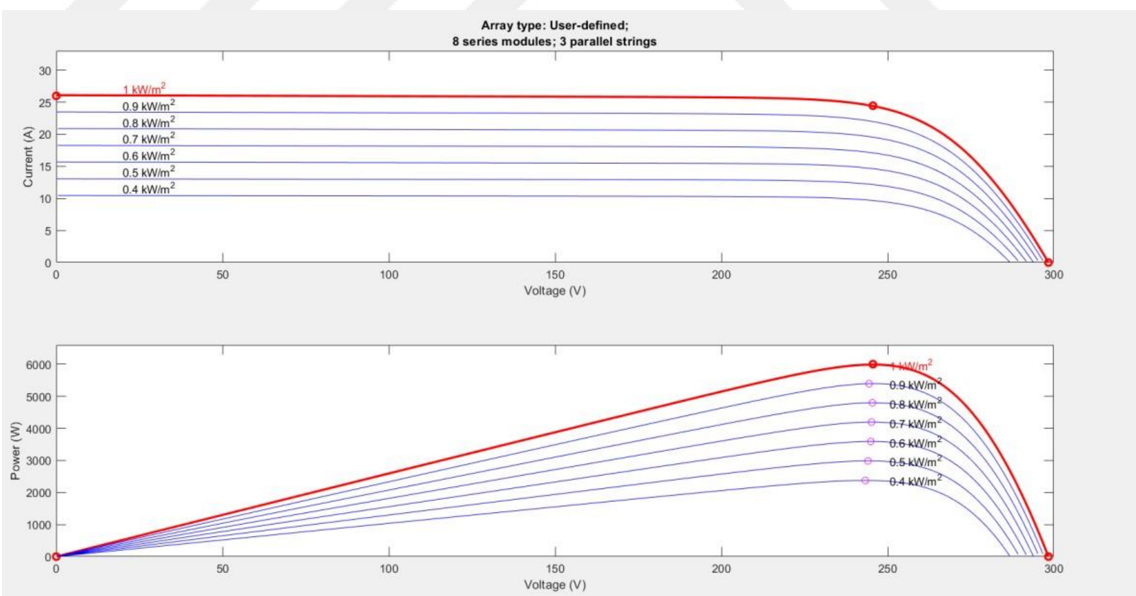

Figure 3.5: Irradiation vs Power Curve

3.4. DC-DC Boost Converter

A DC-DC boost converter is an electronic circuit which is used to convert a lower DC voltage to a higher DC voltage. It operates by using an inductor to store energy and a switch to control the flow of current. A DC-DC boost converter operates in two modes: the continuous conduction mode (CCM) and the discontinuous conduction mode (DCM). The mode of operation depends on the value of the inductance, the input voltage, and the output voltage, as well as the switching frequency and the load resistance [20].

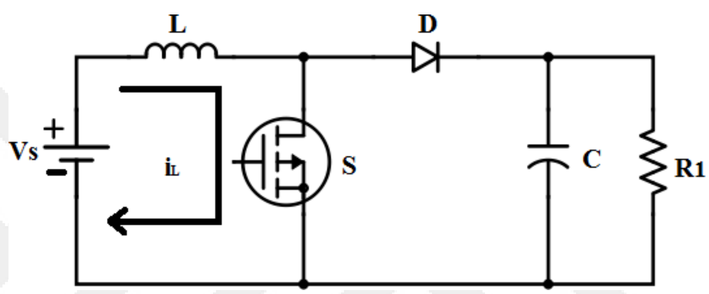

Figure 3.6: Boost converter [20]

Different components required for a boost converter are inductor, capacitors, MOSFET, diode, and load. The inductor is used to store energy during the charging cycle of the boost converter and release during the discharging stage. Inductor selection is the most important part in the designing stage of the boost converter. A switch is used to control the flow of current through the inductor. The switch can be a transistor, a MOSFET, or any other suitable device that can switch on and off, rapidly. A diode is used in a boost converter to prevent current from flowing back into the inductor when the switch is turned off. Capacitor is used to smooth out the output voltage and to provide a steady supply of current to the load [21].

3.4.1. Inductor Design

The design of an inductor for a boost converter is important because it affects the performance of the converter. The inductance value of the inductor determines the amount of energy that can be stored in the magnetic field. A larger inductance value allows for more energy to be stored, which can result in a higher output voltage, but it also increases the size and cost of the inductor. Similarly, the DC resistance of the inductor affects the efficiency of the boost converter. Saturation current, core material and core size are also some factors while designing the inductor, but they are not important from simulation point of view.

The inductor design equation for a boost converter is given in Eq.[3.1] [20]:

$$L = Vin * \frac{(Vo - Vin)}{dI_L * fs * Vo} \tag{3.1}$$

- L is inductor value in Henry
- dI_L is the estimated inductance ripple current in Amp
- V_o is the output voltage in volts
- f_s is switching frequency of MOSFET
- V_{in} is the input voltage in volts (V).

For this system V_{in} is 250 Volts, V_{out} is 400 Volts, change in the inductor current is 1 Amp and switching frequency is 5 KHz. The value of inductor was found out to be around 0.018 Henry. The selected inductor value was 0.038 Henry, 2 times the calculated value to get better and smooth results.

3.5. Battery storage and Load

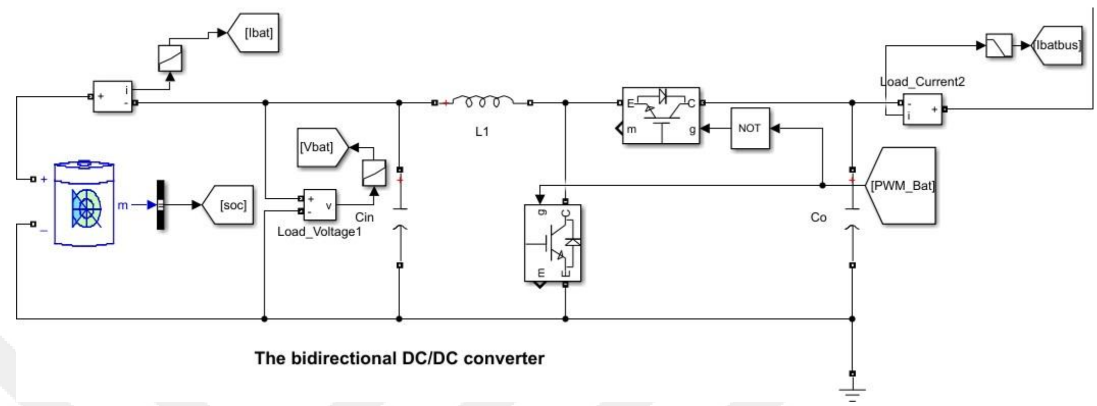

Figure 3.7: Bi-directional DC/DC converter

A battery and DC load are used at the output stage of the system. The DC load resistance is 80 Ω and the battery parameters are given in Table 3.2.

Table 3.2: Battery Parameters

Maximum Capacity	48 Ah
Cut off Voltage	180 Volts
Fully charged Voltage	279.35 Volts
Nominal discharge Current	20.869 Amp
Capacity at Nominal Voltage	43.41 Ah

The DC load is constant and the power across the load is kept constant at 2000 W despite the changes in environmental conditions. Excessive power is used to charge the battery. If the power from both solar and wind does not meet 2000W, the remaining power is delivered from the battery.

A bi-directional DC-DC converter which is controlled by PWM generator is used to charge and discharge the battery. Initially the battery charging is set at 50%. The flow diagram in Fig.3.8 shows the operation of the system.

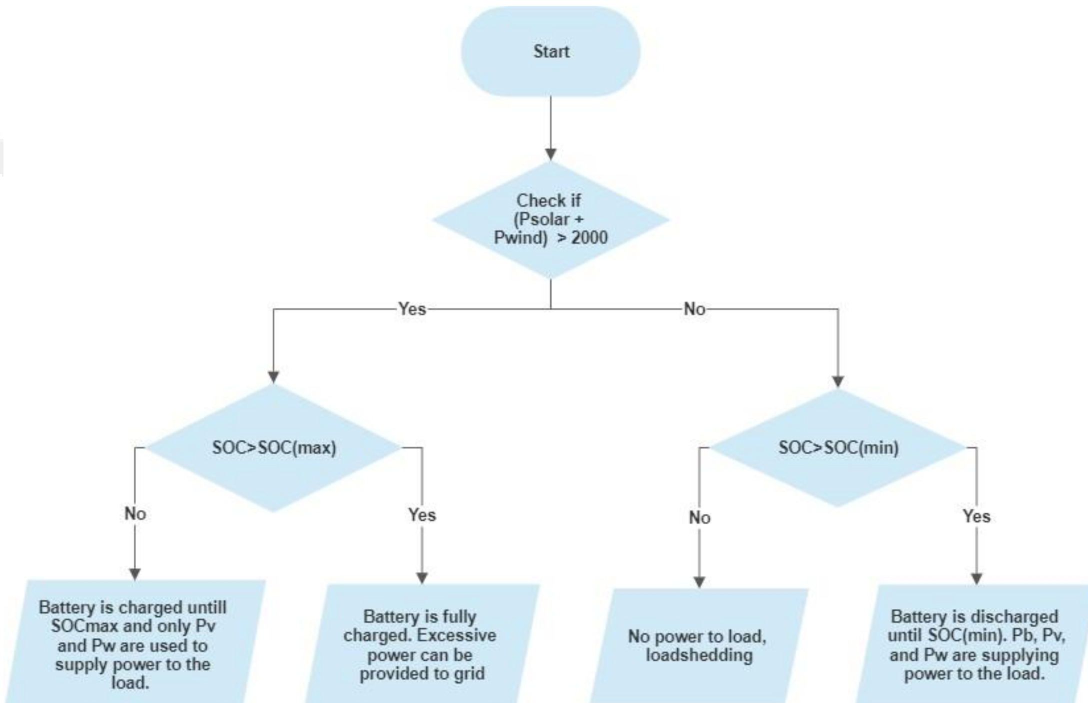

Figure 3.8: Flow chart of Energy Management System

CHAPTER 4

SIMULATION RESULTS

After testing all 8 algorithms under various conditions, the result of each MPPT is discussed below in detail. Different parameters such as settling time, MPP oscillations, oscillations across the load, performance under normal conditions, performance under PSC, MPP accuracy, and MPP time were noted to find out the best performing algorithm for wind and solar.

3.6. Perturb and Observe algorithm (PO)

Table 4.1: PO algorithm results

	Solar PV output			**Wind turbine output**		
Radiation level/Wind speed	**1000 W/m^2**	**700 W/m^2**	**400 W/m^2**	**14m/s**	**12m/s**	**10m/s**
Power (W)	5960	4180	2370	8820	5100	1920
Oscillations (W)	30	15	20	100	400	40
Settling time (sec)	0.2	0.04	0.04	0.22	0.08	0.05
Efficiency (%)	99.3	99.5	99.2	99.5	94.9	69

Solar

For solar PV, performance of PO algorithm was well under normal conditions, and achieved 5960 Watts of maximum power at 1000 watt/m^2. The efficiency of the PO algorithm depends on perturbation size, so a very small step size of 0.00005 was used in the simulation. Due to the small step size, the system was slow, but was able to achieve very high efficiency. There was a small number of oscillations on the output signal after MPPT was achieved.

Performance of PO algorithm was also good under moderate and low irradiation level although the settling time was a little bit slow. Fig.4.1 shows PV output for various irradiation levels. The efficiency of the algorithm was same for all irradiation levels. This means that the PO algorithm can perform well under low and partial shading conditions. The simulation results from the solar panel output are given in Fig.4.1.

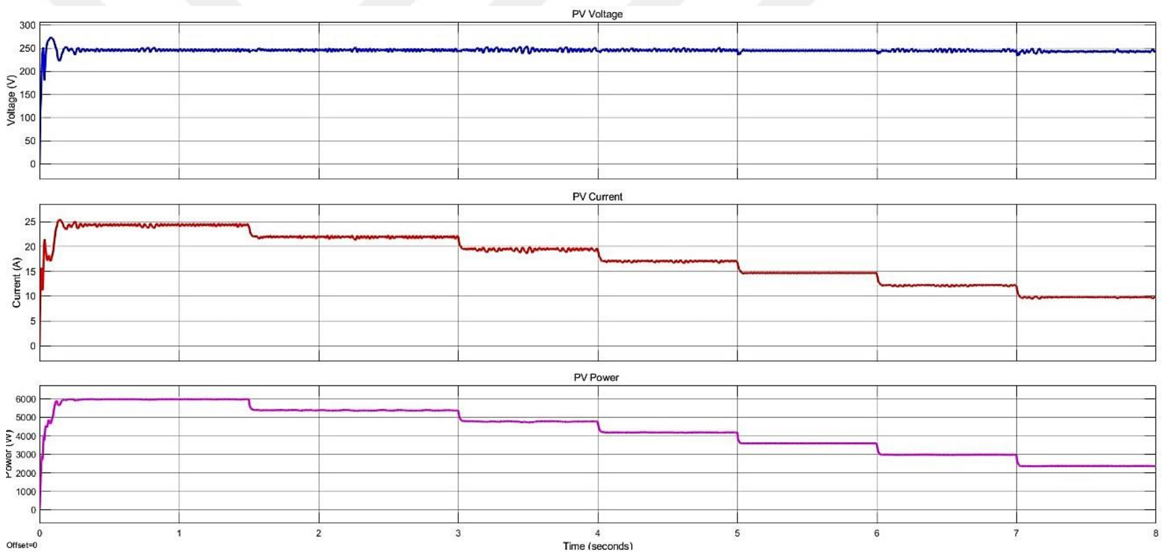

Figure 4.1: PV output results for PO algorithm

Wind

For the wind system, performance of PO algorithm was very poor under low wind speed conditions therefore, it is not an adequate choice. However, the PO algorithm’s performance was well under high wind speeds and maximum efficiency of 99.5% was achieved at 14 m/s wind speed. The efficiency has dropped to 94% at 12 m/s speed and it was only 65% at 10 m/s.

The PO algorithm has shown abnormal behavior at some wind speeds. There was a high number of oscillations present at the output for 12 m/s and 9 m/s wind speeds. In terms of settling time, PO had the lowest settling time of all wind speeds. The simulation results for various wind speeds are shown in Fig.4.2.

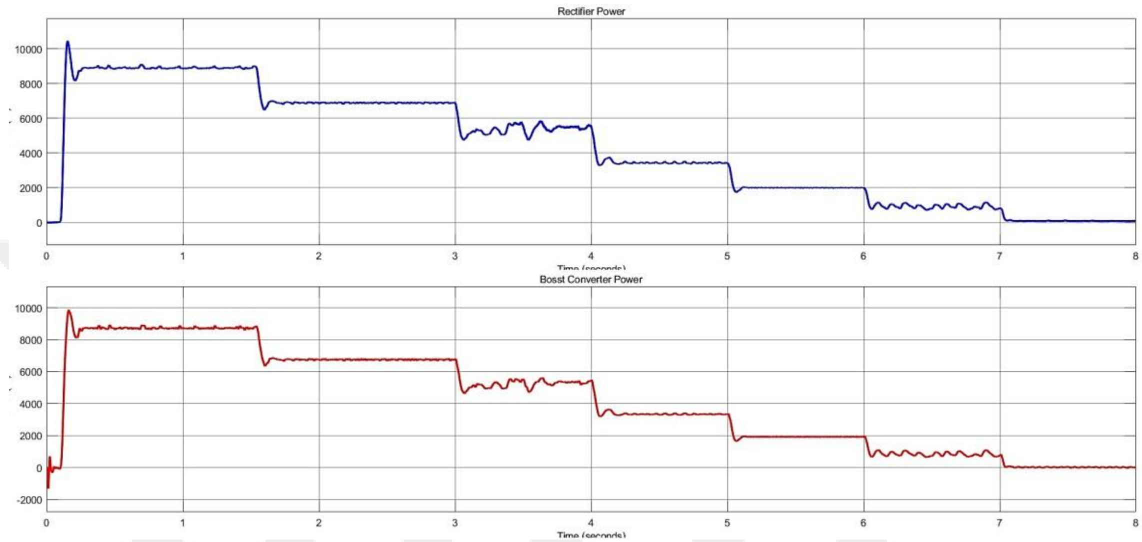

Figure 4.2: Wind turbine output for PO algorithm

Load

The simulation results for load voltage, current and power, for various wind speeds and irradiation levels are shown in Fig.4.3. The oscillations on the load were acceptable. PO algorithm successfully kept the power across the load constant (2000 W) despite the changes in the environmental conditions. There were some spikes in the current whenever the wind speed or irradiation changed.

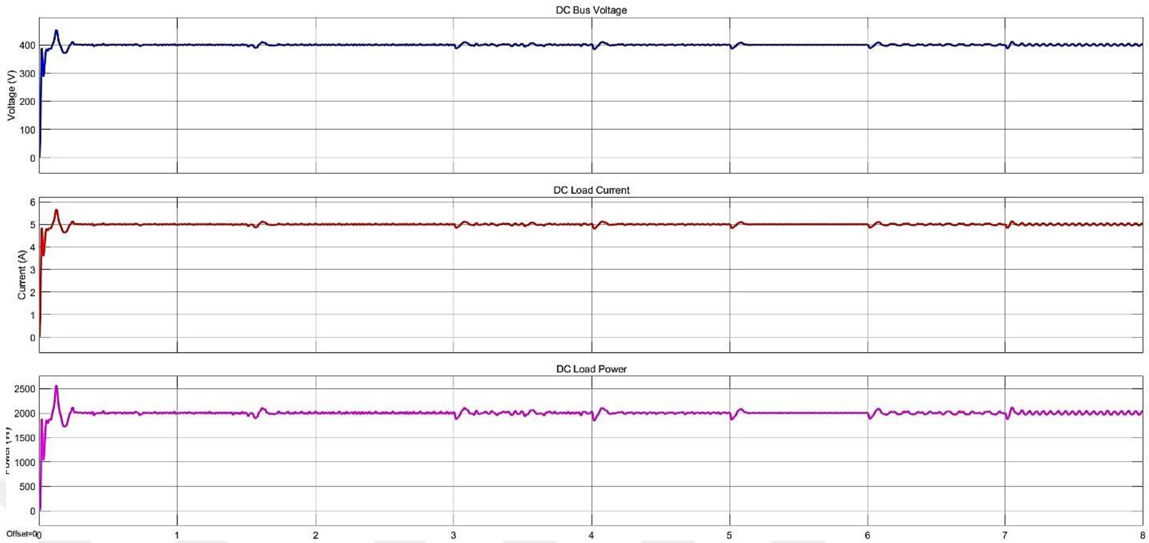

Figure 4.3: Load Power using PO algorithm.

3.7. Incremental Conductance (IC)

Table 4.2: IC algorithm results

	Solar PV output			**Wind turbine output**		
Radiation level/Wind speed	1000 W/m^2	700 W/m^2	400 W/m^2	14m/s	12m/s	10m/s
Power (W)	5950	4162	2360	8775	5080	1935
Oscillations (W)	25	25	15	80	80	30
Settling time (Sec)	0.245	0.05	0.04	0.28	0.22	0.21
Efficiency (%)	99.3	99.6	98.4	99	94.5	68

Solar

Performance of IC algorithm applied to the solar system was good and achieved highest efficiency of 99.6% at 700 W/m^2 . The algorithm can perform well under all irradiation levels and its efficiency does not drop much. One main benefit of IC over PO was that for IC algorithm, the oscillations were very low. The settling time was almost the same as PO method. PV results for IC algorithm are given in Fig.4.4.

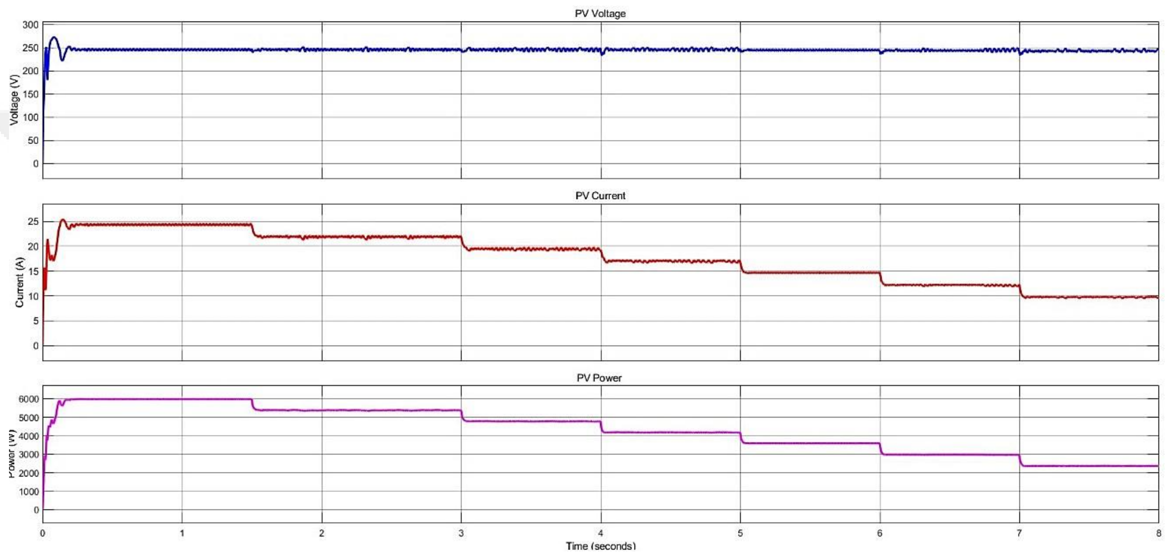

Figure 4.4: PV output for IC algorithm

Wind

Similar to the PO method, efficiency of IC method drops under low wind speed conditions. Efficiency falls from 99% at 14 m/s to 68% at 10 m/s. Apart from this the oscillations were minimum and there were no abnormalities or spikes at any wind speed. Wind results for IC algorithm are given in Fig.4.5.

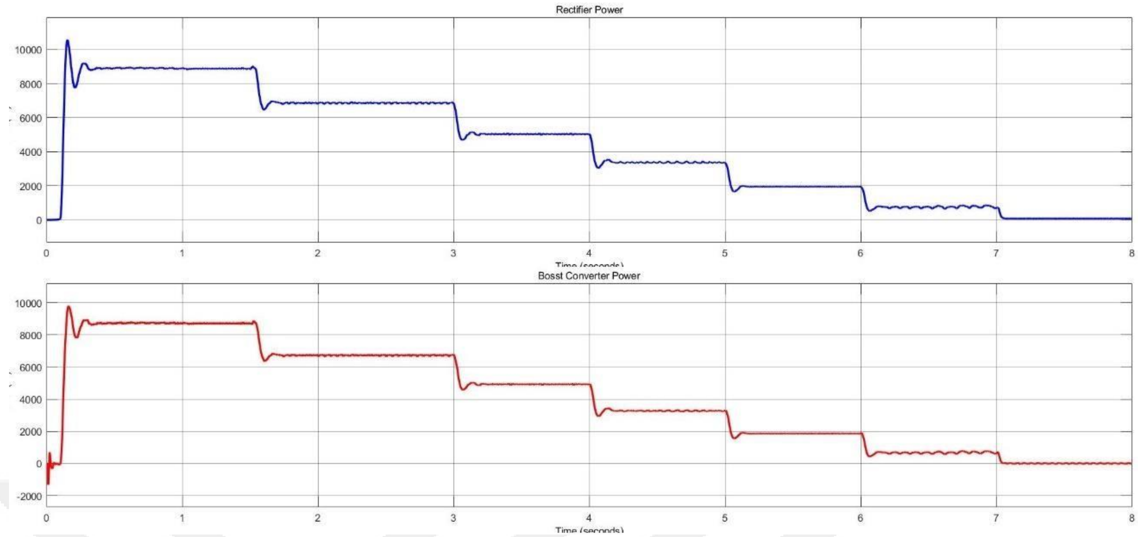

Figure 4.5: Wind turbine output using IC algorithm.

Load

The oscillations on the load voltage, current and power were very low as well and the algorithm kept the load power constant at all wind speeds and irradiation levels. The simulation results for load voltage, current and power, various wind speeds and irradiation levels are shown in Fig.4.3.

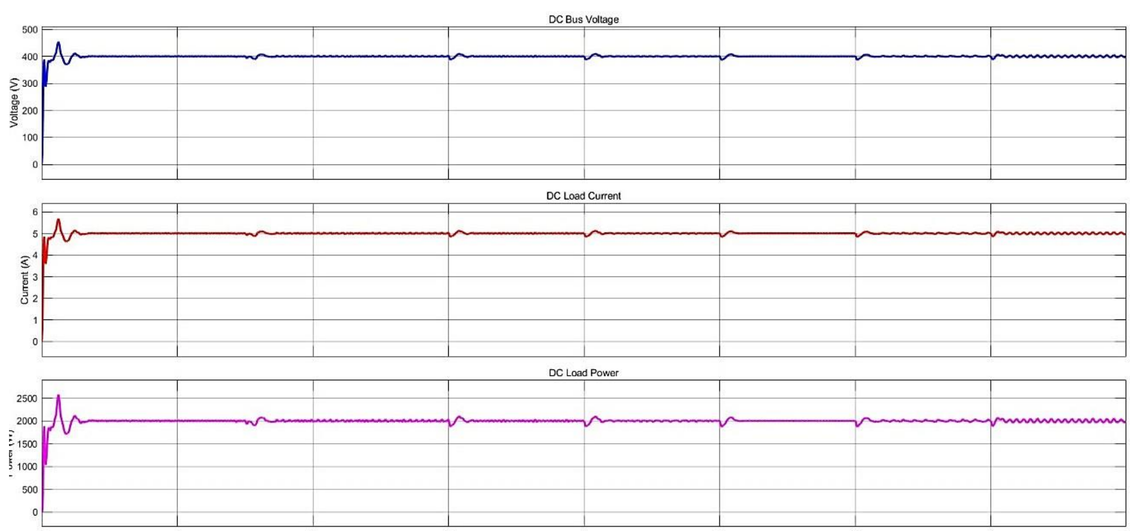

Figure 1.6: Load Power using IC algorithm

3.8. Particle Swarm Optimization (PSO)

Table 4.3: PSO algorithm results

	Solar PV output			Wind turbine output		
Radiation level/Wind speed	**1000 W/m²**	**700 W/m²**	**400 W/m²**	**14m/s**	**12m/s**	**10m/s**
Power (W)	5820	4050	2325	8670	5300	2800
Oscillations (W)	130	75	15	250	250	200
Settling time (Sec)	0.2	0.03	0.02	0.6	0.2	0.15
Efficiency (%)	96.9	96.4	97.2	97.86	97.9	97.6

Solar

Performance of PSO algorithm for solar system was moderate. The average efficiency was 97% and the settling time was very short, especially at low radiation levels. PV results for PSO algorithm for various irradiation levels are given in Fig.4.7.

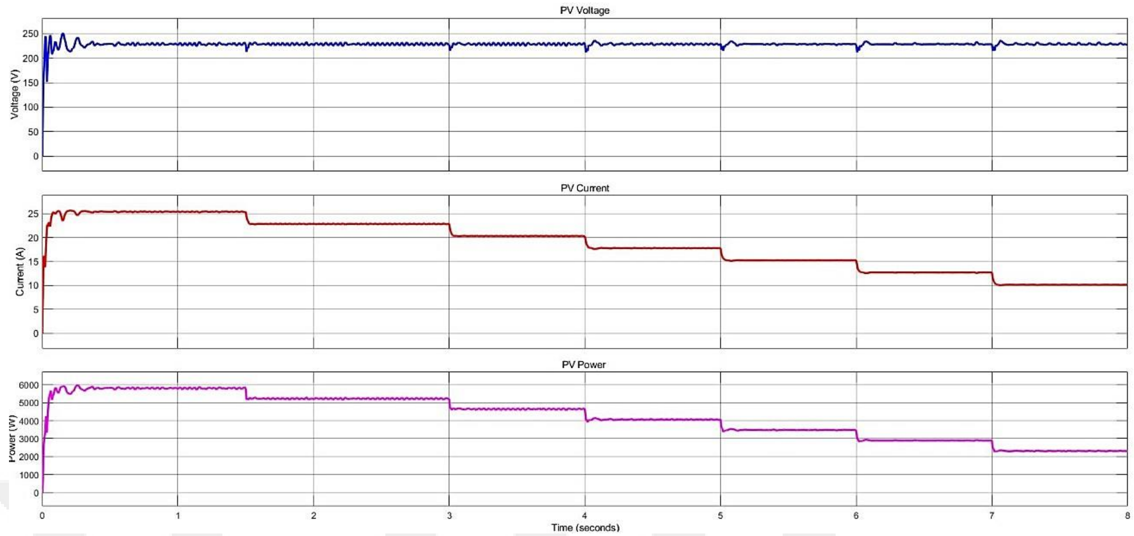

Figure 4.7: PV output using PSO algorithm

Wind

For the wind system, PSO method had very high oscillations at the beginning, and it took considerable time to catch MPP and settle. The initial settling time was 0.6 s which is the highest time among all MPPT techniques.

There was a moderate number of oscillations on the output. The main advantage of PSO algorithm is high efficiency at low wind speeds. The PSO algorithm managed to attain 97% efficiency at 10 m/s which is 29% more than that of the traditional MPPTs like PO and IC. Wind results for PCO algorithm are given in Fig.4.8.

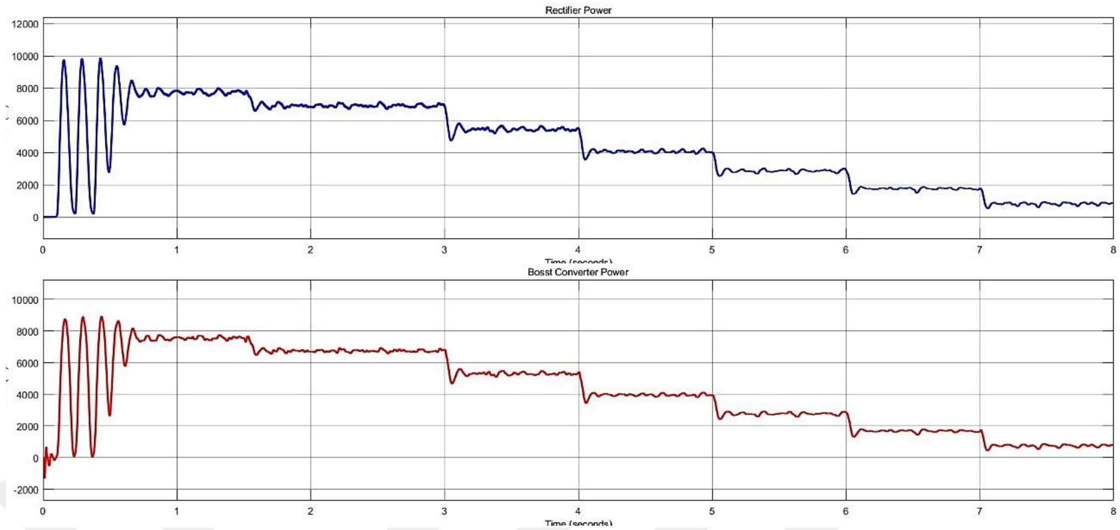

Figure 4.8: Wind turbine output using PSO algorithm.

Load

Oscillations on the load were highest for the PSO method but it still managed to keep the power constant across the 80 Ω load. The simulation results for load voltage, current and power various wind speeds and irradiation levels using PSO algorithm are shown in Fig.4.9.

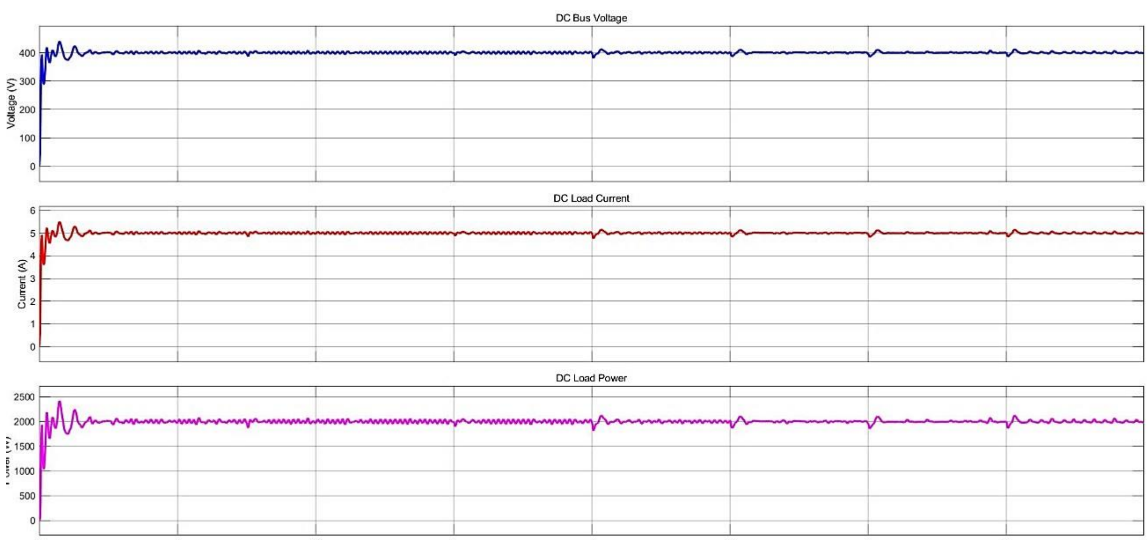

Figure 4.9: Load power using PSO algorithm.

3.9. Fuzzy Logic (FL)

Table 4.4: Fuzzy logic algorithm results

	Solar PV output			Wind turbine output		
Radiation level/Wind speed	**1000 W/m²**	**700 W/m²**	**400 W/m²**	**14m/s**	**12m/s**	**10m/s**
Power (W)	5978	4185	2360	8800	5220	2330
Oscillations (W)	10	10	5	120	100	80
Settling time (Sec)	0.09	0.02	0.04	0.3	0.2	0.2
Efficiency (%)	99.5	99.6	99	99.3	98.2	83.7

Solar

The efficiency of FL algorithm was above 99% for all irradiation levels. FL had the lowest settling time and power oscillations as well. Overall, the algorithm operates very well for the PV system. PV results applying FL algorithm for various irradiation levels are given in Fig.4.10.

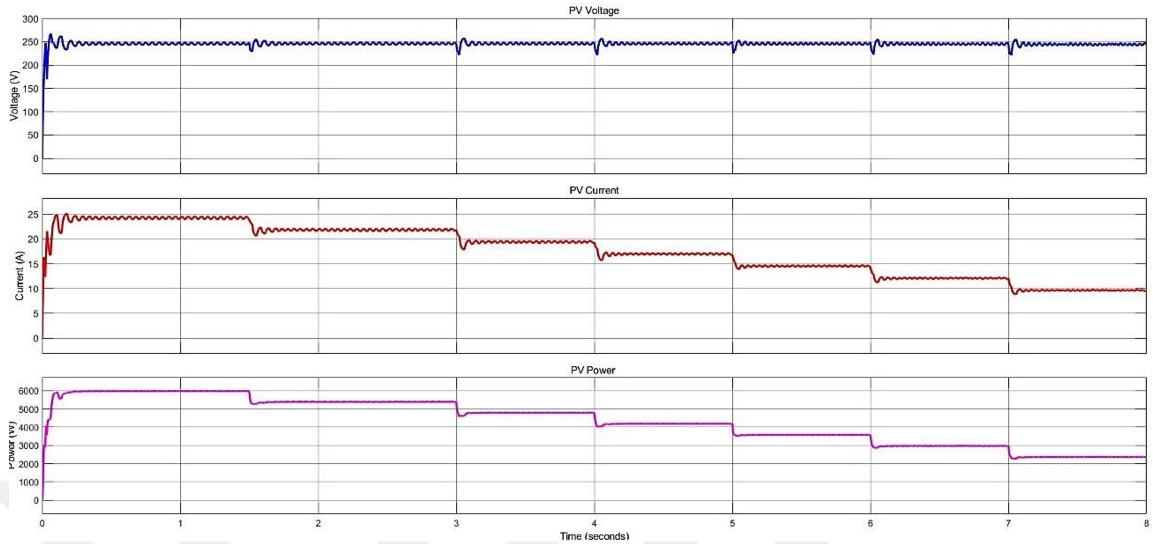

Figure 4.10: PV output for fuzzy logic algorithm

Wind

FL performance was excellent at high wind speeds and moderate at low wind speeds. The efficiency of the wind system drops down from 99% at 14 m/s to 84% at 10 m/s. The efficiency at low wind speeds was still better than that of the traditional MPPT methods. The number of oscillations was low, and the settling time was moderate. Wind results for FL algorithm are shown in Fig.4.11.

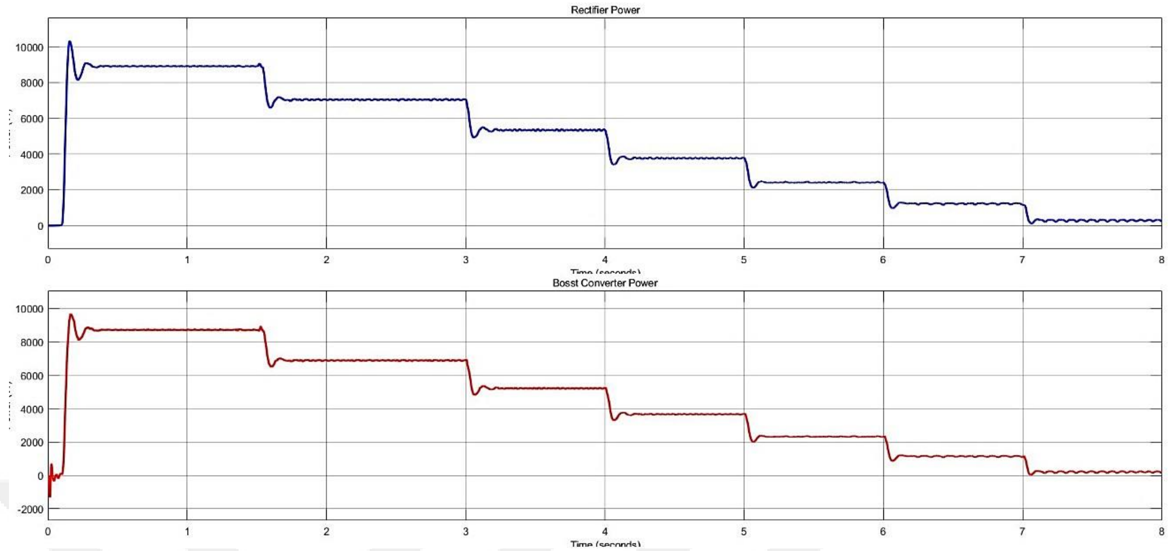

Figure 4.11: Wind turbine output for fuzzy logic algorithm

Load

FL algorithm applied to the hybrid system successfully kept the power across the load constant with minimum fluctuations as seen in Fig.4.12.

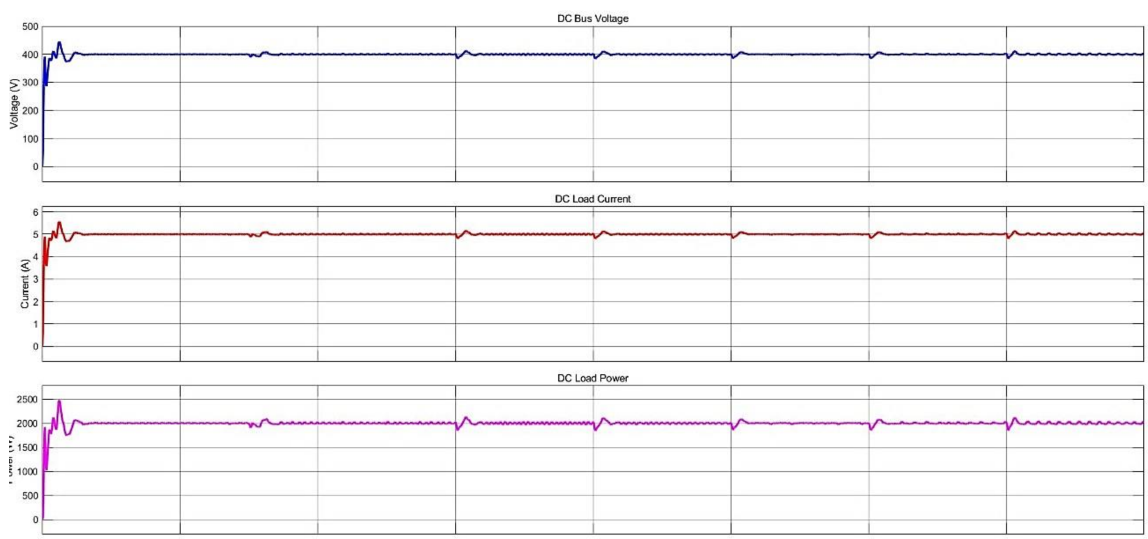

Figure 4.12: Load output for fuzzy logic algorithm

3.10. Artificial Neuron Network (ANN)

Table 4.5: ANN algorithm results

	Solar PV output			Wind turbine output		
Power (W)	**1000 W/m²**	**700 W/m²**	**400 W/m²**	**12m/s**	**10m/s**	**8m/s**
Power (W)	5188	4195	2375	8790	5320	2420
Oscillations (W)	10	10	5	100	80	100
Settling time (Sec)	0.1	0.04	0.04	0.28	0.17	0.10
Efficiency (%)	99.8	99.8	99.3	99.2	99	85

Solar

ANN was the most efficient algorithm for the PV system. The efficiency was above 99.3% for all irradiation levels. With minimum oscillations, ANN was also the best algorithm along with FL. The settling time was the 2^{nd} best after FL. Overall the ANN gave the best results for the PV system. PV results for ANN algorithm for various irradiation levels are given in Fig.4.13.

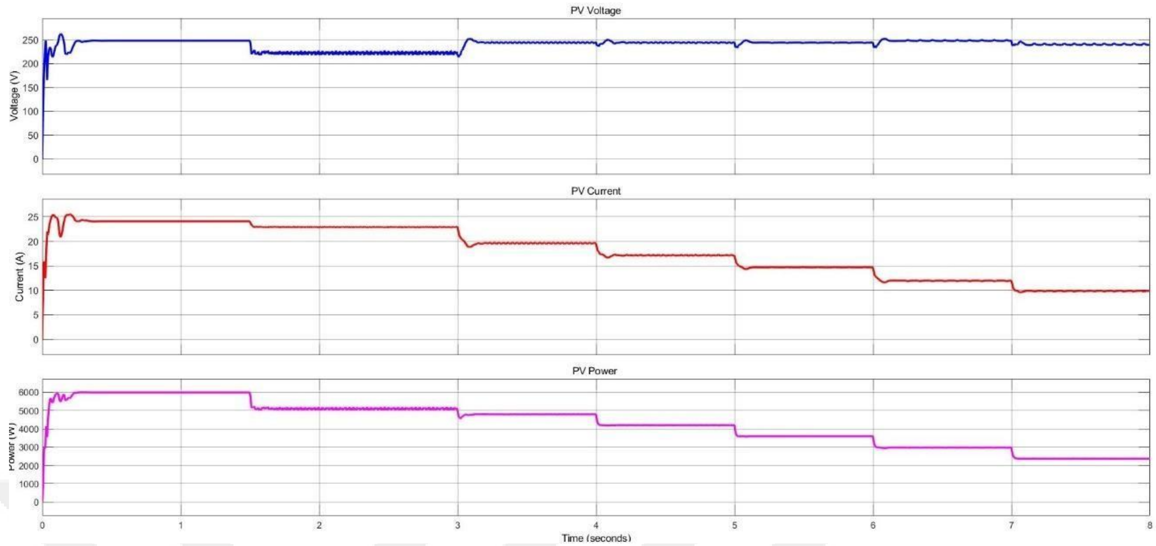

Figure 4.13: PV output for ANN algorithm

Wind

ANN extracted the maximum power from the wind energy system at high and moderate wind speeds with the efficiency of 99.2% and 99%, respectively. The performance of ANN algorithm was not so good at low wind speed (10 m/s) and the efficiency was around 85%. However, the oscillation and settling time were very good for ANN. Wind results for ANN algorithm are shown in Fig.4.14.

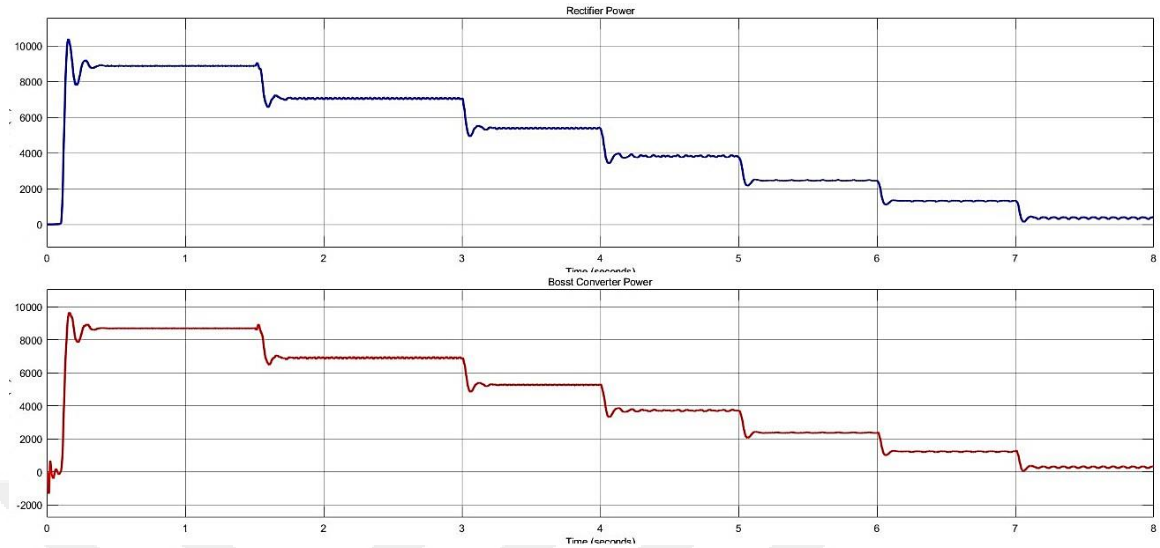

Figure 4.14: Wind turbine output for fuzzy logic algorithm

Load

ANN was able to maintain constant power with minimum oscillations on the load. The settling time was below 0.2 second as seen in Fig. 4.15.

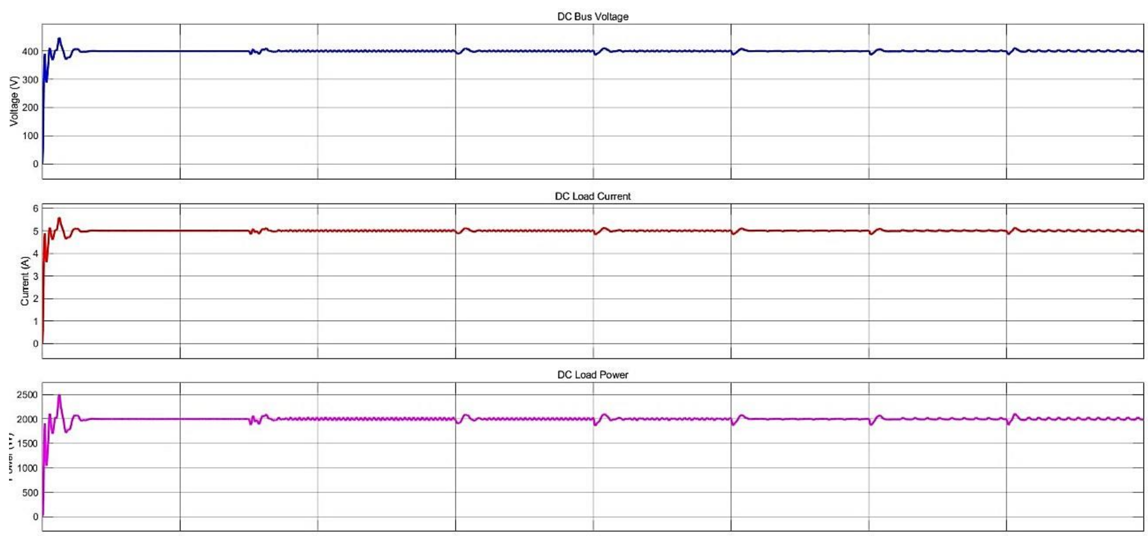

Figure 4.15: Load output for FL algorithm

3.11. Proportional Integral Derivative (PID)

Table 4.6: PID algorithm results

	Solar PV output			**Wind turbine output**		
Radiation level/Wind speed	**1000 W/m^2**	**700 W/m^2**	**400 W/m^2**	**14m/s**	**12m/s**	**10m/s**
Power (W)	5985	4192	2250	8750	5310	2450
Oscillations (W)	10	5	80	40	40	80
Settling time (Sec)	0.2	0.08	0.06	0.32	0.17	0.12
Efficiency (%)	99.6	99.5	95	98.75	98.7	86

Solar

The performance of the PV system using PID controller as MPPT method is very good at high irradiation levels, and moderate at low radiation levels. The efficiency of the PV system applying PID controller drops down from 99.6% at 1000 W/m^2 to 95% at 400 W/m^2 . PID could be a good option if the irradiation level is above 500 W/m^2. However, below this level, the efficiency reduces, and oscillations increase significantly. PV results with PID algorithm for various irradiation levels are given in Fig.4.16.

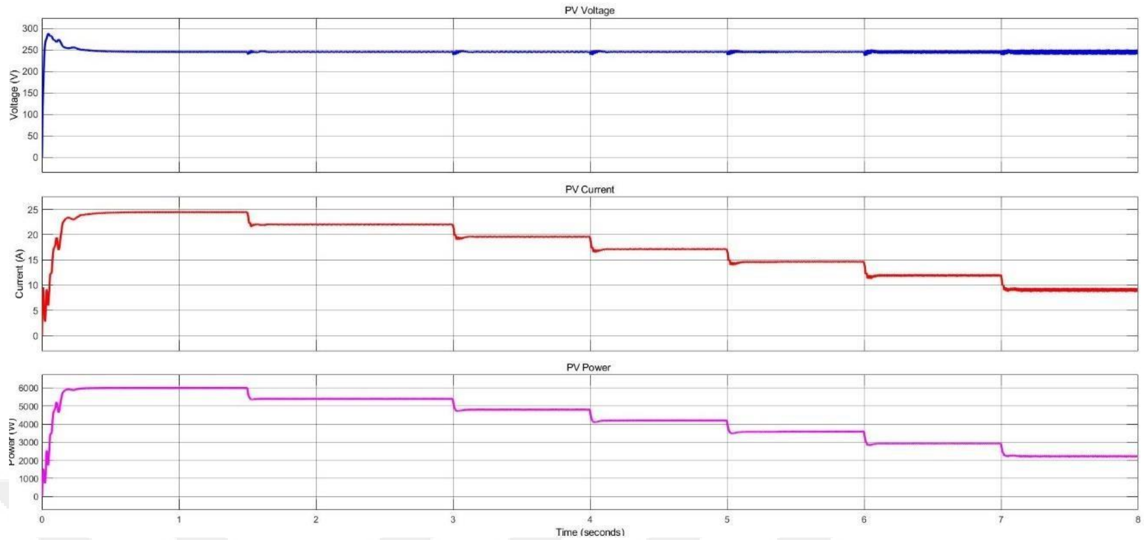

Figure 4.16: PV output for PID algorithm

Wind

PID gives adequate results for the wind system. The highest efficiency was 98.75 at 14 m/s. This efficiency decreases to 85% at 10 m/s. The output has low oscillations, and the settling time is moderate. Wind results for PID algorithm at various wind speeds are shown in Fig.4.17.

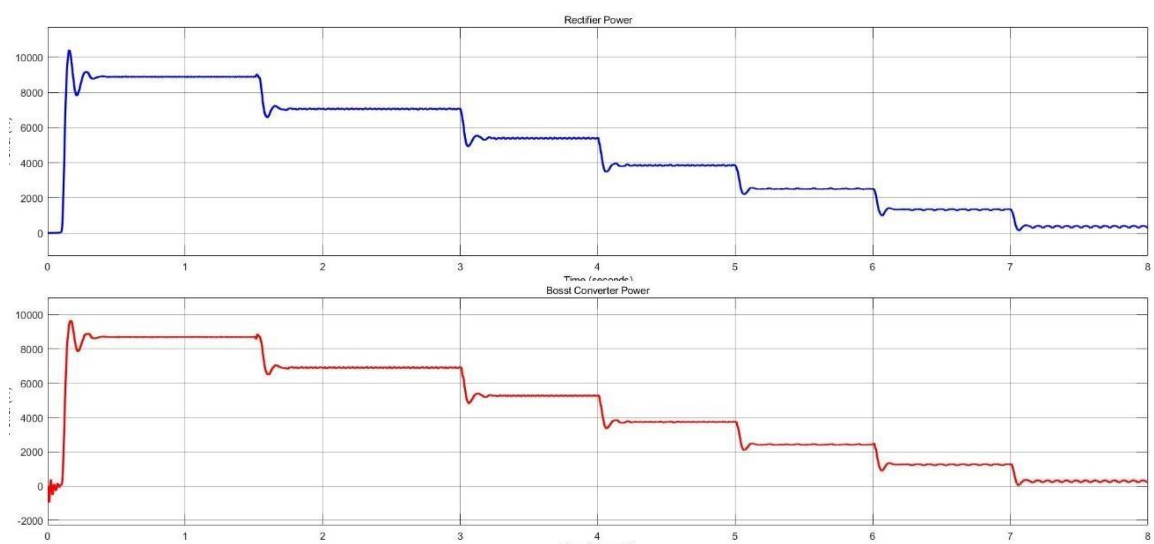

Figure 4.17: Wind turbine output for PID algorithm

Load

The oscillations and current spikes were minimum on the load, and the power was kept constant at 2000 W. The simulation results for load voltage, current and power various wind speeds and irradiation levels using PID algorithm are shown in Fig.4.18.

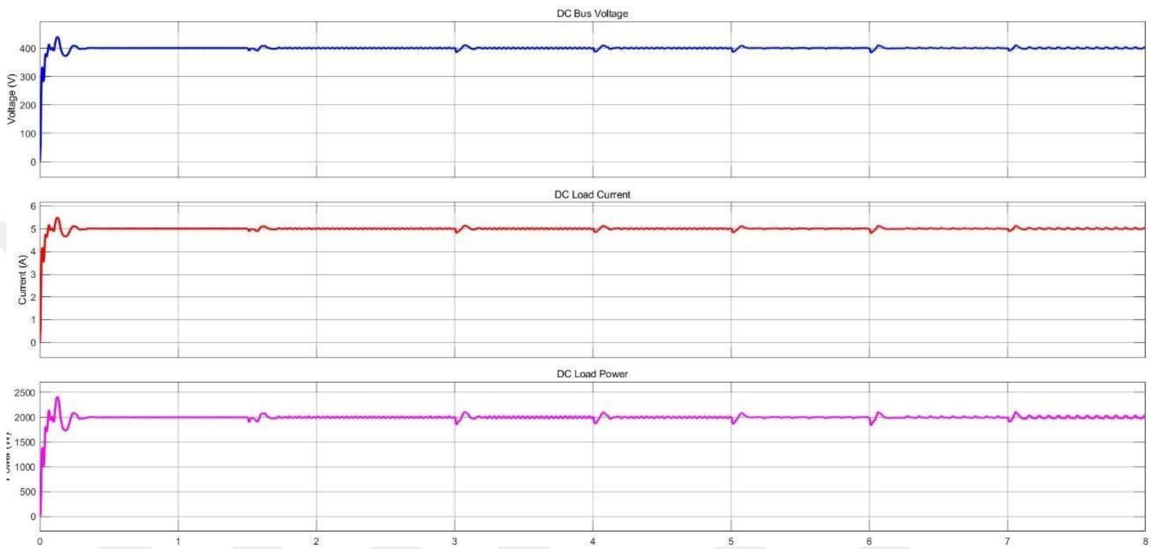

Figure 4.18: Load output for PID algorithm

3.12. Adaptive Neuro Fuzzy Inference System (ANFIS)

Table 4.7: ANFIS algorithm results

	Solar PV output			**Wind turbine output**		
Radiation level/Wind speed	**1000 W/m^2**	**700 W/m^2**	**400 W/m^2**	**14m/s**	**12m/s**	**10m/s**
Power (W)	5985	4190	2365	8810	5310	2410
Oscillations (W)	10	15	5	80	80	100
Settling time (Sec)	0.2	0.05	0.04	0.3	0.2	0.12

Efficiency (%)	99.7	99.6	99	99.4	98.9	85

Solar

ANFIS combines the benefits of ANN and FL. Performance of ANFIS algorithm is one of the best in the PV system. It achieves an efficiency of above 99% for all irradiation levels. The oscillations are minimum, and the settling time is also the lowest among the other algorithms. PV results with ANFIS algorithm for various irradiation levels are given in Fig.4.19.

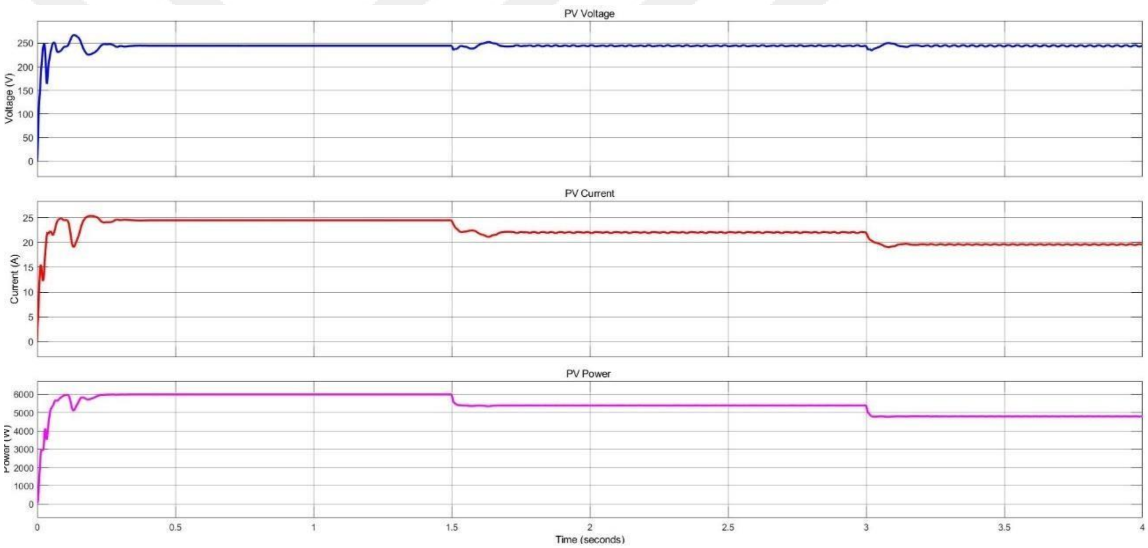

Figure 4.19: PV output for ANFIS algorithm

Wind

The efficiency of ANFIS in the wind system was similar to FL and ANN algorithms. The performance was good at 14 m/s and 12 m/s but decreased significantly at 10m/s. Oscillations on the output and settling time were moderate. Wind results for ANFIS algorithm at various wind speeds are shown in Fig.4.20.

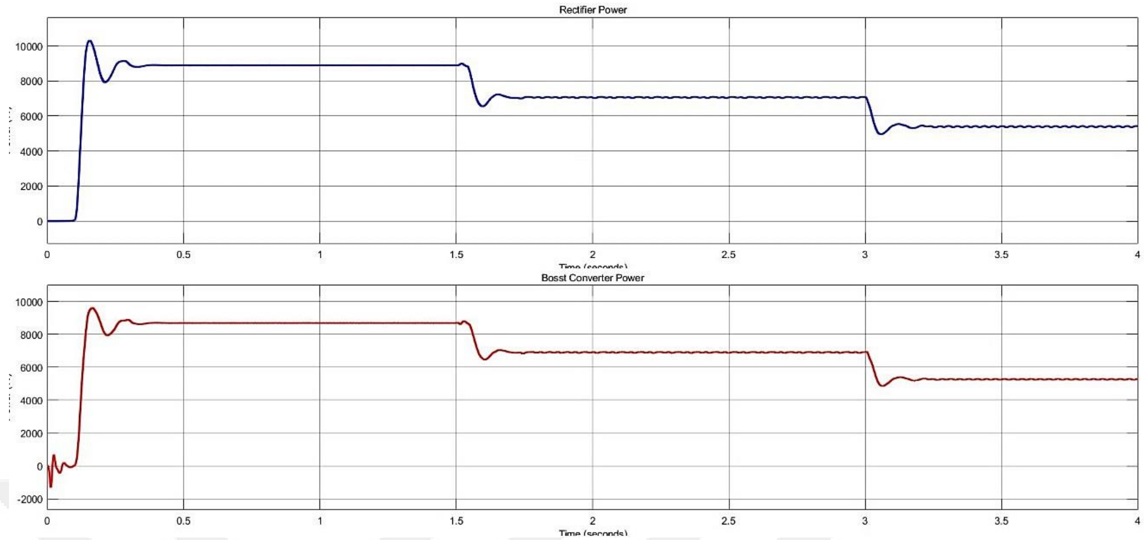

Figure 4.20: Wind turbine output for ANFIS algorithm

Load

ANFIS successfully maintained 2000 W across the load. The oscillation and spikes were also minimum. The simulation results for load voltage, current and power various wind speeds and irradiation levels using ANFIS algorithm are shown in Fig.4.21.

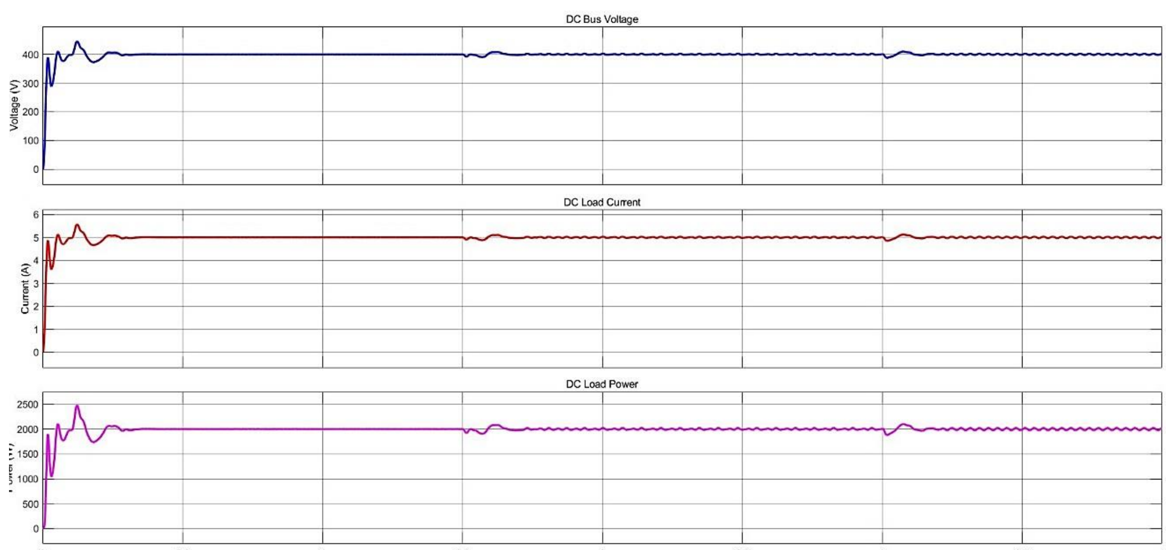

Figure 4.21: Load output for ANFIS algorithm

3.13. Hybrid PSO&PO

Table 4.8: Hybrid PSO&PO algorithm results

	Solar PV output			**Wind turbine output**		
Radiation level/Wind speed	**1000 W/m^2**	**700 W/m^2**	**400 W/m^2**	**14m/s**	**12m/s**	**10m/s**
Power (W)	5965	4110	2330	8780	5340	2750
Oscillations (W)	10	10	10	80	120	140
Settling time (Sec)	0.22	0.05	0.04	0.3	0.2	0.12
Efficiency (%)	99.4	98	97.5	99.09	99.5	97

Solar

The hybrid PSO&PO method is an adequate choice for the PV system. The efficiency is above 97% and the settling time is small as well. Unlike the simple PSO method, the number of oscillations in hybrid method is negligible making it more desirable. PV results with the hybrid PSO&PO algorithm for various irradiation levels are given in Fig.4.22.

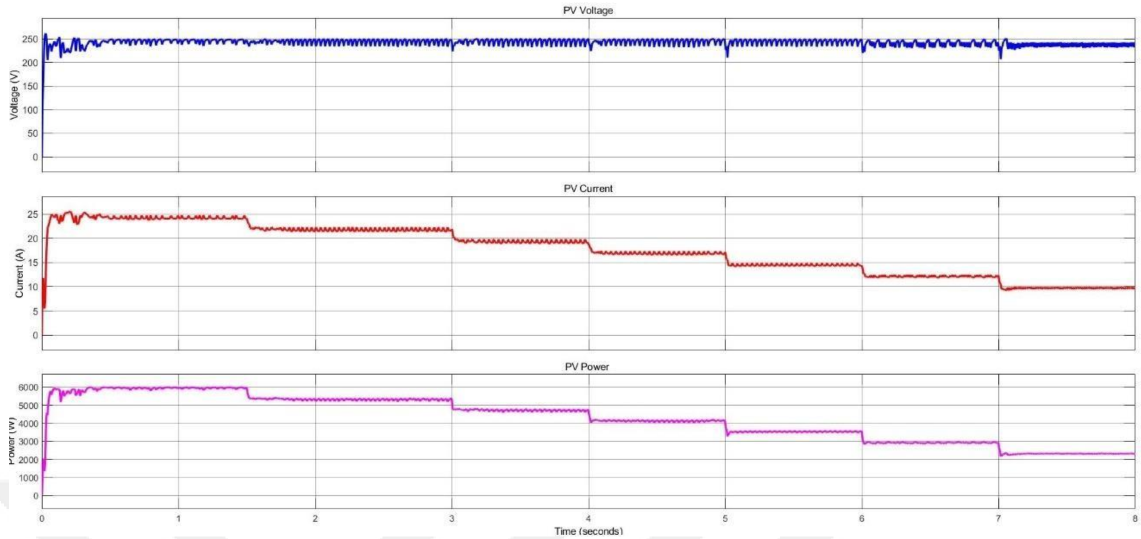

Figure 4.22: PV output using Hybrid PSO&PO

Wind

The hybrid PSO&PO is the most desirable MPPT algorithm for the wind system. PSO algorithm had the highest efficiency for low wind speeds, but the drawback was high initial oscillations and slow settling. On the other hand, the PO algorithm was fast and without any initial oscillations, but it was not efficient at low wind speeds. By combining PSO and PO, the advantages of both algorithms were utilized. PO algorithm was used to initially catch the MPP as fast as possible and PSO algorithm was later used for fine tuning the MPP. PSO&PO algorithm was 99% efficient at 14m/s and 97% efficient at 10m/s. Wind results for the hybrid PSO&PO algorithm at various wind speeds are shown in Fig.4.23.

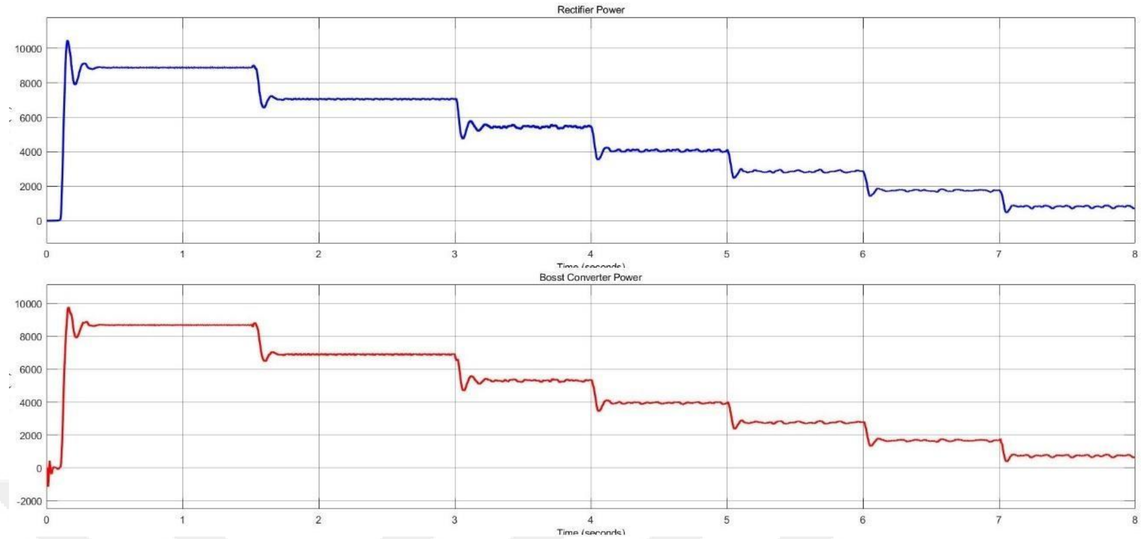

Figure 4.23: Wind turbine using Hybrid PSO&PO

Load

Just like PSO and PO method, the hybrid method successfully maintained 2000W on the load with minimum oscillations as shown in Fig.24.

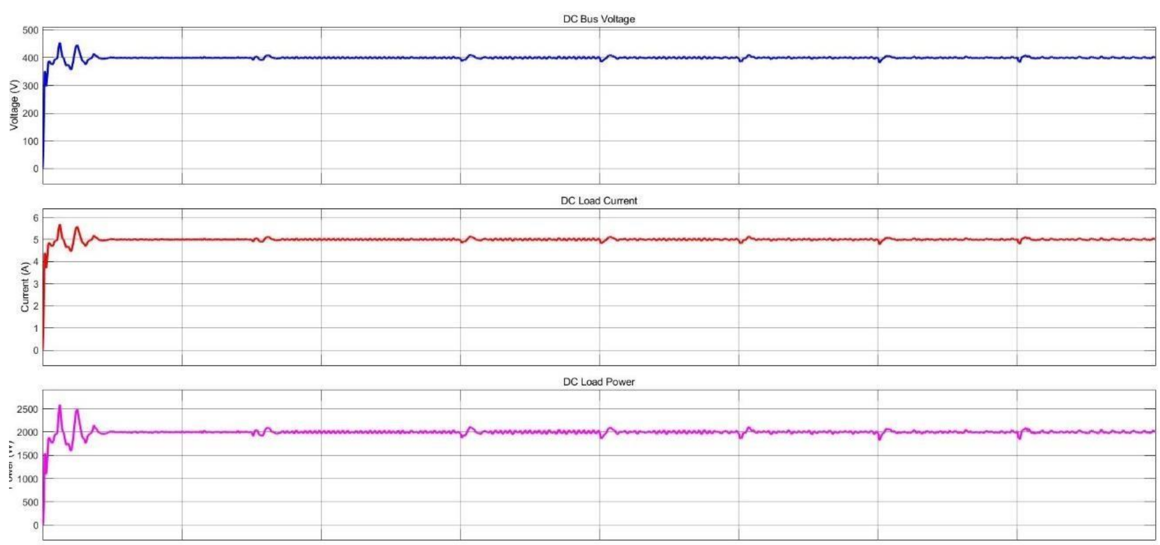

Figure 4.24: Load output using Hybrid PSO&PO

CHAPTER 5

DISCUSSION

5.1. PV system

Table 5.1: Comparison of all MPPT techniques for PV system

Solar	Tracking Speed	Efficiency under normal irradiation	Efficiency under medium irradiation	Efficiency under low irradiation	Settling time	Oscillations around MPP	Complexity
ANN	Fast	High	High	High	Fast	Small	High
FL	Fast	High	High	High	Fast	Small	Moderate
PID	Slow	High	High	Low	Slow	Small	Moderate
ANFIS	Moderate	High	High	High	Moderate	Small	High
IC	Slow	High	High	Moderate	Fast	Medium	Low
PO	Slow	High	High	High	Fast	Large	Low
PSO&PO	Fast	High	Moderate	Moderate	Moderate	Medium	High
PSO	Fast	High	Moderate	Moderate	Moderate	Large	Moderate

After analyzing the simulation results, the comparative results are given in Table 5.1. For the solar PV system, all algorithms performed quite well at high and medium irradiation levels except for PSO. The efficiency of PSO was moderate at high irradiation levels but gradually increased for low irradiation levels.

For low irradiation levels, only ANN, FL, ANFIS and PO were able to achieve efficiencies over 99%. Efficiency of PID algorithm drops significantly at low irradiation levels. Comparing the efficiency of all algorithms for various irradiation levels, the performance of ANN, FL, ANFIS and PO was the best. Efficiency of all MPPTs at various irradiation levels are presented in Fig.5.1.

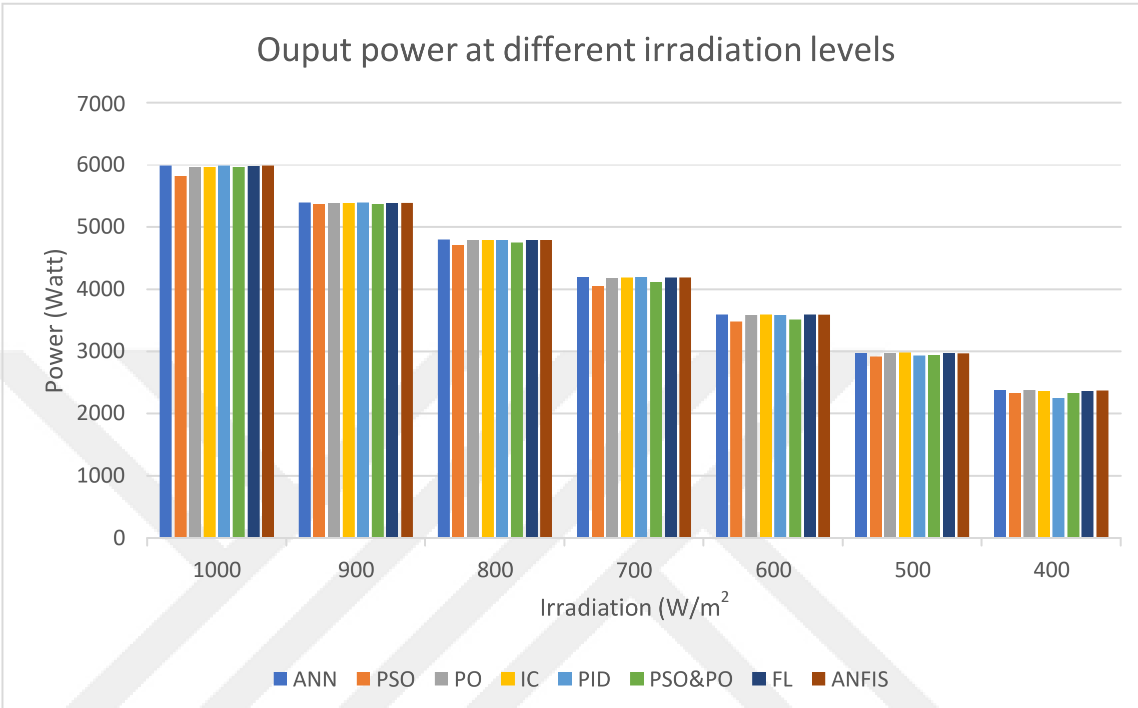

Figure 5.1: PV power at different irradiation levels for all MPPTs

Moving on the MPP tracking speed, performance of AI techniques is quite better than that of the traditional and hybrid techniques. ANN, FL and PSO track the MPP quickly while the IC and PO are the slowest ones. For traditional MPPT, the tracking speed depends on perturbation size. In this experiment, the perturbation was 0.0005 which is very small, but it yields high efficiency. If high MPPT speed is required, the perturbation size can be adjusted accordingly.

Once the MPP was achieved, there were some oscillations around the MPP level. The oscillations were most prominent in PO and PSO method. ANN, FL, ANFIS and PID had almost zero oscillations at MPP. The high oscillations in the PO method can be minimized by tweaking the step size.

Fig 5.2 presents a visual comparison of all MPPTs in terms of efficiency, accuracy, tracking speed, and oscillations. Looking at the results, it can be said that ANN is the best choice overall. ANN algorithm is complex, but it yields high efficiency at all irradiation levels, fast tracking and low oscillations around MPP. Following ANN algorithm, FL and ANFIS are the 2nd best option for the PV system. Here, "1" represents the worst and "10" represents the best performance.

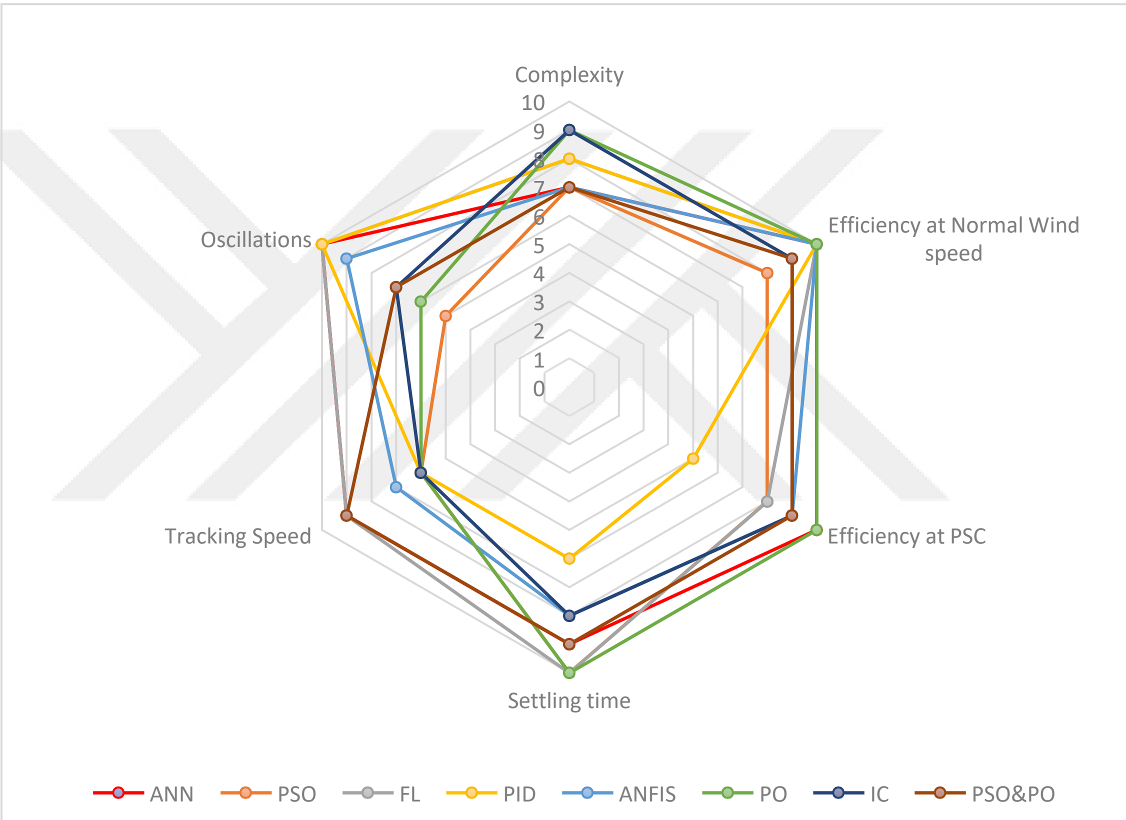

Figure 5.2: Comparative analysis of all MPPTs for PV system

5.2. Wind System

Table 5.2: Comparison of all MPPT techniques for Wind system

	Tracking Speed	Efficiency under high speed	Efficiency under medium speed	Efficiency under low wind speed	Settling time	Oscillations around MPP	Complexity
ANN	Fast	High	High	Moderate	Fast	Small	High
FL	Fast	High	High	Moderate	Fast	Medium	Moderate
PID	Slow	High	High	Moderate	Slow	Small	Moderate
ANFIS	Moderate	High	High	Moderate	Moderate	Small	High
IC	Moderate	High	Moderate	Low	Moderate	Medium	Low
PO	Moderate	High	Moderate	Low	Fast	Large	Low
PSO&PO	Fast	High	High	High	Fast	Medium	High
PSO	Slow	High	High	High	Fast	Large	Moderate

In the wind system, efficiency of the MPPT algorithm significantly changes with the wind speed. Almost all algorithms perform well and have efficiencies of more than 99% at 14 m/s. When the wind speed decreases by 2 m/s i.e., at 12 m/s, the efficiency of traditional MPPTs like PO and IC drops by almost 15%. The efficiency of hybrid and AI techniques is still above 98%.

A further 2 m/s decrease (10 m/s) in the wind speed has more drastic results on the efficiency. The efficiency of conventional MPPT techniques is very poor at 10 m/s. PO and IC have 69% and 68% efficiencies, respectively, which is below the acceptable level. The efficiency of AI techniques drops down as well. PID, FL, ANN and ANFIS have an average efficiency of 85%, which is better than the conventional techniques but still below the acceptable values. Only PSO and hybrid PSO&PO method are able to achieve 99% efficiencies at 10 m/s.

Figure 5.3 shows the efficiency of all MPPT algorithms for various wind speeds.

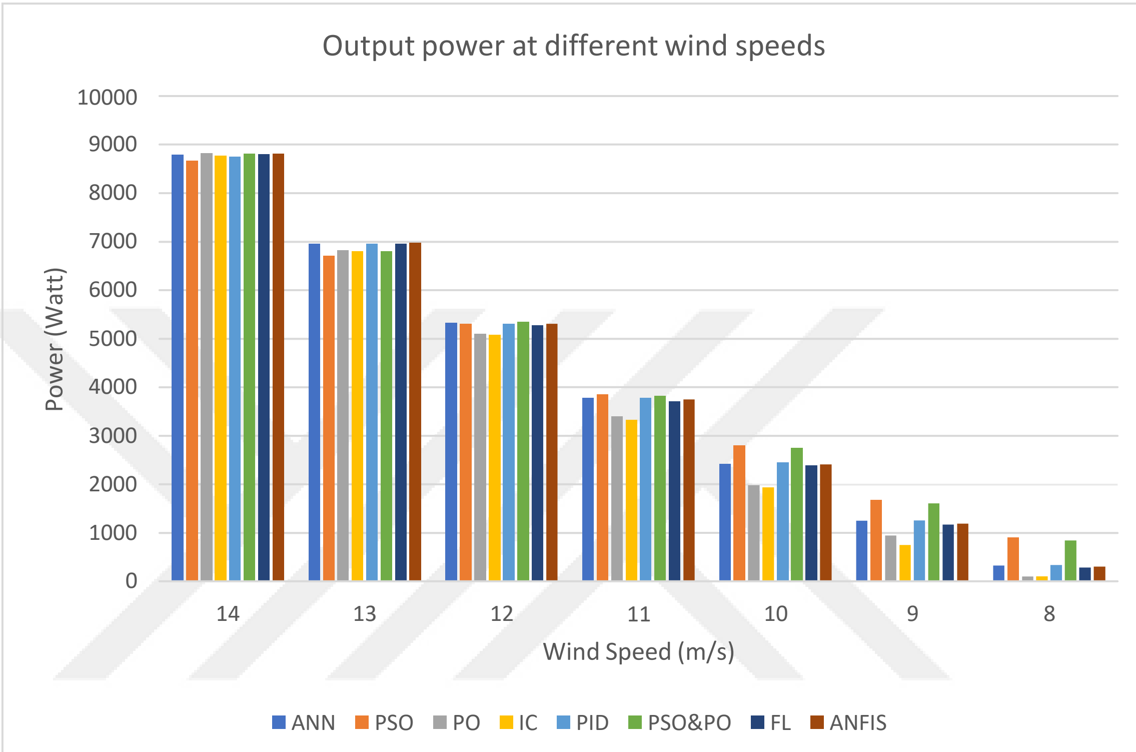

Figure 5.3: Wind system power at different wind speeds for all MPPTs

Figure 5.4 represents the wind turbine output power on log scale. At high wind speeds, all algorithms have almost the same efficiencies, but it changes significantly when the wind speed decreases. At low wind speeds, 10 m/s and below, only PSO and hybrid PSO&PO methods can maintain high efficiency and provide high output power.

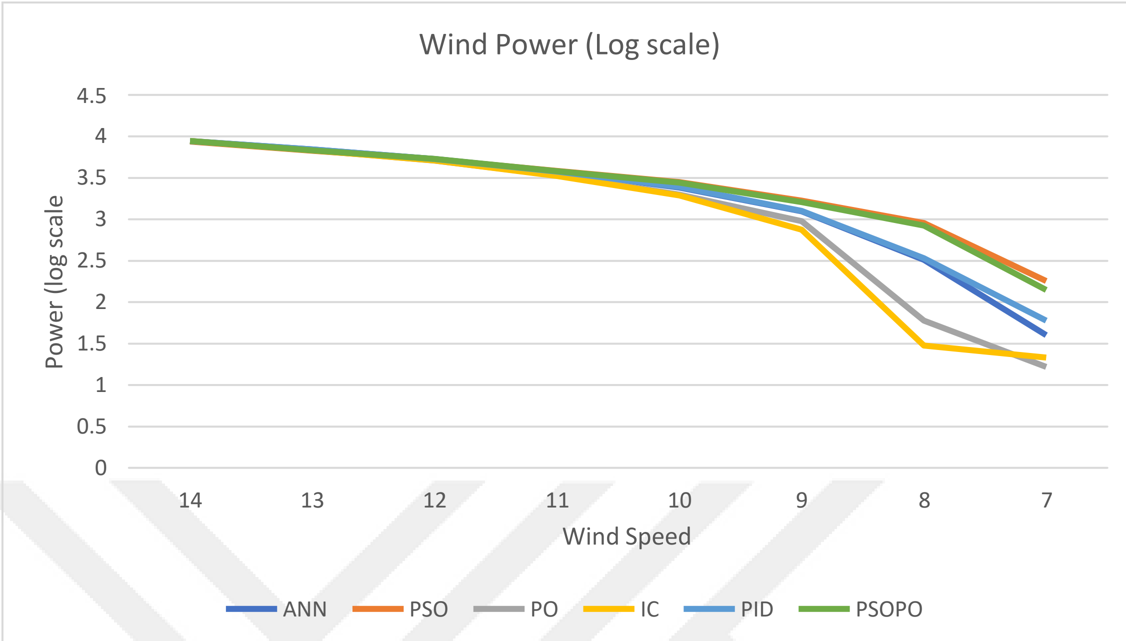

Figure 5.4: Output power comparison of different algorithms (log scale)

Looking at the MPPT tracking time, the speed of conventional MPPTs is moderate. ANN, FL and ANFIS have the fastest MPP tracking speeds. PSO and Hybrid PSO&PO algorithm have high ripples at the beginning and the tracking speed is slow, but once the MPPT is obtained, the settling time of these algorithms is short.

Oscillations around MPP are low for ANN, ANFIS and PID methods and moderate for FL, PSO&PO, and IC methods. For PO and PSO, there are significant oscillations at some wind speeds. The results of ANFIS algorithm are similar to FL and ANN.

The PSO method has high efficiency at low wind speeds with high oscillations and slow MPP tracking speed. By combining PSO with the PO method, the tracking speed, settling time, and oscillations are improved together maintaining high efficiency at low wind speeds.

After analyzing all the parameters such as efficiency at different wind speeds, settling and MPP tracking time, and oscillations, it can be seen that the hybrid PSO&PO is the most suitable algorithm for the wind system. It utilizes the benefits of both PO and PSO methods and yields the best results. Figure 5.5 shows the visual performance of all MPPTs.

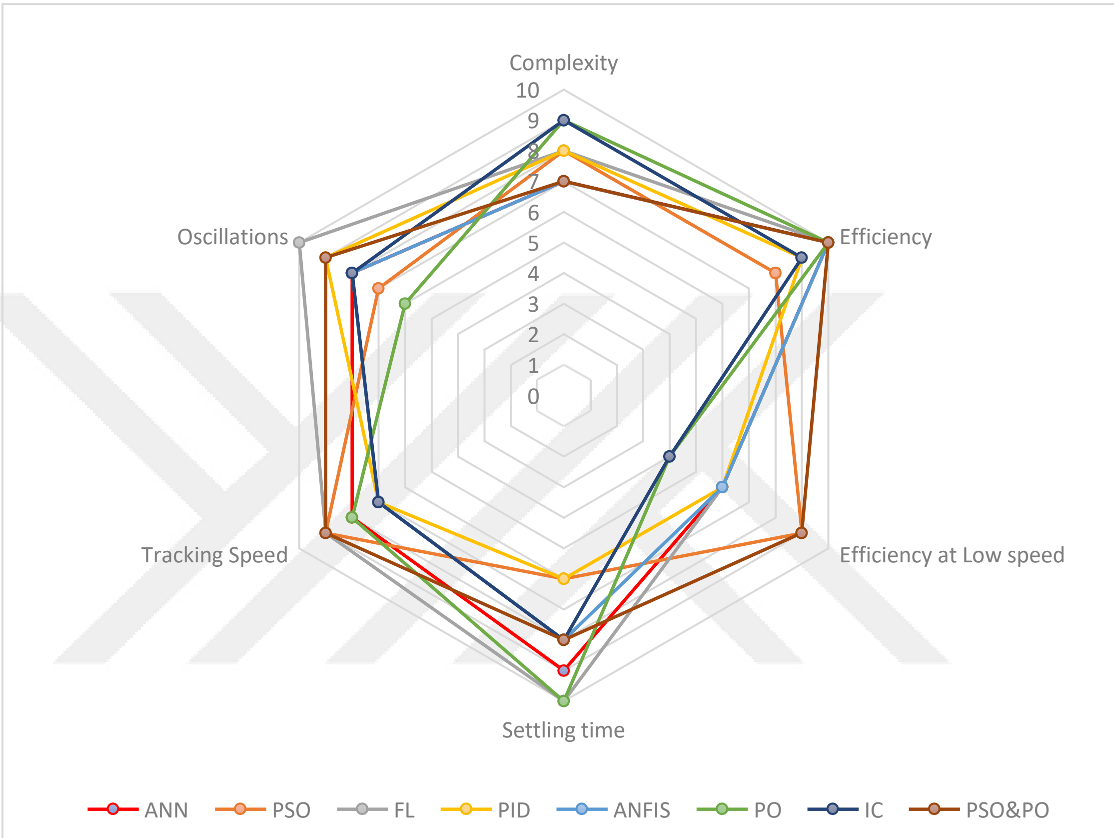

Figure 5.5: Comparative analysis of all MPPTs for Wind system

CHAPTER 6

CONCLUSIONS

This thesis provides a detailed comparison of popular MPPT techniques for solar and wind energy systems. Conventional, AI/ML based, and hybrid techniques were used, and their performance was measured under different operating conditions. Each MPPT was compared based on different metrics such as MPP efficiency at high, normal, and low irradiation levels and wind speeds, MPP tracking time, algorithm complexity, settling time and oscillations around MPP. AI-based techniques are more complex and require more computational power but also provide good convergence speed, low oscillations, and high efficiency under various environmental conditions. For simple and low-cost systems, conventional MPPTs like PO and IC are enough and can deliver adequate results.

ANN and FL were the most efficient MPPT algorithms for solar systems under various irradiation levels. For the wind system, PSO and hybrid PSO&PO were the most efficient algorithms. The PSO method had slow tracking time and large initial oscillations. By combining PSO with PO method, the MPP tracking time improved, and oscillations decreased. An energy management system based on constant load and battery was also developed.

6.1. Recommendations and Future Research

AI-based MPPT techniques are replacing the conventional MPPT techniques. AI techniques use advanced machine learning algorithms to accurately track the maximum power point of the solar panels and wind turbines under a wide range of operating conditions. Conventional MPPT techniques are often designed to work optimally under specific operating conditions. AI-based MPPT techniques can be more adaptable and able to perform well under a wider range of conditions, such as changing weather or panel aging.

In terms of efficiency, AI techniques are more efficient than conventional techniques, as they can optimize the operation of the solar panel or wind turbine in real-time and continuously adjust the operating point to match the maximum power point. This can result in higher output power and improves the overall performance of the system.

Conventional techniques are recommended where a simple and cost-effective solution is required. From the simulation results, it was seen that for both wind and solar systems, AI based techniques are the most effective. A good approach is to combine simple and AI algorithms. For example, for PSO&PO hybrid method, PO method is initially used to catch the MPP quickly and PSO is used to fine tune the MPP.

The analysis is based on simulation results and does not include several factors that are present in real life such as power loss in wires and components, environmental conditions, and other unforeseen events.

For future work, instead of using constant load, a variable load option would be better. In addition to that, energy management system with grid connection will also make the system more efficient and prone to load shedding and excessive power loss.

A good future work would be to implement all these algorithms on actual solar panels and wind turbines to get more accurate practical results which are considered to be more precise.

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