A DISSERTATION

ON

A Qualitative Review of Artificial Intelligence Based MPPT Techniques in PV Systems

Submitted In Partial Fulfilment of the Requirement for the

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In

Electronic Circuits & Systems

Submitted By

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DECLARATION FROM THE CANDIDATE

This is to certify that I, Rubi Khan , (Enrolment No. 1500101121) have completed the M.Tech Dissertation work on topic "**A Qualitative Review of Artificial Intelligence Based MPPT Techniques in PV Systems"** under the supervision of Prof.Tarana Afrin Chandel for the partial fulfilment of the requirement for the Master of Technology in Electronics Circuit and system from Department of Electronics and Communication Engineering, Integral University, Lucknow. This is an original piece of work & I have not submitted it earlier elsewhere.

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CERTIFICATE

This is to certify that Rubi Khan (1500101121) carried out the Dissertation work on "**A Qualitative Review of Artificial Intelligence Based MPPT Techniques in PV Systems** " Submitted in partial fulfilment for the award of degree of Master Of Technology in ECS. From Department of Electronics and Communication Engineering, Integral University, Lucknow under my Guidance. To the best of my knowledge, the contents of this dissertation have not been submitted to any other institute or university for the award of any degree.

Signature of Supervisor

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ABSTRACT

The integration of artificial intelligence (AI) techniques in photovoltaic (PV) systems has gained significant attention in recent years, particularly in the area of maximum power point tracking (MPPT). MPPT plays a crucial role in optimizing the energy conversion efficiency of PV systems by dynamically tracking the maximum power point of the solar panels. This dissertation presents a qualitative review of AI-based MPPT techniques in PV systems, aiming to evaluate their effectiveness, suitability, and potential for improving PV system performance and overall energy efficiency. The dissertation begins with a comprehensive literature review, exploring the fundamental principles underlying MPPT techniques and the advancements in AI algorithms. Various AI-based MPPT techniques, including machine learning, neural networks, fuzzy logic, and genetic algorithms, are analysed in detail, considering their performance, advantages, and limitations. Comparative studies are conducted to assess the efficiency and accuracy of these techniques in real-world PV systems, highlighting the factors influencing their effectiveness.

Moreover, case studies and real-world examples are presented to demonstrate the implementation of AI-based MPPT techniques in PV systems. The outcomes and impacts of these implementations are discussed, shedding light on the practical applications and benefits of AI in advancing MPPT technology. The dissertation also addresses the challenges and potential drawbacks associated with AI-based MPPT techniques, such as computational complexity, model training requirements, and the need for accurate data acquisition.

Based on the findings and analysis, recommendations for future research in the field of AI-based MPPT techniques in PV systems are provided. The dissertation emphasizes the significance of continued research and development to overcome the challenges and enhance the performance of AI-based MPPT techniques. Furthermore, it underscores the potential for AI to revolutionize the field of MPPT and contribute to the increased adoption of PV systems for sustainable energy generation.

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LIST OF ABBREVIATIONS

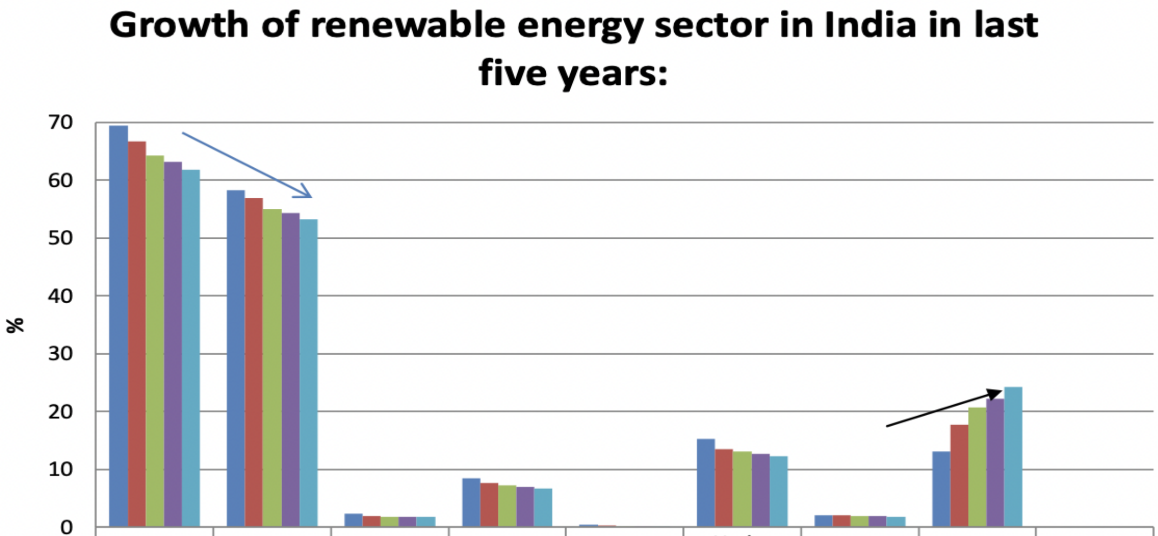
AI	Artificial Intelligence
ANN	Artificial Neural Network
AS	Active Solar
BC	Boost Converter
BP	Back Propagation algorithm
BRM	Boltzmann Restricted Machines
C	Constant
CV	Constant Voltage
COG	Centre of Gravity
CNN	Convolution Neural Network
DC	Direct Current
DBN	Deep Belief Network
E	Error
FL	Fuzzy Logic
FLC	Fuzzy Logic Controller
IC	Incremental Conductance
IGBT	Insulated Gate Bipolar Transistor
I-V PV	Current Vs Voltage
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MFs	Membership Functions
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MSE	Mean Square Error
OC	Open Circuit
PI	Proportional – Integral
P&O	Perturb and Observe
PV	Photovoltaic
P-V	PV Power Vs Voltage

CHAPTER 1

INTRODUCTION

1.1. An Overview

Renewable energy resources have made a noteworthy contribution to India's energy sector. In recent years, heightened environmental consciousness has resulted in the efficient utilization of renewable energy sources. The deleterious impacts stemming from the utilization of fossil fuels have engendered a surge in the attention devoted to sustainable energy alternatives. According to the International Energy Agency (IEA), renewable energy is defined as energy derived from naturally replenishing resources. Renewable energy technologies can be categorized into three generations based on their development and implementation. Currently, the initial cohort of energy technologies, namely biomass, geothermal, and hydro, are widely utilized. Modern forms of second-generation technologies include biomass, solar, and wind power.[1] Presently, these technologies are being implemented and are being encouraged for extensive advancement through governmental incentives aimed at verifying cost mitigation. The third-generation technologies encompass the cutting-edge technologies that are currently in the developmental phase. The utilization of these technologies is not yet prevalent in the market. The aforementioned technologies encompass advanced biomass gasification, biorefinery technologies, concentrating solar power, hot rock geothermal power, ocean energy, and nanotechnology. The aforementioned statement underscores the significance of renewable energy technologies, which serve as primary drivers of energy potential and bolster energy security by mitigating reliance on traditional resources and guaranteeing autonomous energy provisions.[2] Renewable energy technologies have the notable advantage of mitigating the climatological impacts associated with traditional energy sources, including but not limited to global warming. Numerous investigations have been carried out on technologies related to renewable energy. Consequently, the utilization of Renewable Energy Sources (RES) has facilitated the active advancement of power generation systems in numerous nations. Solar energy is considered to be a primary contributor to the production of renewable energy sources (RES). The Photovoltaic (PV) system is utilised in the conversion of the energy emitted by the sun into electricity within the solar energy system.



	Total Thermal	Coal	Lignite	Gas	Oil (Diesel)	Hydro (Renewable)	Nuclear	RES** (MNRE)
2015	69.5	58.26	2.33	8.5	0.4	15.3	2.1	13.1
2017	66.78	56.98	1.92	7.62	0.253	13.5	2.05	17.65
2018	64.23	55.03	1.83	7.18	0.183	13.07	1.95	20.73
2019	63.24	54.34	1.74	6.96	0.178	12.68	1.89	22.17
2020	61.8	53.3	1.7	6.7	0.1	12.2	1.8	24.2

Fig. 1.1: Growth of renewable energy sector in India

The present study concerns the utilisation of solar energy, which is defined as the radiant light and heat energy emitted by the sun. The harnessing of this energy is achieved through the use of photovoltaic cells, which are designed to convert the sun's energy into electrical power. The photovoltaic cell is a semiconductor device that facilitates the direct conversion of solar radiation into electrical energy. The process of photovoltaic conversion holds significant importance in the context of industrialised nations. The utilisation of photovoltaic systems involves the utilisation of solar panels that are composed of multiple solar cells constructed from semiconducting materials that demonstrate the photovoltaic effect.[3] The photovoltaic effect is a phenomenon in which incident photons of light are capable of elevating electrons to higher energy states, thereby enabling them to function as charge carriers for an electric current.The purpose of this dissertation is to present a comprehensive outline of artificial intelligence (AI)-driven maximum power point tracking (MPPT) methodologies for photovoltaic cells. The present study involves an extensive review of the literature to gain a deeper understanding of the progress and accomplishments in the field. It investigates the approaches employed for assessing AI-based Maximum Power Point Tracking (MPPT) methods, presents the findings and analyses, emphasising the advantages and limitations of their implementation, and culminates with an assessment of the importance of AI-based MPPT techniques in augmenting the efficacy of solar cell systems.

1.2. Rationale of the Study

The integration of Artificial Intelligence (AI) in photovoltaic (PV) systems has shown great promise in enhancing the performance of Maximum Power Point Tracking (MPPT) techniques. However, despite the growing interest in AI-based MPPT techniques, there is a need for a comprehensive qualitative review of these techniques in order to assess their effectiveness, advantages, and limitations. Currently, there is a lack of a consolidated body of knowledge that critically evaluates the application of AI in MPPT algorithms specifically for PV systems. Existing research primarily focuses on individual AI-based MPPT techniques without providing a comprehensive comparative analysis or evaluating their real-world implementation and impact. Therefore, the problem to be addressed in this dissertation is the absence of a qualitative review that examines and assesses the potential of AI-based MPPT techniques in PV systems. By conducting a systematic analysis and evaluation of these techniques, including their performance, applicability, and potential benefits, this study aims to bridge the existing knowledge gap and provide valuable insights for researchers, practitioners, and industry professionals in the field of PV systems and AI-based MPPT technology. The dissertation seeks to answer important research questions such as:

1. What are the performance characteristics and limitations of AI-based MPPT techniques in PV systems?
2. How do these techniques compare to traditional MPPT methods in terms of efficiency and effectiveness?
3. What are the key factors influencing the implementation and performance of AI-based MPPT techniques in real-world PV systems?
4. What are the potential benefits and challenges associated with integrating AI into MPPT algorithms for PV systems?

By addressing these research questions, the dissertation aims to contribute to the existing knowledge base, provide valuable insights for decision-making in PV system design and implementation, and lay the groundwork for future advancements in AI-based MPPT techniques for PV systems.

1.3. Aim & Objective

1. To assess the effectiveness of AI-based MPPT techniques in improving the efficiency of solar cells.
2. To compare and evaluate different AI algorithms for MPPT in terms of accuracy and convergence speed.
3. To investigate the impact of AI-based MPPT techniques on the performance of solar cells under varying environmental conditions.
4. To identify the advantages and limitations of AI-based MPPT techniques and propose recommendations for their practical implementation.

1.4. Research Methodology

This dissertation will adopt a non-empirical research methodology, primarily centred on an extensive literature review and critical analysis of previous studies pertaining to AI-based MPPT techniques for solar cells. The objective is to amass exhaustive data and perspectives from diverse academic sources, such as scholarly publications, articles, patents, and other pertinent literature. Through the process of synthesising and analysing the gathered data, my objective is to make a valuable contribution to the current body of knowledge in this particular field. Additionally, I intend to put forth practical recommendations for the successful implementation of AI-based MPPT techniques in solar cell systems.

1.5. Organisation of Dissertation

The present dissertation is structured into five distinct chapters, apart from the current introductory chapter with each section dedicated to a specific aspect of the research. The following is an overview of the organisation of the research work.

Chapter-2: "Unravelling the Fundamentals: Exploring Photovoltaic Cell Operation and Parameters for Solar Energy Conversion"

This chapter provides an in-depth analysis of the fundamental principles underlying the operation of photovoltaic (PV) cells, with a focus on their basic physical mechanisms. The present discourse commences with a comprehensive exposition of the solar spectrum and its pertinence to photovoltaic (PV) technology. Subsequently, the photovoltaic phenomenon is analysed, which serves as the basis for the transformation of solar energy into electrical energy in photovoltaic cells. Furthermore, the fundamental parameters of solar photovoltaic cells that are imperative for modelling their performance are examined.

This chapter aims to provide with a comprehensive comprehension of the fundamental principles that govern photovoltaic (PV) cells, including the solar spectrum, the photovoltaic effect, significant cell parameters for simulation, as well as various array topologies and maximum power point tracking (MPPT) techniques utilised in the PV technology field.

Chapter -3: Exploring the Cutting-Edge AI Technologies for Solar PV: A Comprehensive Review

A thorough investigation of the presently available techniques is imperative to ascertain the potential implementation of artificial intelligence and its scope. This chapter aims to provide an overview of the current state of artificial intelligence (AI) in the solar photovoltaic (PV) value chain. In order to achieve this objective, a comprehensive analysis of multiple research papers from diverse sources has been conducted to provide an accurate portrayal of the scope of artificial intelligence. The forthcoming chapter on results in this dissertation will encompass a specific cohort of AI methodologies that have been employed in the solar photovoltaic value chain.

Chapter -4: Comparative Analysis of AI-Based MPPT Techniques

This chapter presents a thorough examination of various AI-based Maximum Power Point Tracking (MPPT) techniques, with a particular emphasis on their performance, benefits, and drawbacks. The introductory section of the chapter presents a comparative analysis of the efficacy of various techniques in photovoltaic (PV) systems, while taking into account the factors that impact their operational efficiency. Additionally, the paper presents empirical case studies and exemplars that demonstrate the practical application of AI-driven MPPT methodologies in authentic photovoltaic systems. The presented case studies provide valuable insights regarding the practical applicability and effectiveness of utilising AI in MPPT algorithms, thereby shedding light on the resulting outcomes and impacts. The present chapter aims to conduct a comprehensive analysis and assessment of AI-driven Maximum Power Point Tracking (MPPT) methods, thereby facilitating a more profound comprehension of their efficacy and demonstrating their potential advantages in the domain of Photovoltaic (PV) systems.

Chapter 5: Evaluation of AI-Based MPPT Techniques

This chapter presents a thorough evaluation of the efficacy and appropriateness of AI-based Maximum Power Point Tracking (MPPT) methods. The evaluation is based on a comprehensive analysis and the insights obtained from the case studies presented. This chapter investigates the capacity of artificial intelligence (AI) techniques to augment the performance of photovoltaic (PV) systems and improve their overall energy efficiency. The chapter endeavours to conduct a thorough evaluation process to offer a comprehensive assessment of the advantages and disadvantages linked to AI-driven Maximum Power Point Tracking (MPPT) techniques. Through an examination of performance metrics and an evaluation of their suitability across various contexts, the chapter provides significant perspectives on the potential of these techniques to enhance the efficiency and efficacy of photovoltaic systems. In general, this chapter presents a scholarly assessment of AI-driven Maximum Power Point Tracking (MPPT) methods, imparting a more profound comprehension of their influence on photovoltaic (PV) system operation and their capacity to augment overall energy efficacy.

Chapter 6: Simulation Test Results of Different Maximum power point tracking (MPPT) Methods

This chapter provides an overview of various MPPT techniques that can be employed to maximize the output power of a photovoltaic (PV) array. The research work presented in this chapter focuses on different maximum power-point tracking techniques, namely perturb and observe (P&O), fuzzy logic control (FLC), artificial neural network (ANN) systems, convolutional neural networks (CNN), and deep belief networks (DBN).The research work discussed in this chapter aims to address the challenges of maintaining the MPP in the context of rapid changes in irradiance and temperature conditions. By evaluating and comparing different MPPT techniques, researchers can identify the most suitable method for optimizing power output in dynamic scenarios. Overall, this chapter sets the stage for further exploration of the proposed MPPT techniques, providing insights into their application and potential benefits in maximizing the power output of PV arrays under challenging environmental conditions.

Conclusion and Future Research Directions

The final section of this scholarly dissertation provides a summary of the principal discoveries obtained from the investigation carried out on AI-driven Maximum Power Point Tracking (MPPT) methodologies in photovoltaic (PV) systems. The chapter elucidates the principal findings and perspectives garnered during the investigation. The chapter presents a succinct overview of the principal discoveries, highlighting the efficacy of AI-driven maximum power point tracking (MPPT) methods.

CHAPTER-2

"UNRAVELLING THE FUNDAMENTALS: EXPLORING PHOTOVOLTAIC CELL OPERATION AND PARAMETERS FOR SOLAR ENERGY CONVERSION"

2.1. Solar Energy

Solar energy is widely regarded as a prominent and highly promising source of energy in comparison to other renewable energy sources, including geothermal and tidal energy. The sun is widely recognised as a spheroid composed of scorching gases, and it holds the distinction of being the most sizable constituent of our solar system. The object in question exhibits a black-body temperature of 5777 K, which is deemed to be effective. The Sun can be described as a spherical object with a diameter measuring 1.39 x 109 metres. It is situated at an average distance of 1.5 x 1011 metres from the Earth. The object in question is a spheroid composed of highly heated gaseous material, wherein the energy is produced through the process of fusion reactions involving the combination of four hydrogen nuclei with a single helium nucleus. Figure 1.1 illustrates that the peak spectral intensity is observed at approximately 0.48 μm within the green region of the visible spectrum. Approximately 8.73% of the overall energy received falls within the ultraviolet region at a wavelength of 0.40 μm. Additionally, approximately 38.15% of the energy is present in the visible region, spanning from 0.40 μm to 0.70 μm. The remaining 53.12% of the energy is situated in the infrared region at a wavelength of 0.70 μm.[13]

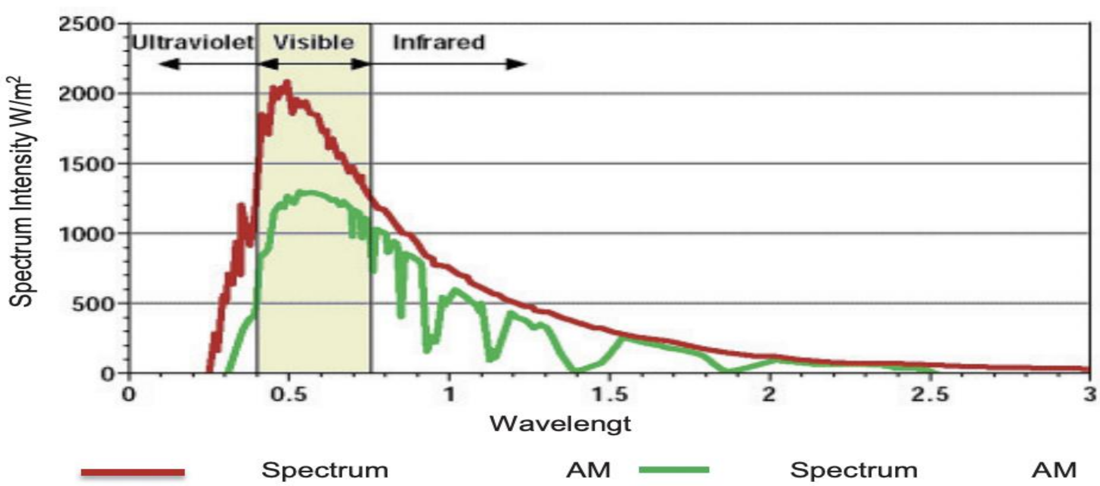


Fig.2.1. Extra-terrestrial and terrestrial spectrum of sunlight

2.2. Photovoltaic Technology

Photovoltaic (PV) modules, composed of numerous solar cells made from semiconductors like silicon, have the ability to convert sunlight directly into electrical energy. The etymology of the term photovoltaic can be traced back to its Greek roots, where "photo" signifies light and "voltaic" refers to electricity. The widely accepted acronym for photovoltaic is PV. The discovery of the photovoltaic phenomenon dates back to 1839, when Edmond Becquerel, a French physicist, observed that a metal electrode exposed to light could produce electricity from a weak electrolyte solution. The photovoltaic effect in solids was initially investigated by Adam and Day in 1876. A selenium-based solar cell was fabricated with an efficiency ranging from 1% to 2%. Further, in 1954, the initial production of solar cells yielded an efficiency of approximately 5%. Initially, solar cells were designed with a primary focus on their utility in space-related contexts, thereby rendering cost considerations relatively insignificant. In recent decades, there has been a steady increase in the efficiency of solar cells, coupled with a significant decline in costs. The utilisation of silicon as the primary constituent in the construction of solar cells has been widely acknowledged. However, in order to enhance efficiency and minimise expenses, alternative components and compounds have been devised (Quaschning, 2016)[14].

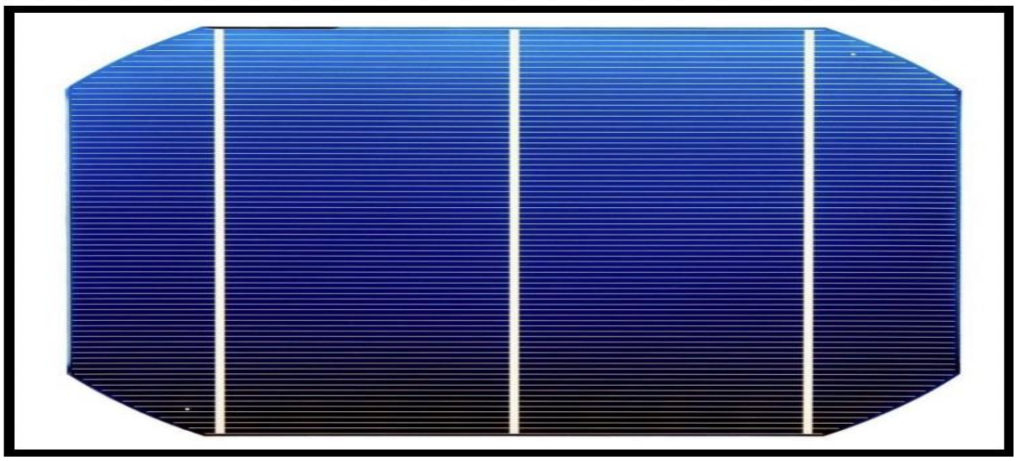


Fig.2.2 Solar Cell

Figure 1.2 depicts a basic solar cell. The utilisation of solar photovoltaic technology is a compelling option due to its ability to harness an abundant and pristine energy source, namely the sun. In other words, a photovoltaic (PV) system harnesses the energy emitted by the sun and transforms it into electrical energy through the utilisation of semiconductors. The output terminal of a solar photovoltaic (PV) panel generates both current and voltage upon exposure to sunlight. The electrical potential difference and flow of electric charge at our disposal can be harnessed to provide energy for residential dwellings. The process of converting light into electrical energy in solar photovoltaic technology is facilitated through the utilisation of semiconductor materials. For a solar cell to operate, it is imperative that it possesses a junction that interconnects two distinct semiconductors.[15]

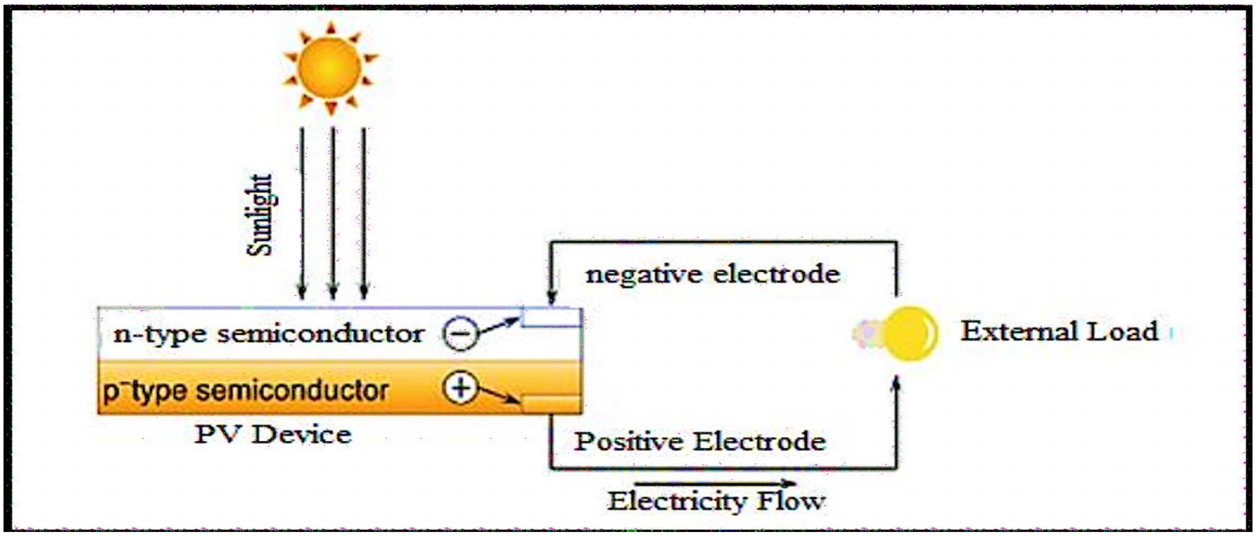


Fig.2.3. Fundamental Operation of a PV Cell

2.3.The theory of photovoltaic system

The photovoltaic (PV) system operates on the principle of transforming solar energy into electrical energy by means of solar cells. Photovoltaic cells, commonly referred to as solar cells, are semiconductor instruments that produce an electrical current upon exposure to light. The fundamental basis of a photovoltaic (PV) system is the photovoltaic effect. The aforementioned phenomenon is observed when photons originating from solar radiation come into contact with the surface of a photovoltaic cell, leading to the transference of their energy to electrons present in the semiconductor material. Consequently, the excitation of electrons leads to their liberation, thereby generating an unobstructed movement of electric charge, commonly referred to as electric current. A photovoltaic cell is comprised of two distinct layers of silicon, namely the n-type and p-type layers, arranged in a sandwich-like structure. When a p-type semiconductor is joined with an n-type semiconductor, the electrons in the vicinity of the junction migrate from the n-region to the p-region, while the holes in the vicinity of the junction move from the p-region to the n-region. This process results in the formation of a depletion layer. The depletion layer in a semiconductor device is characterised by the localization of electrons in the P region and holes in the N region.[4] This spatial separation of charge carriers results in the establishment of an electric field within the depletion layer, which arises from the migration of electrons and holes. The depletion layer, also known as the space charge region, serves as a barrier that impedes the movement of charge carriers from one side to the other. When a semiconductor is exposed to sunlight, photons collide with the electrons of the silicon atoms, resulting in the displacement of these electrons and the creation of additional free electrons and free holes. The phenomenon of photogeneration of charge carriers occurs in both negative and positive type semiconductors, wherein the electric field causes the direction of electron movement to be towards the negative side and the direction of gap flow towards the positive side. The phenomenon of the generation of positive and negative charges during the formation of a junction is commonly referred to as voltage or potential difference.[1] A potential difference of approximately 0.5 V is formed between the sides of the solar cell where the negative charge accumulates on one position and the positive charge accumulates on the other position, as depicted in Figure 1.4.The magnitude of the electric potential difference in a solar cell is contingent upon the material utilised and is independent of the surface area of the cell.

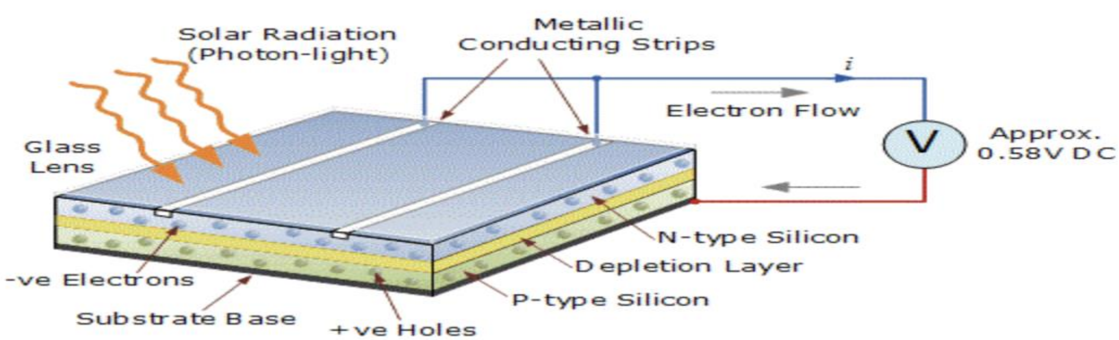


Fig.2.4. Solar cell components and its principle

2.4. Basic parameters of solar PV cell

The fundamental aspects of solar cells can be effectively elucidated through the electrical properties of photovoltaic cells, which demonstrate a correlation between cell voltage and current, as well as a correlation between cell voltage and power. The electric parameters that are crucial in characterising the functioning of the photovoltaic (PV) cell comprise the open circuit voltage (V_{OC}), short circuit current (I_{SC}), and the voltage, current, and power at the maximum power point (V_{MPP}, I_{MPP}, and P_{MPP}, respectively).[7]

2.4.1.Short circuit current (I_{SC})

The short circuit current refers to the highest attainable magnitude of current within a circuit, achieved when the positive and negative terminals are joined together at zero voltage. Stated differently, when the circuit is not connected to any load. The magnitude of the short circuit current is directly correlated with the intensity of the incident sunlight.(**Maki & Valkealahti,2012**)[18]

2.4.2.Open circuit voltage (V_{OC})

The open circuit voltage refers to the maximum voltage value that can be achieved when there is no current flowing through the circuit. Stated differently, the open circuit voltage denotes the highest attainable voltage magnitude in a circuit when a substantial load is introduced. **(Tiwari & Dubey,2010)[19]**

2.4.3. Maximum power point (P_{MPP})

The maximum power output is defined as the product of the voltage (VMPP) and the current (IM_{PP}). This operating point is decided by choosing the correct value of the connected load:

$$P_{MPP} = V_{MPP} \chi I_{MPP}$$

Where V_{MPP} and I_{MPP} are voltage and current values at the maximum operating power.

2.4.4. Fill factor (FF)

The fill factor is a metric that denotes the efficacy of the photovoltaic cell. The fill factor attains its upper bound at unity, which represents the maximum theoretical value. The magnitude of this parameter is contingent upon the specific type of semiconductor material employed. The highest attainable fill factor in silicon that is practically feasible is 0.88. The term FF, or fill factor, is characterised as the quotient of the highest produced power at the maximum power point (MPP) and the maximum potential power, which is obtained by multiplying the short-circuit current (I_{SC}) by the open-circuit voltage (V_{OC}).

$$FF = \frac{\text{Power Generated (Practically)}}{\text{Power Generated (Theoritically)}} = \frac{V_{MPP} \chi I_{MPP}}{V_{OC} \chi I_{OC}}$$

2.4.5.Efficiency of solar cell

Out of total energy, only part of the solar radiation incident on the solar cell is converted into electricity. The conversion efficiency of the PV cell is defined as “the ratio between the produced electrical power and the amount of incident solar energy per second” . The equation of solar cell power conversion efficiency is:

$\eta = (P_{max} / P_{in}) * 100\%$

Here:

η represents the power conversion efficiency, expressed as a percentage.

P_{max} denotes the maximum power output of the solar cell, typically obtained at the maximum power point (MPP).

P_{in} refers to the input power from the incident sunlight onto the solar cell.

The assessment of a solar cell's performance is heavily reliant on the crucial parameter of power conversion efficiency. The photovoltaic efficiency of a solar cell is a measure of its capacity to convert solar radiation into electrical energy. This parameter is subject to the influence of multiple factors, including the composition of the materials employed, the design of the cell, and external variables such as temperature and irradiance. The enhancement of power conversion efficiency in solar cells can be achieved by optimising the power output (Pmax) and minimising the input power (Pin). This approach leads to the generation of higher electrical power output from the available sunlight, thereby increasing the efficiency of the solar cell.[11]

2.4.6. Characteristics of a PV cell

The PV cell's performance can be represented by various parameters, including voltage (V), current (I), and power (P), as demonstrated in the following display of PV cell characteristics. The aforementioned values are contingent upon the incident solar radiation received by the surface of the solar cell. The current-voltage characteristic (I-V) and power-voltage characteristic (P-V) are formed by the values of V, I, and P. The photovoltaic cell exhibits non-linear characteristics. [20]

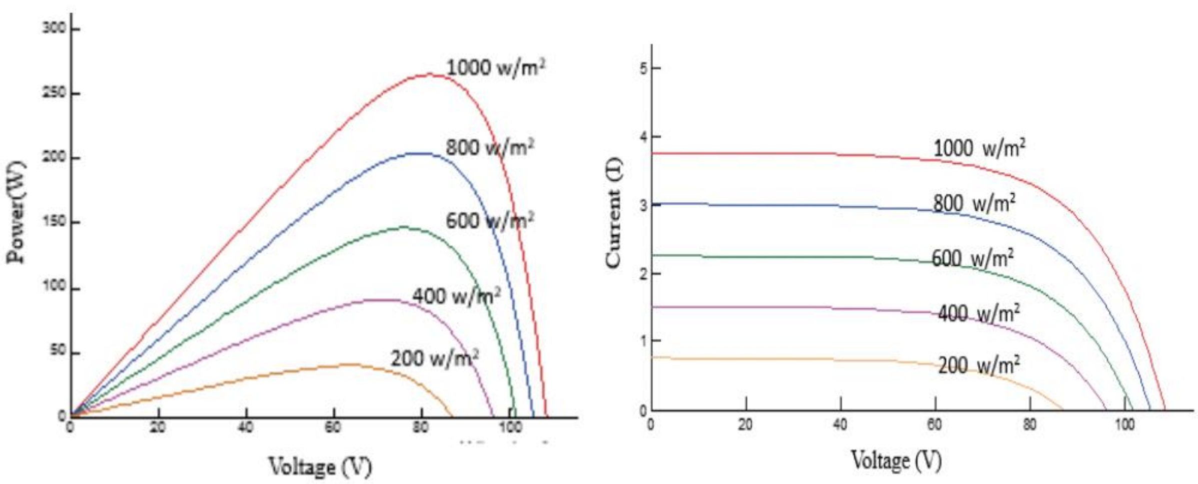


Fig.2.5. Power–Voltage and Current-Voltage solar cell characteristics

The performance of a photovoltaic (PV) cell is influenced by various factors, including the material composition of the solar cell, ambient and cell temperature, solar radiation intensity, inclination angle, and irradiation mismatch of the cells. Solar irradiance and temperature are the primary factors that significantly impact the performance of photovoltaic cells. The relationship between irradiance and output power is direct, whereby an increase in the former leads to a corresponding increase in the latter, while holding temperature constant. However, an increase in temperature of the cell has an inverse effect on output power, resulting in a reduction thereof.

2.5.Types of Photovoltaic Systems

PV power systems are commonly classified based on their functional requirements, module arrangements, manner of connection with other energy sources, and electrical loads. Photovoltaic systems are being evaluated as a potential source of DC and/or AC power, capable of functioning either in conjunction with or independently of the utility grid.[21] Photovoltaic (PV) systems facilitate the establishment of a correlation between alternative power sources and power storage systems. There are two primary classifications, namely:

1. Grid-connected or utility-interactive systems

2. Stand-alone systems

2.5.1. Grid-connected or utility-interactive systems

Grid-connected or utility-interactive systems, commonly known as grid-tied systems, are photovoltaic (PV) systems that are directly linked to the electrical grid. The aforementioned systems facilitate the smooth amalgamation of electricity generated through solar means with the utility grid, thereby enabling the utilisation of solar energy as well as the option to procure power from the grid as per requirement. The grid-connected photovoltaic (PV) systems possess several noteworthy attributes and benefits, which are as follows:

Grid Integration: The photovoltaic (PV) systems that are connected to the grid are intended to function simultaneously with the utility grid. The conversion of direct current (DC) generated by solar panels into alternating current (AC) that aligns with the voltage and frequency of the grid is achieved through the utilisation of an inverter. The system is capable of facilitating the process of supplying surplus electricity to the grid and procuring electricity from the grid during periods of inadequate solar energy production. [21]

Net Metering: The utilisation of net metering is a noteworthy benefit associated with grid-connected systems. The practise of net metering enables proprietors of photovoltaic systems to obtain compensation for the surplus electrical energy they produce and supply to the power grid. The utilisation of this credit has the potential to mitigate the amount of electricity sourced from the grid during periods of inadequate solar energy generation, thereby leading to a reduction in the overall cost of electricity bills.

Grid Stability and Backup: The dependability and accessibility of the utility grid are crucial for the operation of photovoltaic (PV) systems that are connected to the grid. During instances of reduced solar output, such as during overcast weather or at night-time, the system has the capability to procure electricity from the grid to fulfil the energy requirements. The implementation of this approach guarantees an uninterrupted and dependable source of electricity, thereby obviating the necessity for auxiliary power sources such as battery storage units or backup generators.[11]

Environmental Benefits: The integration of photovoltaic (PV) systems with the grid has been shown to have a positive impact on the environment and promote sustainable energy practises. Through the utilisation of solar energy and the reduction of dependence on electricity generated from fossil fuels, these systems aid in the reduction of carbon emissions and the alleviation of environmental consequences linked to conventional power production.[22]

Cost Savings: The implementation of grid-connected photovoltaic (PV) systems has the potential to yield considerable economic benefits in the long run. Net metering allows for the surplus electricity produced by a given system to be utilised to offset the amount of electricity drawn from the grid, thereby resulting in a reduction or complete elimination of electricity expenses. Furthermore, a range of financial incentives, including tax credits and feed-in tariffs, may be accessible to provide additional motivation for the deployment of grid-tied photovoltaic systems.[23]

Grid Services and Integration: Photovoltaic (PV) systems that are connected to the grid have the potential to offer significant benefits to the grid, including the ability to reduce peak demand and balance loads. In times of elevated electricity demand, the solar production of the system can mitigate the burden on the grid and bolster its stability. In addition, the distributed nature of photovoltaic (PV) systems that are connected to the grid can be utilised by grid operators to improve the overall resilience of the grid and optimise energy management.[24]

Grid-connected or utility-interactive PV systems offer numerous benefits, including the ability to leverage solar energy while maintaining a reliable power supply from the grid. These systems play a crucial role in the transition to a cleaner and more sustainable energy future, promoting the widespread adoption of solar power generation while ensuring grid stability and reliability. Grid-connected or utility-interactive PV systems are executed to function parallel and interrelated by the electric grid. The general architecture of grid-connected PV systems consists of components namely,

- Photovoltaic array
- Power conditioner or Inverter
- Distribution panel.

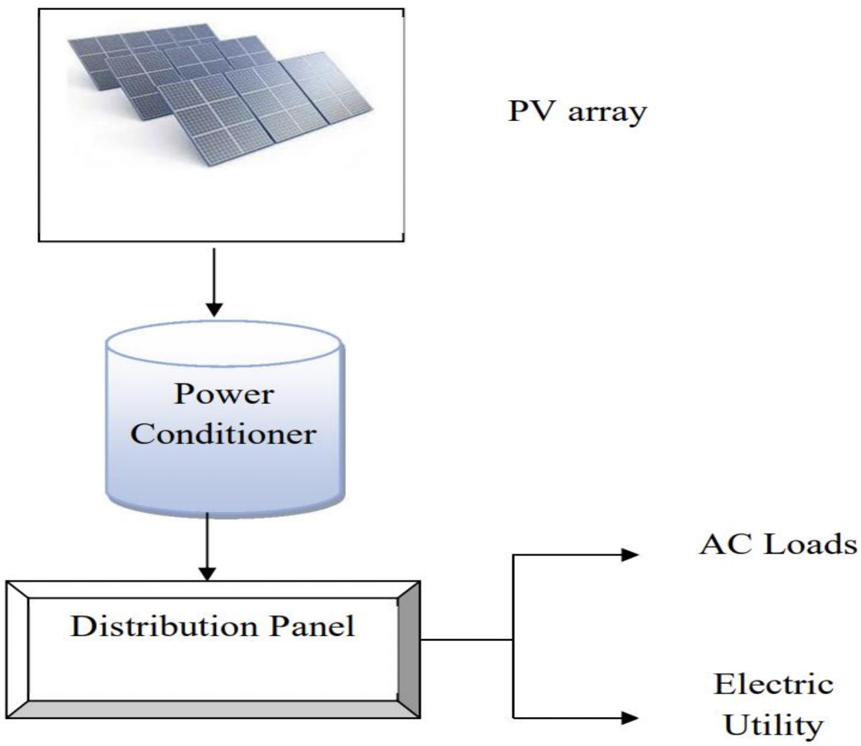


Fig.2.6 Architecture of Grid-connected PV System

2.5.2. Stand-Alone Photovoltaic Systems

Autonomous solar energy systems, commonly referred to as off-grid systems or stand-alone photovoltaic (PV) systems, function independently without any reliance on the utility grid. The aforementioned systems are specifically engineered to furnish electrical power in regions that are geographically isolated or where access to conventional grid power is either unfeasible or unattainable. Photovoltaic (PV) systems that operate independently of the electric utility grid are designed to provide targeted DC and/or AC electrical loads. The PV-hybrid system, which is a self-contained power system, is fueled by either a photovoltaic (PV) array or a utility power as a supplementary power source. The direct-fixed stand-alone photovoltaic (PV) system involves connecting the DC output of a PV array directly to a DC load. Direct-coupled systems lack batteries for electrical energy storage, thus the loads are restricted to daytime operation.

Here are some key characteristics and advantages of stand-alone PV systems:

Independence from the Grid: Stand-alone PV systems are not reliant on the utility grid for electricity supply. They generate and store their own power using solar panels and batteries, allowing for self-sufficiency in electricity generation. This makes them suitable for remote locations, rural areas, or off-grid applications where extending grid infrastructure is not feasible.

Solar Panels: Stand-alone PV systems consist of solar panels that convert sunlight into direct current (DC) electricity. These panels are typically mounted on rooftops, ground mounts, or other suitable structures to maximize solar energy capture.

Battery Storage: To provide electricity during periods of low or no solar production, stand-alone PV systems incorporate battery storage. Excess energy generated during sunny periods is stored in batteries for later use, ensuring a continuous power supply even during cloudy days or at night.

Charge Controller: A charge controller is an essential component in stand-alone PV systems. It regulates the charging and discharging of batteries, preventing overcharging or deep discharge, which can damage the batteries. The charge controller also optimizes the charging process to maximize battery life and performance.

Inverter: Stand-alone PV systems use an inverter to convert the DC electricity from the solar panels and batteries into alternating current (AC) electricity. This AC power can be used to operate standard household or commercial appliances.

Load Management: To ensure efficient use of available energy, stand-alone PV systems require careful load management. This involves balancing the electrical load with the available solar energy and battery capacity to meet the energy demands of the system without depleting the stored energy.

Backup Generator: In some stand-alone PV systems, a backup generator may be incorporated to provide additional power during prolonged periods of low solar energy or high electricity demand. The generator can charge the batteries or directly supply power to critical loads when needed.

Sustainability and Environmental Benefits: Stand-alone PV systems contribute to sustainable energy practices by utilizing clean and renewable solar power. They reduce reliance on fossil fuel-based electricity generation and help mitigate carbon emissions, making them environmentally friendly and promoting energy independence.

Stand-alone photovoltaic systems offer the flexibility and reliability of generating electricity in locations without access to the utility grid. They provide a viable and sustainable solution for powering remote communities, off-grid buildings, telecommunications infrastructure, and various other applications where grid connection is not feasible or cost-effective.

2.6. Types of Solar Panels

There are three types of solar panel namely :

1. Mono crystalline

2. Poly crystalline

3. Thin film

2.6.1.Mono Crystalline

Monocrystalline cells represent one of the earliest methods for generating electrical power. This method represents the optimal approach for generating electrical energy from solar radiation. Each module comprises a singular silicon crystal. The silicon cells are fashioned cylindrically and bear resemblance to a wafer. The process involves the fusion of individual wafers to form a monocrystalline panel. It exhibits superior performance rates. However, there is a negative correlation between temperature and performance, as an increase in temperature results in a decrease in performance. This is only appropriate for higher temperatures. It is possible for a circuit to break down if the panel is obstructed or shaded. The mono crystalline photovoltaic module exhibits an efficiency range of approximately 15% to 20%.[26]

2.6.2.Poly Crystalline

Polycrystalline silicon solar panels made their debut in the commercial market in 1981. In contrast to mono crystalline solar panels, polycrystalline solar panels do not necessitate the utilisation of the Czochralski process. The process involves the melting of raw silicon, which is then cast into a square mould. Subsequently, the substance is subjected to a cooling process and is subsequently divided into precise square-shaped wafers. The level of silicon waste is lower in comparison to monocrystalline. The polycrystalline solar panel exhibits an efficiency range of approximately 13-16%. [27]

2.6.3.Thin Film

Thin film solar panels are produced through the process of depositing one or multiple thin layers of photovoltaic material onto a substrate. Thin film solar panels can be categorised into various types based on the photovoltaic material that is deposited on the substrate. One such type is amorphous silicon (a-Si).

Cadmium telluride, abbreviated as CdTe, is a compound composed of the elements cadmium and tellurium. Copper indium gallium selenide (CIS/CIGS) is a semiconductor material that has gained significant attention in the field of photovoltaics due to its potential for high efficiency solar cells. Thin film modules exhibit an efficiency range of approximately 7-13%. The performance of solar systems is relatively less affected by high temperatures and shading.[28]

2.7.Equivalent Circuit Of Solar Panel

When a solar cell is connected in parallel with a diode, it would demonstrate the characteristics of a current source. **Ramaraj et al. (2015)**[29] have presented an equivalent circuit model for a solar cell/panel, which comprises a diode, a current source, and two resistors (one in series and the other in parallel). The production of current and voltage occurs when a solar panel is exposed to irradiation, resulting in the generation of electricity. In the context of solar panel modelling, it is common to represent the current source as being in parallel with the diode. However, in practical applications, it is rare to encounter an ideal solar cell. As a result, it is necessary to incorporate two resistances into the circuit: one in series and one in shunt. Semiconducting materials of various kinds are utilised in the fabrication of solar cells. Upon exposure to light, these materials with semiconducting properties exhibit electrical conductivity. The prevalent utilisation of silicon in over 95% of solar cells is attributed to its abundant presence in the Earth's crust.

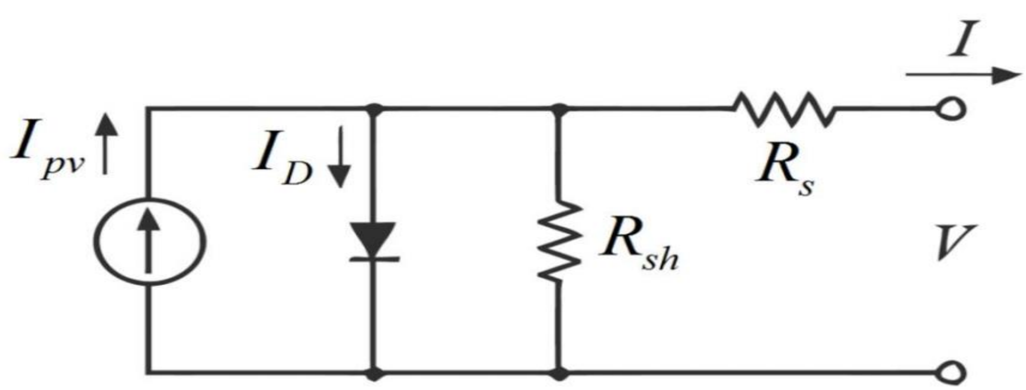


Fig.2.7 Equivalent circuit of a solar panel

2.8. I-V Curve Of Solar Cell

The I-V curve of the above equivalent circuit of a solar panel is given in the figure 1.8 . It includes three points namely short circuit current, maximum power and open circuit voltage.

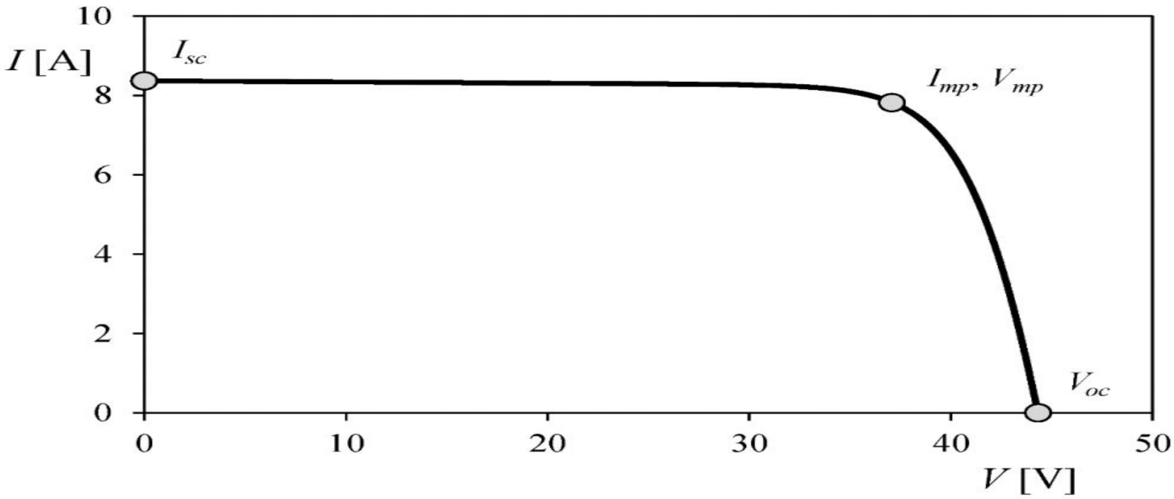


Fig.2.8. I-V curve of a solar panel

2.9. PV Cell Performance With Different Irradiations/ Temperature

Irradiance is the quantification of the power density of sunlight that is received at a specific location on the surface of the Earth. The unit of measurement is expressed as watt per metre square. The scientific term used to quantify the energy density of sunlight is Irradiation. The terms Irradiance and Irradiation are closely linked to solar components. The I-V and P-V characteristics of a solar array exhibit variability in response to fluctuations in solar insolation over the course of a day. Consequently, the maximum power point exhibits variability as a function of the rising solar irradiance due to the concurrent increase in both the short circuit current and the open circuit voltage. The temperature is a significant determinant of the efficiency of solar cells. The relationship between the rate of photon generation and temperature is direct, resulting in a corresponding increase in the reverse saturation current. This increase occurs at a rapid pace and leads to a reduction in the band gap.

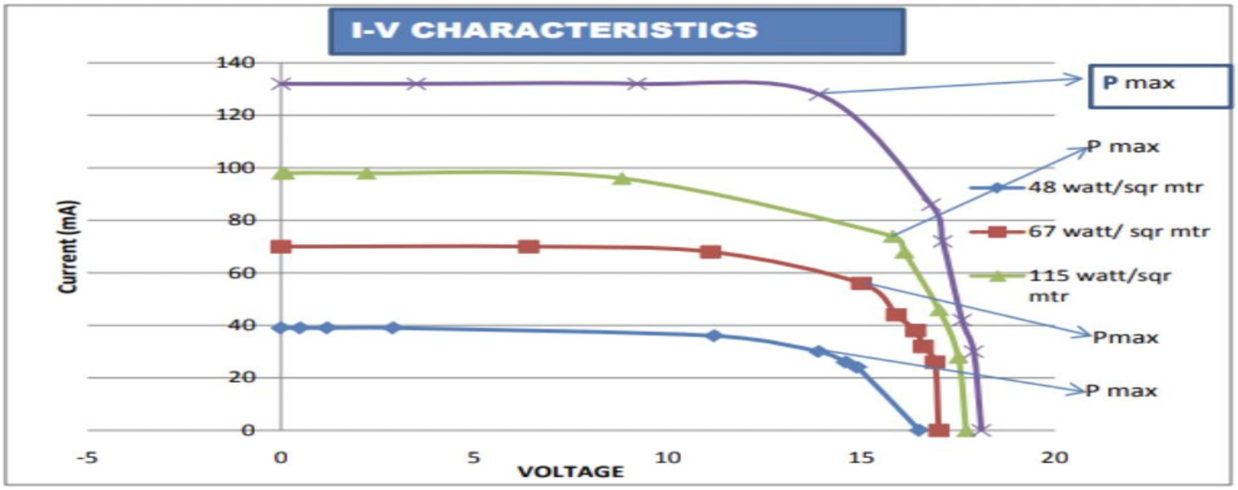


Fig.2.9. Current versus voltage curve at various irradiance levels

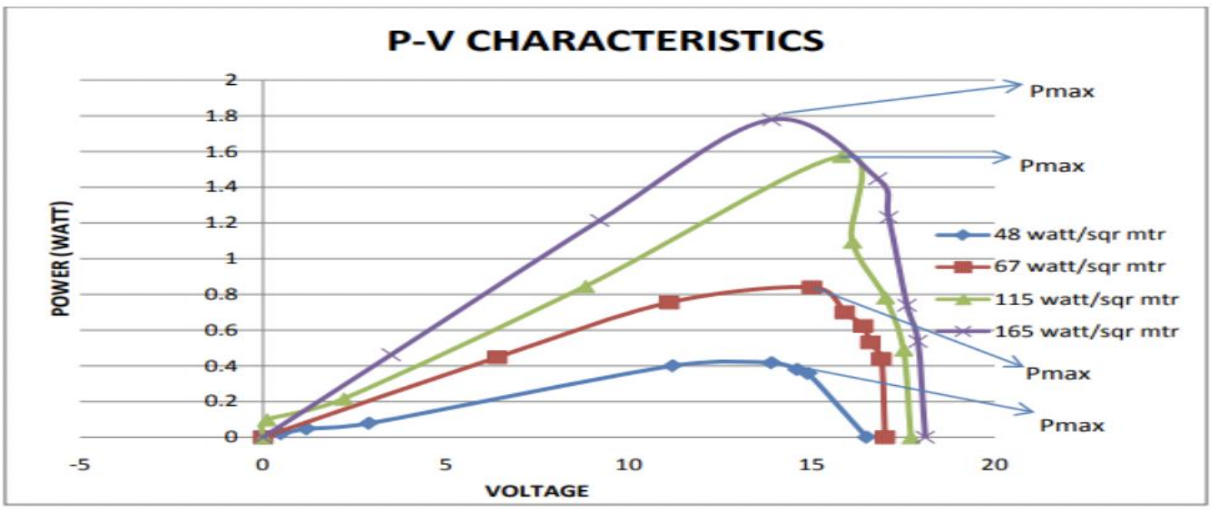


Fig.2.10. Power versus voltage characteristics at various irradiance levels

2.9.1 PV Cell Performance with Different Temperature Level

The generation of solar power is significantly influenced by temperature, which is considered a primary factor. It is commonly misconceived that an increase in solar radiation results in a proportional increase in electricity production. It is a well-established fact that solar panels exhibit varying responses under different operating ambient temperatures. The efficiency of a solar panel experiences a decline with an increase in temperature. The temperature coefficient is a term used to describe the effect of temperature on the efficiency of a solar panel. The evaluation of the power output of the solar panels is conducted at a temperature of 250 degrees Celsius. The percentage of the temperature coefficient of solar panels pertains to the alteration in efficacy. Given a temperature coefficient of -0.5%, it can be inferred that a 10^{o}C increase in temperature will result in a corresponding decrease of 0.5% in the maximum power output of a solar panel. In the event that the panel temperatures rise to approximately 450C on a day with high temperatures, and exhibit a temperature coefficient of -0.5%, a decline of 10% in the maximum power output would be observed. [12] Conversely, in the event of a winter morning characterised by clear skies and ample sunshine, the solar panels will operate with heightened efficacy, thereby producing optimal levels of output power. The following presents the temperature coefficients of various types of solar cells:

- The temperature coefficient P_{max} of both mono-crystalline and polycrystalline cells are between -0.45% to -0.50%.
- The rating of amorphous based thin film panels are between -0.20% to -0.25%.
- The temperature coefficient P_{max} of hybrid solar cells with a between -0.32%

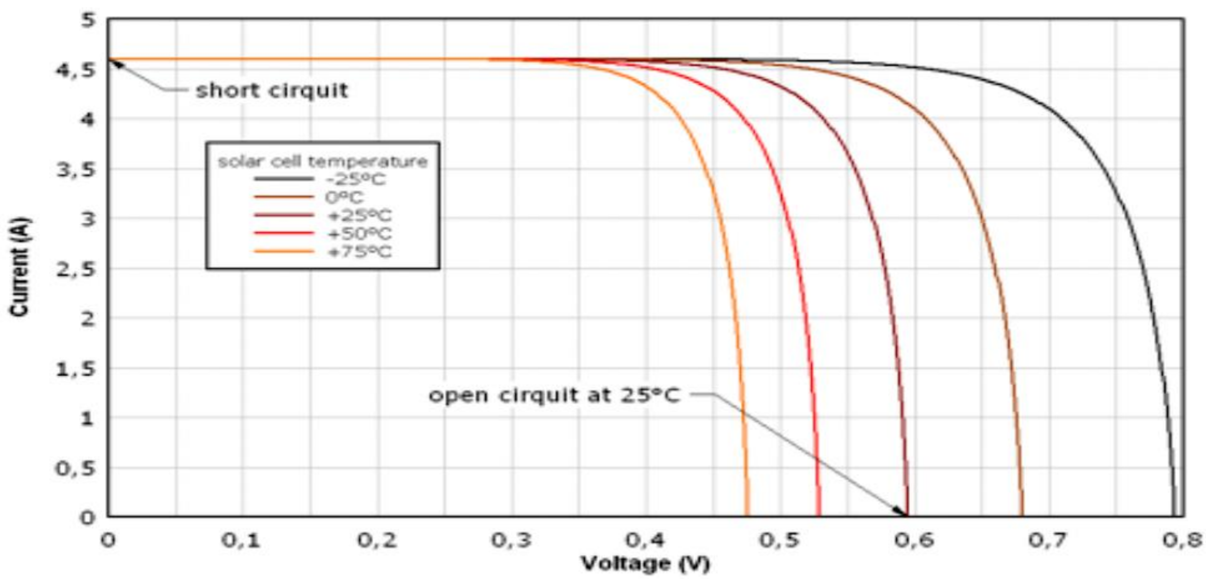


Fig.2.11. Solar cell I-V characteristics temperature dependency

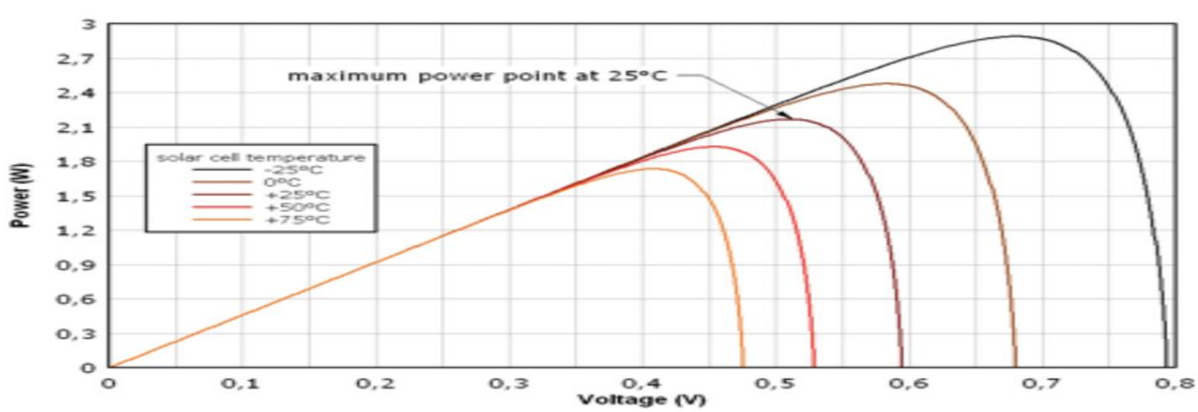


Fig.2.12. Solar cell power characteristics temperature dependency

2.10. Solar Panel Efficiencies With Heat

The output of PV panels may experience a significant reduction as a result of excessive heat. Moreover, an increase in temperature has a detrimental impact on the efficiency of the solar panel. Photovoltaic modules undergo testing at a temperature of 25ºC, which is considered the Standard Test Condition (STC). The installed locations have a significant impact on the reduction of output efficiencies, ranging from 10% to 25%. As the temperature of the photovoltaic (PV) panel rises, there is an exponential increase in the output current, while the output voltage experiences a linear reduction. The predictability of voltage reduction and the ability to measure temperature with precision are noteworthy.

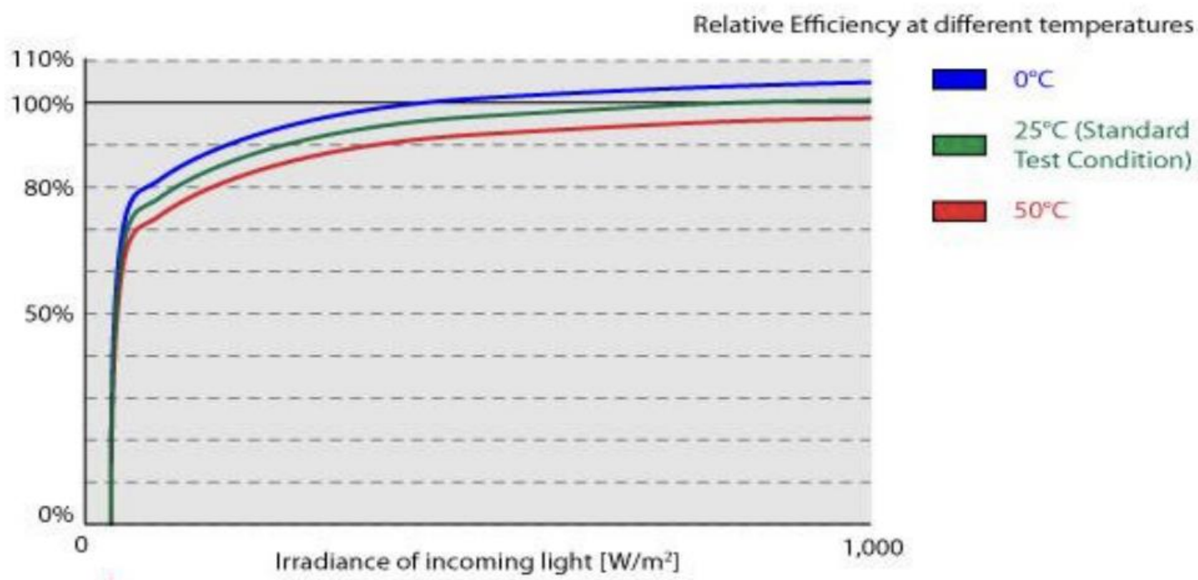


Fig.2.13. Solar cell efficiencies temperature dependency

2.11. Module Design

Module design is an important parameter to be considered.

1. Module structure

2. Module materials

3. Packing density

The above mentioned parameters should be taken care of while designing a PV module.

2.11.1 Array Construction

Normally the solar PV cells are organized to form module or panel and panels are unified to form array.

The interconnections depend on the mandatory voltage and current levels. Figure below shows the stepladder in PV array assembly.

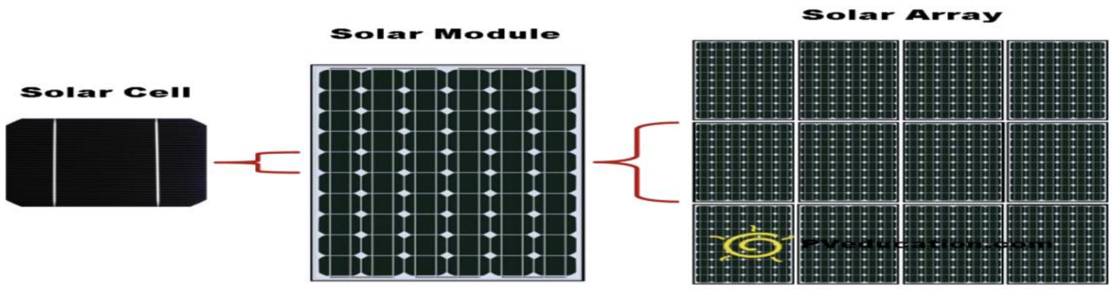


Fig. 2.14. Steps in PV array construction [31]

2.12. Maximum Energy Extraction

The maximum energy in solar PV can be extracted by:

1. Electrical Reconfiguration
2. Physical Reconfiguration
3. Fault Identification and Rectification
4. Hybrid PV/T system

2.12.1 Electrical Reconfiguration

Electrical reconfiguration is a methodology employed to modify the electrical connections in the event of circuit errors or partial shading, with the aim of extracting the highest possible power output. Typically, power electronic switches are utilised for the purpose of reconfiguration. The primary limitation of the approach is the disconnection of photovoltaic (PV) solar panels during loading circumstances.

2.12.2. Physical Reconfiguration

The technique of physical reconfiguration is employed to distribute partial shading uniformly, thereby optimising power output. This technique involves interconnecting PV panels between two arrays. The primary challenge associated with this approach is the need for additional cables.

2.12.3.Fault Identification and Rectification

The detection and refinement of faults in solar photovoltaic (PV) systems is of significant importance, as a single panel malfunction within the array can have a substantial impact on the overall productivity of the entire system. Identifying and rectifying faults is imperative for achieving improved generation. The identification of faults is carried out through inspection methods that require significant labour input, as well as thermographic methods. The primary limitations are the significant expenses involved and the challenges associated with accurately identifying faults.

2.12.3. Hybrid PV/T system

The reduction in the efficiency of photovoltaic panels is caused by the rise in temperature resulting from the irradiation of the sun. The integration of photovoltaic (PV) panels with a solar still results in the formation of a hybrid PV/T system. Hybrid photovoltaic/thermal (PV/T) solar systems can effectively lower the temperature of PV modules through the utilisation of fluid heating. The efficiency of a solar still is enhanced by preheating the fluid through the use of solar panels. On the other hand, a decrease in temperature of solar photovoltaic systems leads to an increase in their efficiency.

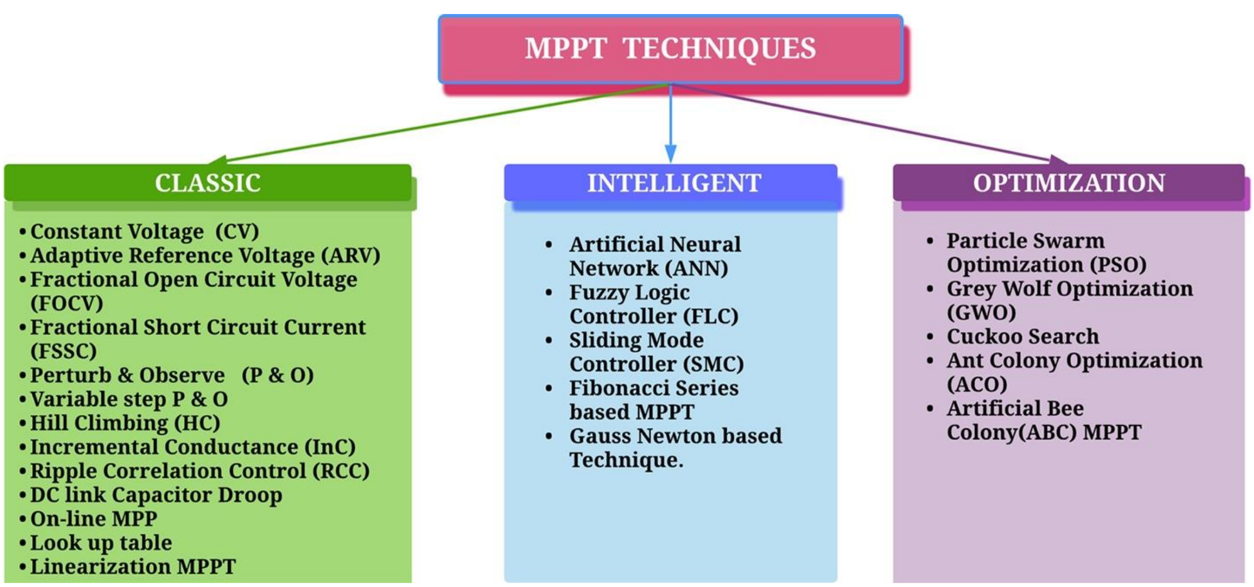
CHAPTER 3

"EXPLORING THE CUTTING-EDGE AI TECHNOLOGIES FOR SOLAR PV: A COMPREHENSIVE REVIEW"

3.1. Concept of MPPT

The concept of Maximum Power Point Tracking (MPPT) holds significant importance in the domain of solar photovoltaic (PV) systems. Photovoltaic (PV) panels are capable of producing electricity through the conversion of sunlight. However, the quantity of power generated is contingent upon a multitude of factors, including solar irradiation, temperature, and the electrical properties inherent to the panel. The Maximum Power Point Tracking (MPPT) technique is designed to identify and sustain the optimal operating point at which the photovoltaic (PV) panel provides the highest possible power output to the load. The optimal operating point of a photovoltaic (PV) panel, known as the maximum power point (MPP), is determined by the voltage and current combination that results in the highest efficiency of the panel. The maximum power point (MPP) of a photovoltaic (PV) system is subject to fluctuations in environmental conditions. Failure to implement maximum power point tracking (MPPT) may result in suboptimal utilisation of the panel's power output capacity. Maximum Power Point Tracking (MPPT) algorithms are designed to constantly monitor the Maximum Power Point (MPP) and make necessary adjustments to the operating point, thereby ensuring the highest possible power conversion efficiency. The fundamental concept of Maximum Power Point Tracking (MPPT) entails the modulation of the electrical load on the photovoltaic (PV) panel and the subsequent evaluation of the corresponding power yield. Through the systematic perturbation of the operating point, achieved by altering either the voltage or current, the algorithm is capable of ascertaining the direction that results in a rise in power output. The aforementioned iterative process persists until the Maximum Power Point (MPP) is attained.

3.2. Review of MPPT Techniques



3.3.Review of Classical Methods

The classic methodologies encompass techniques that primarily focus on maintaining a constant voltage output of the Photo Voltaic unit, as emphasised by **Ahmad et al. (2019**)[32]. Additionally, these methodologies also emphasise the adoption of reference voltages, short circuit currents, open circuit voltage, among other factors, as noted by **De Brito et al. (2012)**[33] and other scholars. Numerous algorithms and techniques have been developed to determine the optimal point of power generation on solar panels. These include the Perturb & Observe Technique by **Silva et al. (2019**) [34], **Balato et al. (2018) [35], Elgendy et al. (2011)[36], Elgendy et al. (2014) [37], Killi, M & Samanta (2015) [38], Kollimalla, SK & Mishra (2014) [39], and Sharma et al. (2018)[40]**. While these studies have focused on classical methodologies and employed advanced tools to extract maximum power from solar photovoltaic arrays, they have overlooked the continuous and dynamic nature of the surrounding environment. The power generated by PV panels is significantly influenced by factors such as irradiance and varying shadowing conditions.

3.3.1.Constant voltage (CV)-based MPPT technique

The primary objective of this Maximum Power Point Tracking (MPPT) mechanism is to regulate the photovoltaic (PV) voltage and compare it with a constant reference voltage (RV) that corresponds to the Voltage at Maximum Power Point (V_{MPP}) to ensure that the PV power operates in close proximity to the MPP. This particular method of CV is employed to ensure consistent irradiation conditions, while disregarding the impact of insolation and temperature. This particular curriculum vitae methodology approximates the maximum power point at a slight distance from the actual maximum power point. Therefore, it is imperative to consider various topographical positions to achieve the optimal RV and reduce the error value, as the working point does not effectively coordinate the MPP. The figure below depicts the schematic block diagram of the Constant Voltage Maximum Power Point Tracking (CV MPPT) technique. This approach involves utilising a solitary sensor for the purpose of voltage measurement, specifically to obtain the PV module voltage V_{PV}, which is subsequently utilised to determine the appropriate duty ratio for the converter. The approach is characterised by its straightforwardness, expeditiousness, and ease of execution, albeit exhibiting restricted accuracy. This methodology necessitates the periodic measurement of volatile organic compounds (V_{OC}). Furthermore, this methodology is applicable in situations where there is minimal temperature fluctuation. Leedy and colleagues conducted a hardware implementation of this technique, utilising the TL494 IN from Texas Instruments for pulse width modulation (PWM) generation. Wang and colleagues conducted a practical implementation of a novel maximum power point tracking

(MPPT) algorithm utilising a constant current (CV) DC-DC converter. This approach facilitated precise determination of the optimal point. The efficacy of this MPPT is evaluated through the utilisation of the commercial product FM80-150VDC from OutBack Power Systems by means of an algorithm.

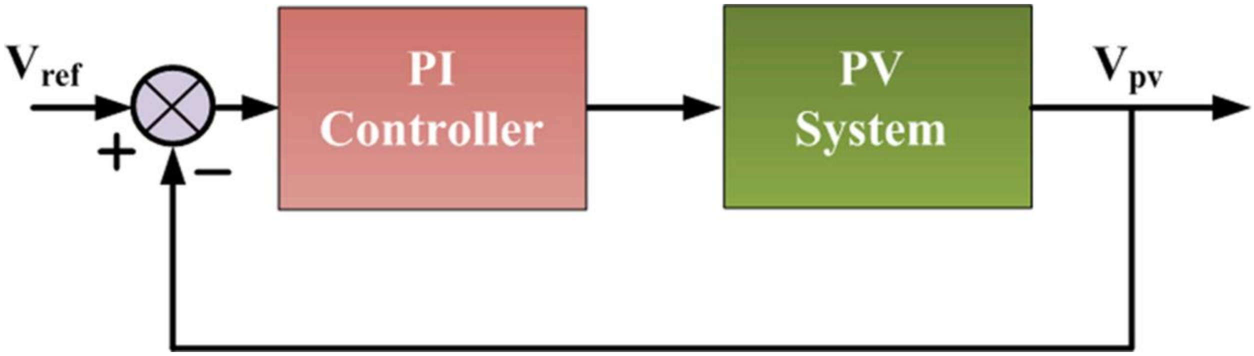


Fig.3.1. Schematic block diagram of CV MPPT technique

3.3.2.ARV MPPT technique

The ARV-based MPPT system represents an extension strategy to the CV technique, as it offers enhanced flexibility in adapting to dynamic climatic conditions. The intentional manipulation of radiation and temperature levels serves to regulate the Regulated Voltage (RV) for Maximum Power Point Tracking (MPPT). The figure below presents the schematic block model of the ARV MPPT method. The range of radiation's operational parameters at a specific temperature is segmented into multiple categories, and the corresponding RV is documented offline in a truth table. The discrepancy between the PV voltages that are referenced and assessed is rectified by utilising the corresponding proportional-integral (PI) controller, which produces a suitable duty cycle that is proportionate to the converter being employed.

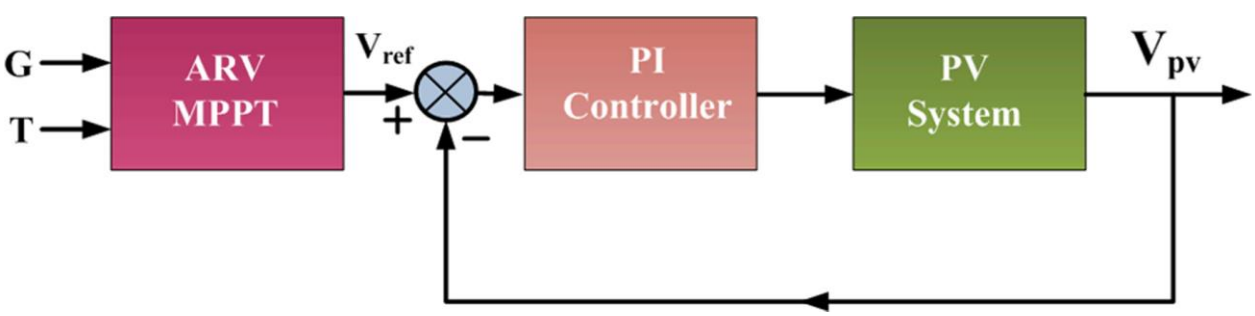


Fig.3.2. Schematic block diagram of ARV MPPT technique

The ARV procedure that has been suggested does not necessitate a temporary cessation of the photovoltaic module. This system takes into account the prevailing climatic conditions by utilising two additional sensors as compared to the conventional CV system and one additional sensor than the P&O method for estimating temperature (*T*) and irradiation (*G*) levels. However, this feature of the system comes at an increased cost. Nevertheless, the enhanced productivity offset this aspect. The simulation comparison between this method and the CV technique is presented by Lasheen et al. The efficiencies of both techniques were nearly identical, exceeding 99.7%, under conditions of constant radiation at approximately 1000 W/m^2. Nonetheless, the efficiency of the CV decreases to 98.3% at an irradiation level of 400 W/m^2. Conversely, the ARV method maintains a consistent efficiency across all radiation variables.

3.3.3.Hill Climbing (HC) method

The present approach constitutes an algorithm for searching the optimal point mathematically. The fundamental operational concept of this approach entails commencing with a suitable preliminary estimation of the solution, typically an indiscriminate point. Subsequently, the search is directed towards identifying the optimal solution through a series of iterative modifications to the initially obtained solution. In the event that the acquired solution results in an additional optimal point, the exploration process will be reiterated utilising identical increments. This iterative process will persist until the solution reaches a state of optimal performance, where no further enhancements can be made. The basic operational methodology of these strategies is presented in the table below and is consistent across the remaining techniques. However, each strategy employs distinct calculations/algorithms.

Table.3.1. Methodology of HC MPPT

Change in terminal voltage	**Change in power**	**Next perturbation**
positive	positive	positive (increment in duty ratio *D*)
positive	negative	negative (decrease in duty ratio *D*)
negative	positive	negative (decrease in duty ratio *D*)
negative	negative	positive (increment in duty ratio *D*)

3.3.4.Perturb And Observation Algorithm Based Maximum Power Point Tracking Of Solar Photovoltaic System

According to **Yilmaz et al. (2019)**,[44] the P&O technique is a commonly utilised method for power modulator control in photovoltaic systems due to its straightforward integration into a cost-effective system. The integration of a perturbation mechanism into a conventional P&O algorithm enables the modulation of the reference voltage or current through the boost converter duty cycle (D), thereby facilitating the detection of the maximum power point (MPP) even in the presence of varying weather conditions. According to Esram and Chapman (2007), the output of the photovoltaic (PV) array experiences differential changes in response to variations in the instantaneous output values. Failure to account for these changes may result in a reduction in the output voltage or current. The figure presented below illustrates the sequential execution of the traditional P&O control method through a flow-chart.

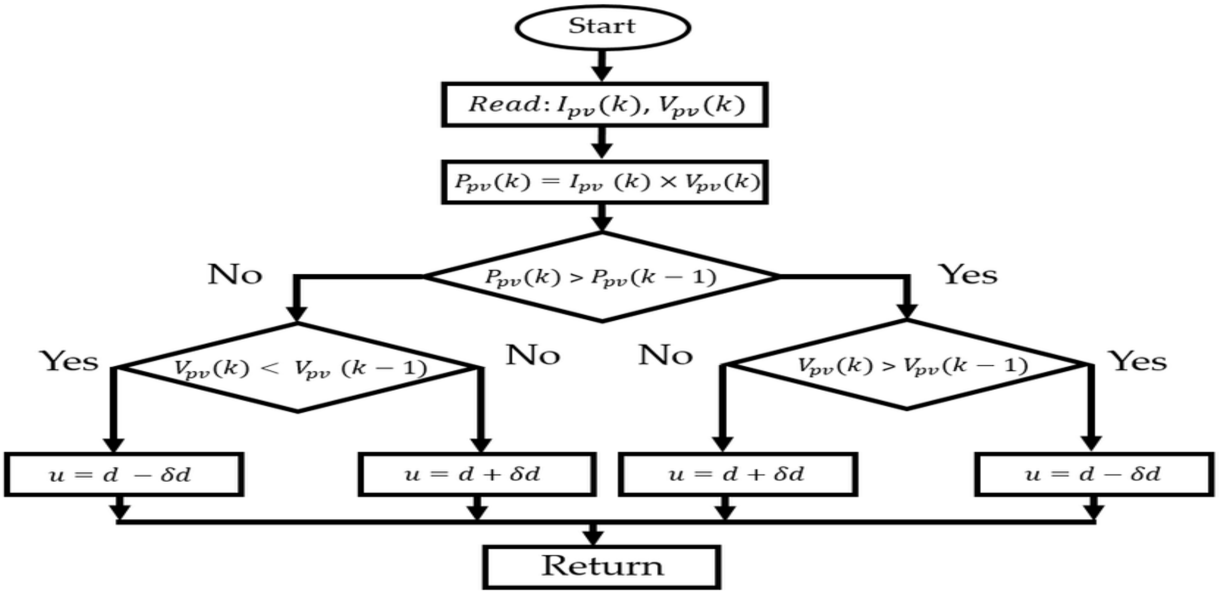


Fig.3.3. FlowChart of P&O algorithm

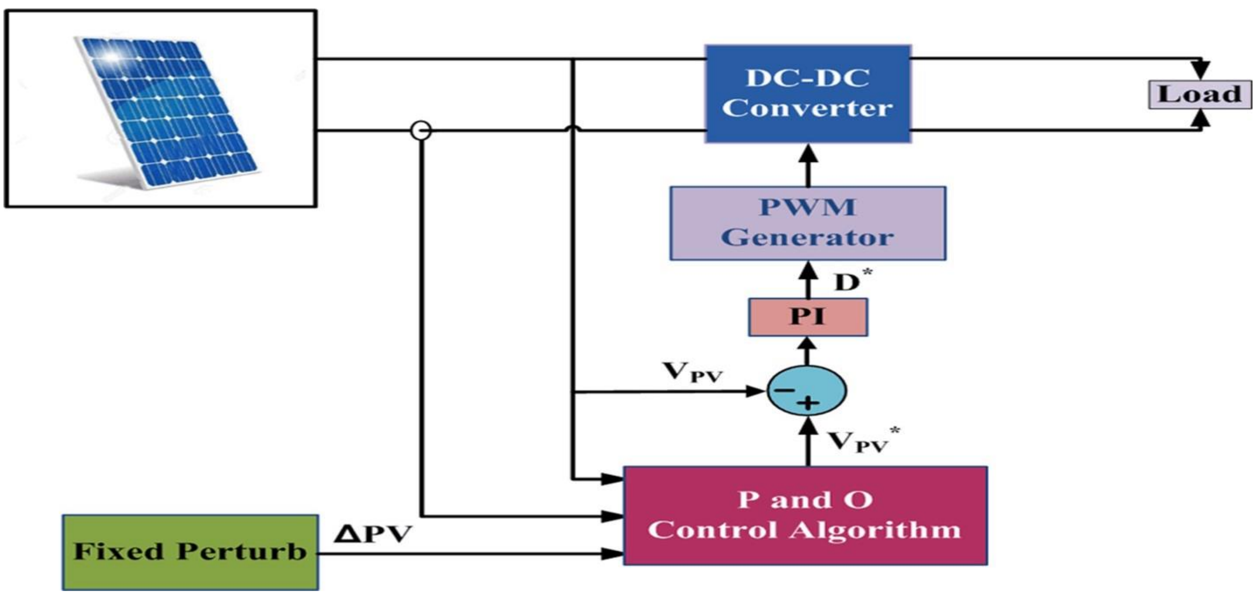


Fig.3.4. Conventional P & O with fixed perturbation step

3.4. Review of AI Based MPPT Techniques

The Maximum Power Point Tracking (MPPT) controller utilises the Maximum Power Point (MPP) algorithm to ascertain the highest power output potential of the Photovoltaic (PV) modules at a specific moment, contingent upon the appropriate solar radiation and temperature. Algorithmic numbers are utilised to efficiently monitor the Maximum Power Point (MPP). The primary concern with the majority of current algorithms is their sluggish tracking performance, which can be attributed to suboptimal resource utilisation.

3.4.1. Artificial neural network (ANN)

The methodology utilised in this approach involves the utilisation of a neural network that incorporates multiple layers of feedback, along with back propagation networks that have undergone a learning process. The present study proposes a two-phase off-line trained Maximum Power Point Tracking (MPPT)-based artificial neural network (ANN) that comprises two cascaded ANNs. The proposed approach evaluates current signals at varying photovoltaic (PV) array voltage, temperature, and irradiance levels. The implementation of maximum power point tracking (MPPT) is frequently achieved through the utilisation of a three-tier radial basis function neural network (RBFN NN). This approach is capable of accommodating swift alterations in environmental conditions, both in steady-state and transient scenarios, while also necessitating a smaller training dataset.

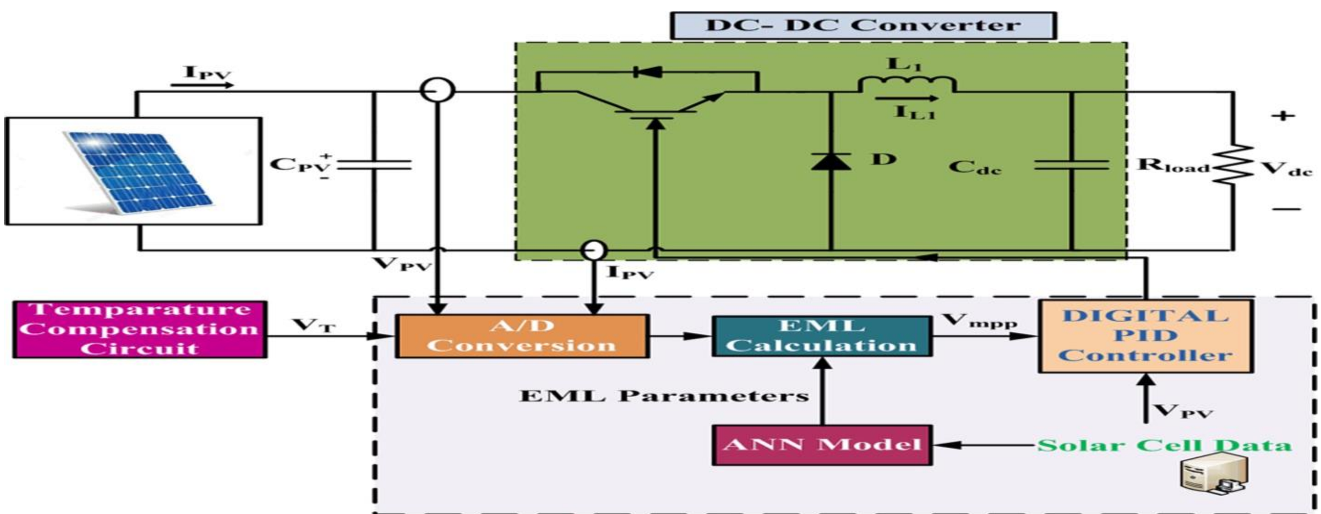


Fig.3.5. Detailed implementation of ANN method

3.4.2.Fuzzy Logic Controller

Fuzzy logic is based on fuzzy theory, which can comprise one or more sets of variables with varying degrees of membership. Fuzzification, inference, and deflation are the three main blocks of a floating logic controller. **Chokri mount, Salaah et al., (2011)** [60] focuses on controlling dc–dc elevator inverters to directly extract the MPPT from solar and photovoltaic cell temperature climatic data is one of the algorithms planned in FL and NN. Furthermore, the 2 MPPT provides a simple, low-cost system. The FLC is more powerful than the neural network controller, and it has the potential to be as powerful as a combination of techniques .

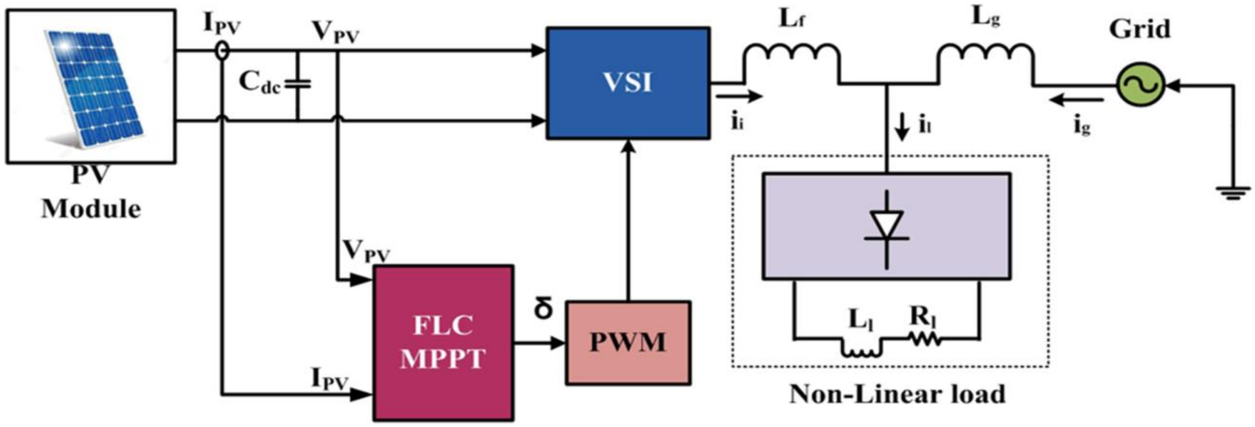


Fig.3.6. Block diagram of FLC MPPT technique

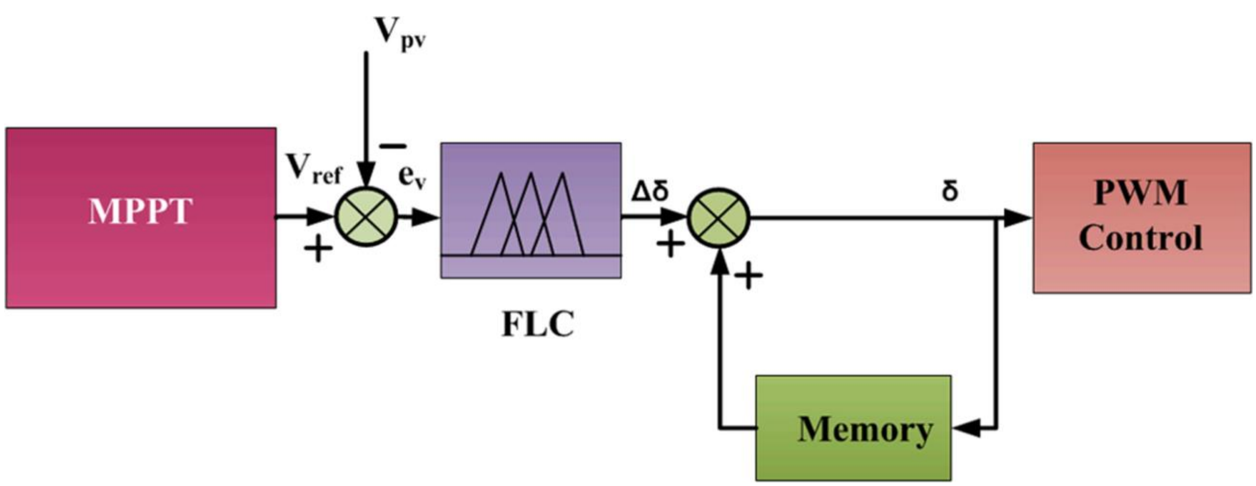


Fig.3.7. Control block diagram of fuzzy logic controller

3.4.3. Convolution Neural Network (CNN)

Chen et al. (2017) [68] present a software engineering estimation model that relies on numerical weather predictions and convolutional neural networks. The technique of GP relapse is employed for the purpose of reconstructing the incoming SE values of solar farms into a standardised grid format with a reduced grid size, which is subsequently utilised for training the Convolutional network. Moreover, the Convolutional network can effectively map a 6 by 6 input to a 31 by 31 output through the utilisation of the transposed convolution process. The postulations pertaining to solar-powered residences are subsequently derived through the process of computing the mean values of the projected estimates of adjacent grid locations. Potential avenues for future work include feature engineering of input variables, translation of data for regression modelling, selection of appropriate regression models, design of convolutional network architectures, and ultimately, probabilistic forecasting.

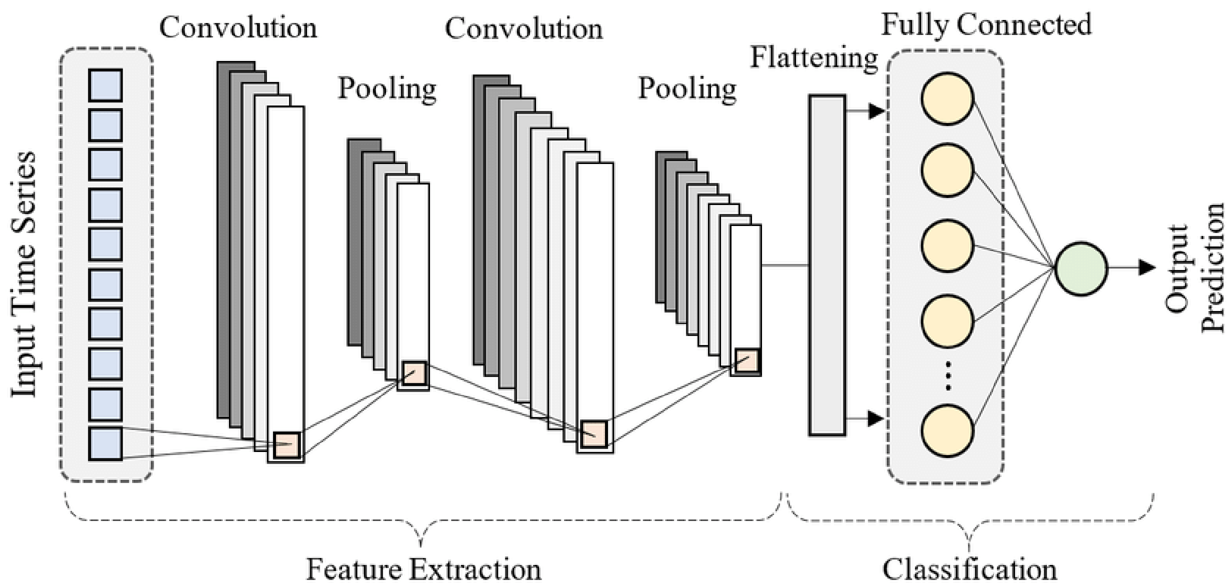


Fig.3.8. Schematic diagram of a basic convolutional-neural network

3.4.4. Deep Belief Network (DBN)

The aim of utilising the deep architecture of feature extraction and exhibiting intelligent performance in extensive predictive analyses is the primary focus of DBN. To achieve this objective, DBN intends to integrate a forward-looking unsupervised training algorithmic layer-by-layer with a reverse rear-projection algorithmic rule. A novel approach is currently under development that utilises a combination of VMD, ARMA, and DBN techniques. This approach aims to accurately capture variations in photovoltaic (PV) output size, while also decomposing the fluctuation series into a simpler and more robust periodic parameter collection. This decomposition is expected to significantly reduce the complexity of PV output prediction. The objective of the Seasonally Deep Believing Network (SDBN) as proposed by **Ching-Hsin Wang et al. (2019)** [73] was to provide monthly data on solar power output. The creation of the SDBN involved the application of both seasonal decomposition and DBN techniques. The forecasting system that has been proposed has exhibited superior performance in relation to its competitors with regards to the accuracy of its predictions. The results of an independent inquiry were juxtaposed with the proposed SDBN framework, the generalised regressive neural network (GRNN), and the DBN, with the latter exhibiting superior performance relative to the other three models.

CHAPTER 4

COMPARATIVE ANALYSIS OF MPPT TECHNIQUES

4.1. Classical MPPT techniques

Author	Year	MPPT	GI	CV	DC–DC converter	Observations
Wang, H., Vinayagam, L., Jiang, H., et al [76]	2016	CV	no	array V	boost converter	"the proposed algorithm's working is compared with a company manufactured high-efficient MPPT, namely solar charger with advanced MPPT function, FM80-150VDC from OutBack Power Systems."
Lasheen, M., Abdel Rahman, A.K., Abdel-Salam, M., et al [77]	2017	ARV	no	V	boost	"this method is an improvement to CV, and this ARV based MPPT is modelled and done simulation against conventional P & O and CV MPPTs."
Kota., V.R. [78]	2017	FOCV	no	V & C	boost	"in this paper, intelligent novel FOCV connected fractional order InC is coined, and operation is done in Matlab."
Kota.,V.R. [79]	2017	FSCC	no	V & C	boost	"in this paper, a novel hybrid FSCC with P & O method is performed on dSPACE DS1104-based experimental setup, and the initial guess of a proportional constant is selected in an intelligent way such that irradiance sensor is not required."
De Brito, Moacyr Aureliano Gomes, Luigi Galotto., et al [80]	2017	P & O	no	V & C	boost	"PV system is simulated using variable irradiance and temperature, but due to fixed-step perturbation, huge oscillations are present, which reduces overall efficiency."
Abdel-Salam, M., El-Mohandes, M.-T., Goda, M [81]	2018	variable P & O	yes	V	boost (LPF)	"in this, MPP is achieved by using an efficient methodology of variable step P & O algorithm."
Ahmed, A., Ran, L., Bumby, J. [82]	2012	HC	no	V or C	boost converter	"the essential factor of the initial guess for the perturbation variable is demonstrated with numerical analysis."

Putri, R.I., Wibowo, S., Rifa'i, M [83]	2015	InC	yes	V or C	boost converter	“thermoelectric generators are connected as the load to the system where InC with boost converter supplied the load. The performance of this InC has compared with P & O also.”
Srinivas, C.L.S., Sreeraj, E.S. [84]	2016	RCC	yes	V & C	boost converter	“the RCC technique is utilised with Fuzzy based MPPT, and the PV system is integrated into the grid. As the Ripple is always present in the converter, there is no need for separate perturbation variable.”

Note. GI, grid integration; CV, control variable; LPF, low pass filter; V, voltage; C, current

4.2. AI Based MPPT techniques

Authors	**Year**	**MPPT**	**Input parameters**	**Output parameter**	**Observations**
Elobaid *et al.* [89]	2012	ANN	T_{amb},I_{sc}	P_{max},V_{mpp}	“the ANN is trained using a Levenberg Marquardt AF function with the *trainlm* training function and the ANN-based MPPT algorithm is tested under two dynamic variations in the MATLAB environment.” “Results show that ANN is well able to track the MPP in those PSC's also. Data is acquired from 35 *P–V* curves.”
Li *et al.*[90]	2019	FLC	P_{pv}, V_{pv}	V_{ref}	“a novel parameter based FLC is coined with three input and one output, and the hardware implementation is done, and the this method will reduce the no. of membership functions.”
Kihal *et al.* [91]	2018	SMC	V_{pv}, I_{pv}	V_{mpp} V_{ref}	“a novel voltage-oriented MPPT for the standalone system is proposed with the end goal of dynamic fast-tracking under PSC's. This method uses the adaptive integral derivative sliding mode

4.3. Intelligent MPP tracking techniques: simulation, implementation of hardware and remarks

Technique	Control strategy	G I	Simulink/hardware	Tracking under PSC's	Remarks
ANN	back propagation	yes	simulation and hardware	yes	"the ANN has to train with the appropriate irradiation and temperature along with the or . Extensive data is needed for the training procedure. PV information like module utilised, no. of modules and shading patterns have to be considered."
FLC	fuzzy inference system	yes	Matlab & hardware	yes	"this technique is implemented without the knowledge of the PV system, and also its inputs are imprecise."
SMC	current sensing	yes	Matlab/hardware	yes	"the sliding mode controller (non-linear) is implemented such that the sliding surface will be useful as the trajectory for the optimum point search."
Fibonacci MPPT	continuous range updation	yes	Matlab and hardware	yes	"the MPP is intelligently tracked at a very faster rate by inherently updating its range. The method uses the Fibonacci series based searching algorithm for approaching the optimum point."
Gauss–Newton MPPT	reduction in MSE	yes	Matlab and hardware	yes	"the algorithm is off at a faster level, uses a mathematical approach for a reduction in iterations, no need of solving second order derivatives."

Note: GI, grid integration; MSE, mean square error and PSC's, partial shading conditions.

To summarize, the most common MPPT methods, Table below reports a comparative overview of the main properties of the conventional and intelligent techniques as P&O, FLC, ANN, CNN and DBN techniques used in PV systems.

4.4. Comparison of Different MPPT Techniques from Research Survey

Authors Publication Year	MPPT Technology	MPPT		Converter Type and Application	Observations
		Input	Output		
Tamas et al., 2020 [94]	P&O	Vpv, Ipv	Duty cycle	DC-DC Converter	The present study suggests an investigation into the effects of the Maximum Power Point Tracking (MPPT) algorithm, specifically the Perturb and Observe (P&O) method, on the performance of photovoltaic (PV) panels. The aim is to enhance the efficiency of PV panels by translating mathematical equations into a Matlab/Simulink model.
Reza Iskharisma Yuwanda et al., 2020 [95]	P&O	Vpv, Ipv	Duty cycle	SEPIC Converter	The proposed method, known as MPPT P&O-CPG, aims to regulate the functioning of solar panels under two distinct conditions, namely MPPT and CPG operations, with the objective of preventing overvoltage on the load. The MPPT P&O-CPG technique has undergone assessment via a PSIM simulation.

Manna et al., 2021 [96]	P&O	Vpv, Ipv	Duty cycle	Boost Converter	The study presents a methodology for conducting a just evaluation of boost converter-based systems, comparing conventional, updated, and drift-free perturb and observe maximum power point tracking techniques. power tracking and efficiency when compared to alternative approaches.

4.5. An Overview of the Main Features of the Most Popular MPPT Methods

MPPT	**Control strategy**	**Tracking**	**Complexity**	**Sensors**	**Accuracy/ efficiency**	**Speed**
P&O	Sampling	High	Simple	Current, Voltage	Medium	Varies
IC	Sampling	Medium	Medium	Current, Voltage	Medium	Varies
FLC	Probabilistic	Medium	Complex	Current, Voltage	Very high	Accurate
ANN	Probabilistic	Low	Complex	Current, Voltage	Very high	Accurate
CNN	Probabilistic	Low	Complex	Current, Voltage	Very high	Accurate
DBN	Probabilistic	Medium	Complex	Current, Voltage	Very high	Accurate

Based on the above analysis , following major observations can be made with regard to the major MPPT methods:

1. Perturb and Observe (P&O):

- P&O is a popular MPPT algorithm that perturbs the operating point and observes the resulting change in power output.
- It adjusts the operating point in the direction that increases the power output.
- P&O is simple to implement, but it may exhibit oscillations and slow tracking speed under rapidly changing conditions.

2. Incremental Conductance (IC):

- Incremental Conductance is an enhanced version of the P&O algorithm.
- It considers both the instantaneous power change and the derivative of power with respect to voltage.
- IC adjusts the operating point by comparing the instantaneous power change with zero to track the MPP.
- This method provides faster and more accurate tracking than P&O but may have slight oscillations near the MPP.

3. **Fuzzy Logic Control (FLC):**

- Fuzzy Logic Control utilizes fuzzy logic principles to make decisions regarding the operating point.
- It uses linguistic variables and if-then rules to determine the direction and magnitude of adjustments.
- FLC adapts well to varying environmental conditions and non-linear characteristics of the PV system.
- Setting up the fuzzy logic rules and membership functions requires expertise.

4.Artificial Neural Network (ANN):

- Artificial Neural Networks are used in MPPT algorithms to predict the MPP based on inputs such as solar irradiation and temperature.

- They are trained with historical data to learn the mapping between input parameters and the optimal operating point.
- ANN-based MPPT provides fast and accurate tracking, adapting to various PV system configurations.
- Training the neural network requires training data and computational resources.

5.Convolutional Neural Network (CNN):

- Convolutional Neural Networks are a type of ANN commonly used in computer vision tasks.
- In the context of MPPT, CNNs can be employed to analyze and predict the MPP using inputs such as images of the PV panel or environmental conditions.
- CNN-based MPPT can provide accurate tracking and adaptability but requires training data and computational resources.

6. Deep Belief Network (DBN):

- Deep Belief Networks are a type of neural network architecture that combines multiple layers of neurons.
- In MPPT, DBNs can be utilized to predict the MPP by learning complex patterns and relationships in the input data.
- DBN-based MPPT algorithms offer high accuracy and adaptability, but training them requires large amounts of data and computational resources.
- These methods represent different approaches to MPPT, each with its own strengths and considerations. The choice of method depends on factors such as system requirements, computational resources, and the specific characteristics of the PV system and its operating conditions.

CHAPTER 5

EVALUATION OF AI-BASED MPPT TECHNIQUES

5.1. Comparative Analysis: Traditional vs. AI-Based MPPT Methods in Solar PV

Traditional MPPT methods have long been utilized in solar PV systems, but the introduction of AI-based MPPT algorithms has brought new possibilities and advancements to optimize power generation. Here's a comparative analysis of the traditional and AI-based MPPT methods in solar PV systems:

Tracking Accuracy:

Artificial intelligence (AI) based maximum power point tracking (MPPT) techniques, such as artificial neural networks (ANN) and convolutional neural networks (CNN), exhibit the potential for enhanced tracking precision in comparison to conventional methods such as perturb and observe (P&O) and incremental conductance (IC). Artificial intelligence (AI) algorithms possess the ability to acquire knowledge from past data and adjust to diverse operational circumstances, thereby capturing intricate correlations and patterns that may elude conventional techniques.

Adaptability:

Artificial intelligence (AI) based maximum power point tracking (MPPT) techniques, such as artificial neural networks (ANN), convolutional neural networks (CNN), and fuzzy logic control (FLC), demonstrate superior performance in accommodating alterations in environmental circumstances, non-linear system attributes, and fluctuations in load. By utilising real-time inputs and historical patterns, individuals are able to make informed decisions and optimise the operating point accordingly.

Computational Requirements:

Conventional Maximum Power Point Tracking (MPPT) techniques such as Perturb and Observe (P&O) and Incremental Conductance (IC) are known to possess relatively lower computational demands in contrast to Artificial Intelligence (AI)-based approaches. Artificial intelligence algorithms, specifically artificial neural networks (ANN) and convolutional neural networks (CNN), may necessitate increased computational resources during both the training and operational phases. Nonetheless, the disparity is being alleviated by progressions in hardware and optimisation methodologies.

Implementation Complexity:

In comparison to AI-based techniques, conventional MPPT approaches are comparatively less complex to execute. Traditional techniques such as Perturb and Observe (P&O) and Incremental Conductance (IC) entail uncomplicated computations and regulatory algorithms. In contrast, AI-driven techniques necessitate supplementary procedures, including the acquisition of data, instruction, and meticulous calibration of algorithms.

Availability of Training Data:

Artificial intelligence (AI) based maximum power point tracking (MPPT) techniques, specifically those utilising artificial neural networks (ANN) and convolutional neural networks (CNN), necessitate the availability of training data in order to effectively train the models. Accurate predictions may necessitate adequate and inclusive training data. Conventional techniques such as Perturb and Observe (P&O) and Incremental Conductance (IC) do not depend on pre-existing training data, but instead function by utilising instantaneous measurements.

5.2. Advantages of using AI-based MPPT in solar PV

Using AI-based MPPT (Maximum Power Point Tracking) algorithms in solar PV systems offers several advantages over traditional methods. Here are the key advantages of using AI-based MPPT:

1.Enhanced Efficiency: Compared to conventional methods, AI-based Maximum Power Point Tracking (MPPT) algorithms have demonstrated superior efficacy in optimising the power output of solar photovoltaic (PV) systems. Through the utilisation of machine learning methodologies, artificial intelligence algorithms possess the capability to scrutinise intricate patterns within data in real-time, and subsequently adapt the operational parameters accordingly. As a consequence, there is an enhancement in efficiency and a more optimal utilisation of the solar energy that is accessible.

2.Adaptability to Dynamic Conditions: Solar photovoltaic (PV) systems function under diverse environmental circumstances, including fluctuating levels of solar irradiation, variations in temperature, and partial shading. MPPT algorithms that are based on artificial intelligence have the ability to adapt to dynamic conditions. This is achieved through continuous learning from historical data and real-time adjustment of control parameters. The ability to adapt enables the photovoltaic (PV) system to function at or near the maximum power point (MPP) in a variety of demanding situations.

3.Higher Tracking Accuracy: Even in quickly changing or non-linear circumstances, AI systems can reliably follow the MPP. AI-based MPPT algorithms may make better judgements and more precise operating point adjustments by examining historical data and real-time inputs. As a consequence, tracking precision is increased, power losses are decreased, and the PV system's power production is maximised.

4.Faster Response Time: Response times using traditional MPPT techniques might be slower, especially when dealing with abrupt changes in the environment. On the other hand, AI-based MPPT algorithms are able to swiftly adjust to changes in load conditions, temperature, and sun irradiation. AI algorithms are able to quickly modify the operating point by analysing real-time data and making judgements, which minimises power losses under transitory settings.

5. Optimization under Partial Shading: The performance of photovoltaic (PV) panels can be significantly affected by partial shading, resulting in the emergence of several local maxima in the power-voltage curve. MPPT algorithms based on artificial intelligence have the ability to efficiently manage situations of partial shading by utilising past data and recognising the most advantageous operational state, even in intricate shading circumstances. By operating in proximity to the worldwide maximum power point (MPP), the photovoltaic (PV) system is able to minimise power losses that result from shading.

6.Reduced Maintenance and Downtime: The implementation of AI-powered Maximum Power Point Tracking (MPPT) algorithms has the potential to mitigate maintenance needs and minimise system downtime. The implementation of AI algorithms can improve the stability and reliability of photovoltaic systems by dynamically adjusting to varying conditions and optimising power output. The outcome of this phenomenon can be a decrease in maintenance requirements and an enhancement in the availability of the system, ultimately resulting in cost-effectiveness and a surge in energy generation.

CHAPTER 6

SIMULATION TEST RESULTS OF DIFFERENT MAXIMUM POWER POINT TRACKING (MPPT) METHODS

In this study, the simulation of maximum power point tracking (MPPT) for a photovoltaic (PV) module was conducted using various algorithms, including conventional perturb & observe (P&O), fuzzy logic control (FLC), artificial neural network (ANN), convolutional neural network (CNN), and deep belief network (DBN). The simulations were carried out in the MATLAB/Simulink environment, utilising the Sim-Power toolbox. This research study presents several simulation circuit models, which are illustrated through various figures in different subsections.

Various MPPT techniques are accessible to optimise the output power of a photovoltaic (PV) array. This study presents several techniques for maximum power-point tracking, namely perturb and observe (P&O), fuzzy logic control (FLC), artificial neural network (ANN) system, convolution neural network, and deep belief network. The primary objective is to uphold the highest level of power point within the framework of swift alterations in irradiance and temperature circumstances.

6.1. MATLAB Simulation of PV system with Conventional MPPT Controller

The MATLAB codes were utilised to simulate the Conventional Perturb and Observe (P&O) method and Incremental Conductance (IC) method, following a prescribed flow diagram. The standard testing conditions (STC) necessitate a minimum irradiance of 1000 W/m^2 and a temperature of 25°C. The photovoltaic module comprises 60 cells that generate a power output of 100 watts. A solar photovoltaic (PV) array is formed by arranging six modules in series and parallel combinations. Two panels are linked in a series configuration, and subsequently, all three series configurations are connected in parallel.

The fundamental MPPT algorithms comprise of the Incremental Control (IC) and the Perturb and Observe (P&O) techniques. The primary objective of this research endeavour is to optimise the peak output power of a photovoltaic system. In order to meet the prerequisite for obtaining an MPP, the simulation models for PV systems are configured. The MATLAB codes were utilised to execute simulations of the Perturb and Observe (P&O) method and Incremental Conductance (IC) method, following a prescribed flow diagram. The models designed using MATLAB-Simulink. The simulation model.

The figures below depict the models of MPPT controllers utilising the Perturb and Observe (P&O) and Incremental Conductance (IC) algorithms. The previous chapter has expounded upon the algorithms and flow charts of both methodologies.

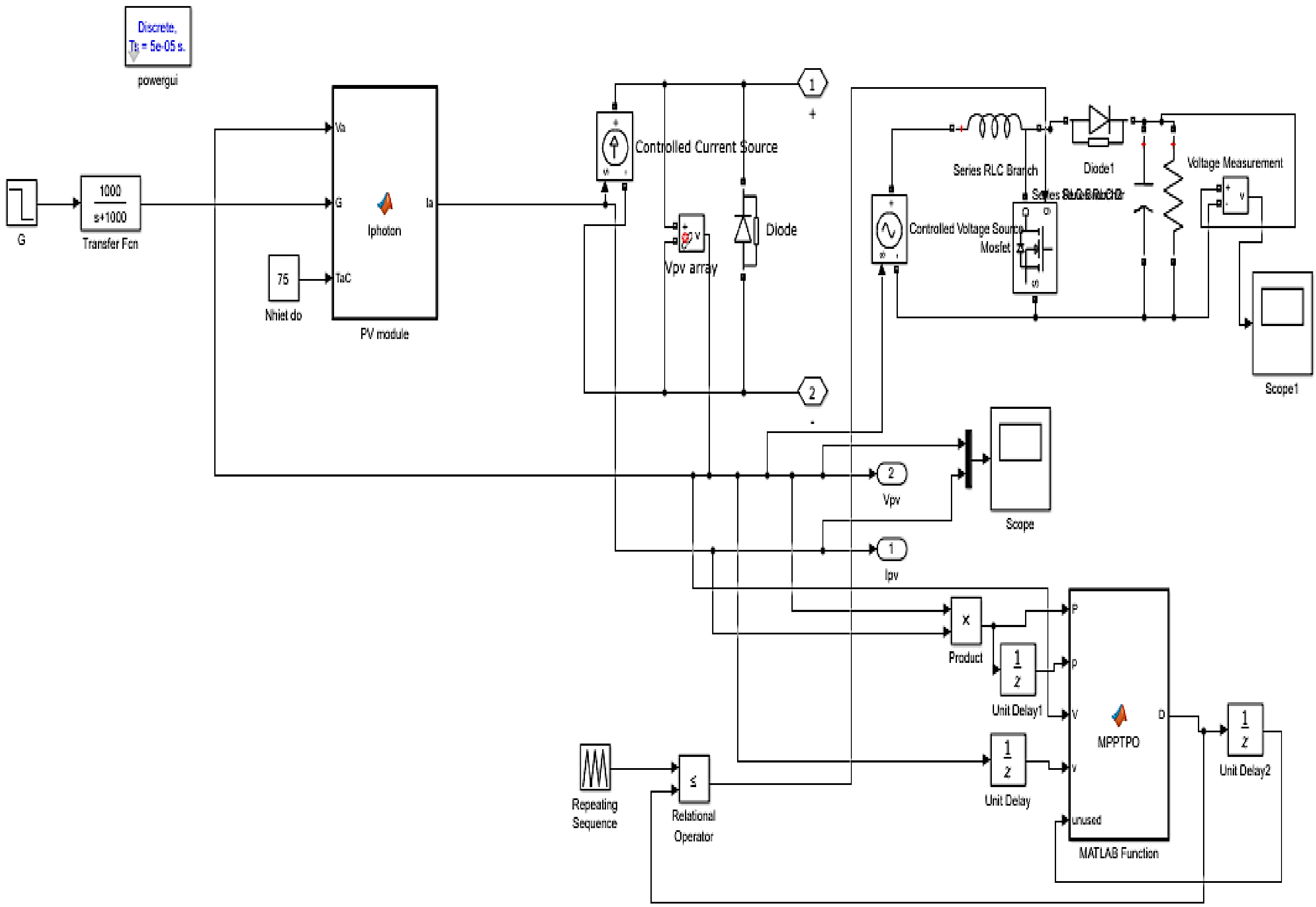


Fig.6.1.: Simulation Model of PV System with P&O MPPT Algorithm.

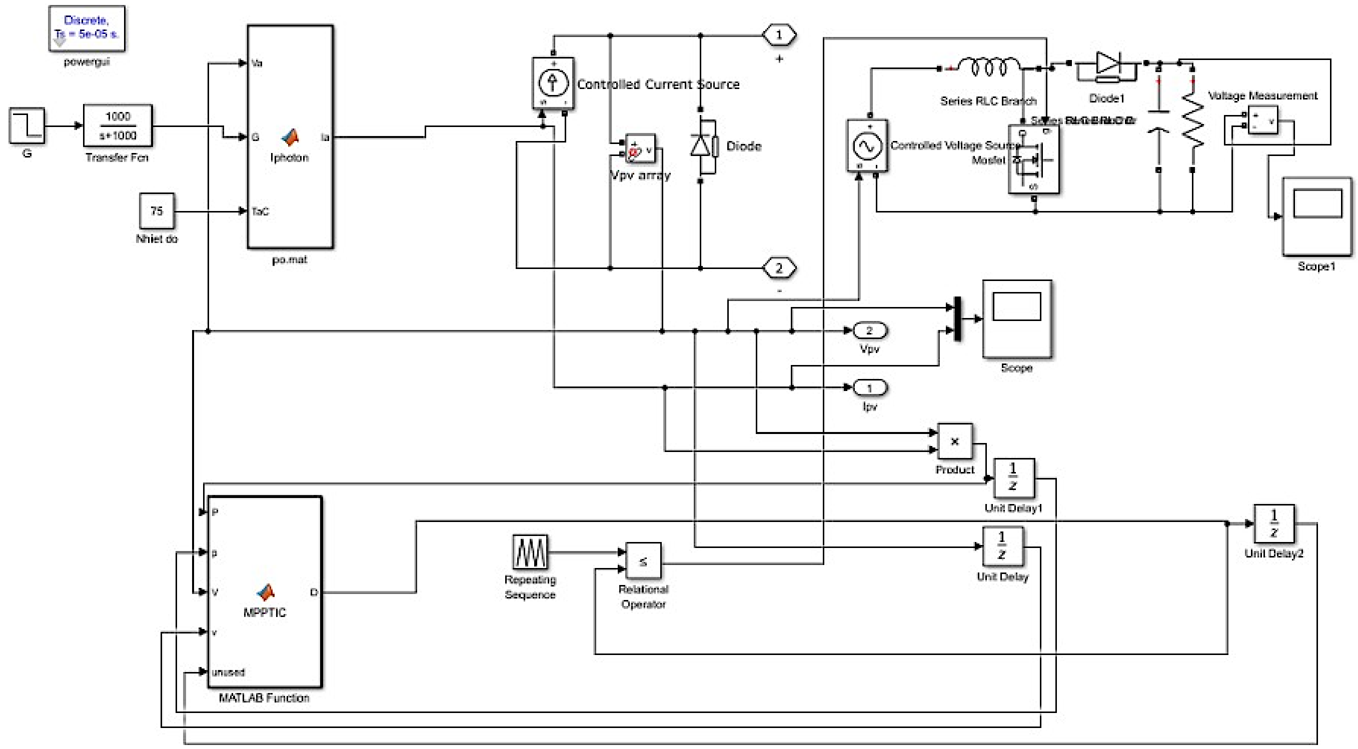


Fig.6.2: Simulation Model of PV System with IC MPPT Algorithm

6.2. Simulation Results of Conventional MPPT P&O Controller

The simulations were conducted utilising identical parameters as those employed in the absence of maximum power point tracking (MPPT), as well as with conventional incremental conductance (IC) and perturb and observe (P&O) MPPT techniques. Initially, the model was executed in the absence of Maximum Power Point Tracking (MPPT) and the outcomes were recorded. Subsequently, the simulation model was employed to operate the Photovoltaic (PV) system both with and without the Inverter Controller (IC) and Perturb and Observe (P&O) MPPT controller. As depicted in Figures 6.2(a) and 6.2(b), the solar irradiance was maintained at a constant value of 1000 W/m^2 and the temperature was set at 25°C for the duration of the weather conditions. Figures 6.3(a), 6.3(b), and 6.3(c) depict the comparative magnitudes of voltage, current, and power, respectively. The observed characteristics indicate that the P&O MPPT method yields superior outcomes compared to both the IC MPPT technique and the absence of MPPT. The utilisation of the Maximum Power Point Tracking (MPPT) controller resulted in a greater output power of the photovoltaic (PV) system in comparison to its absence. The recorded values for the output power were approximately 100 W, 90 W, and 80 W, respectively. The reason for this is that the Maximum Power Point Tracking (MPPT) controller precisely monitors the Maximum Power Point (MPP) of the Photovoltaic (PV) array. The outcomes of the modelling process indicate that the modulus open circuit voltage is 37.51 volts, the short-circuit current is 8.63 amps, and the power output is approximately 100 watts. The array's open circuit voltage is measured at 75.11 volts, while the short circuit current is recorded at 26.02 amps. The maximum power point (MPP) yields an approximate power output of 1000 watts. The results of the simulated output voltage, current, and power are presented as follows. In order to ascertain the comparability between the P&O and IC methods, the simulated outcomes of both techniques have been presented in a single plot for comparative analysis

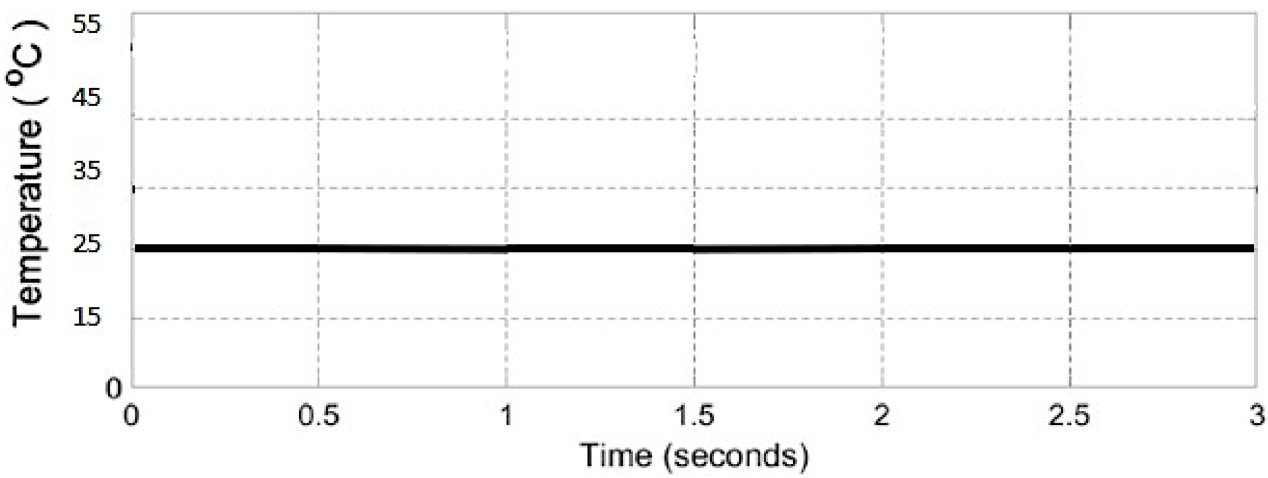


Fig. 6.3(a): The input irradiance under constant conditions

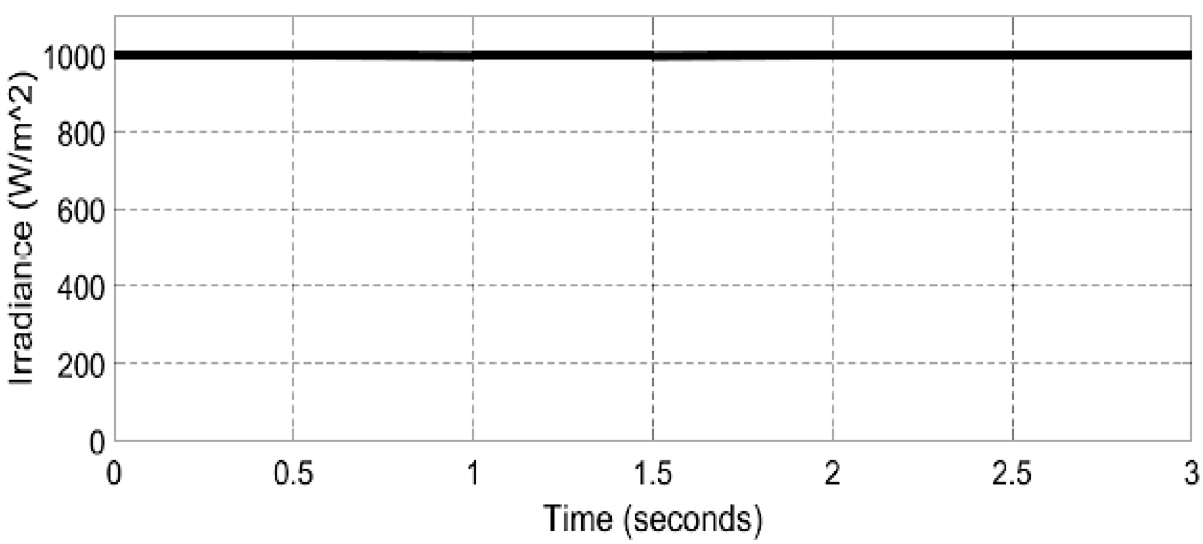


Fig. 6.3(b): The input irradiance under constant conditions

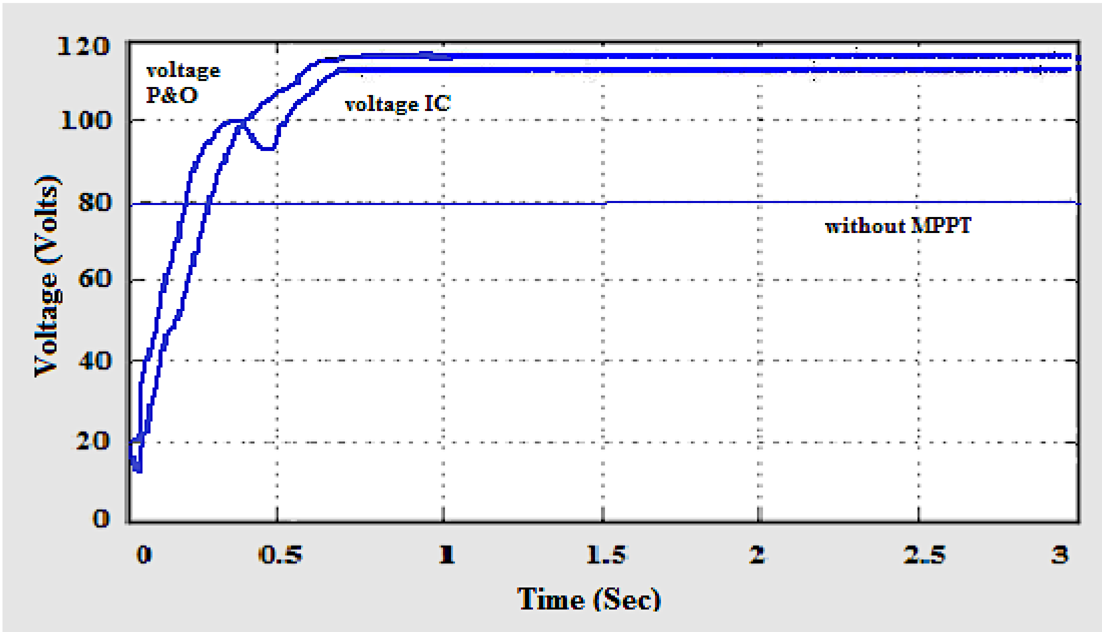


Fig. 6.4(a): Output Voltage in P&O and IC Method

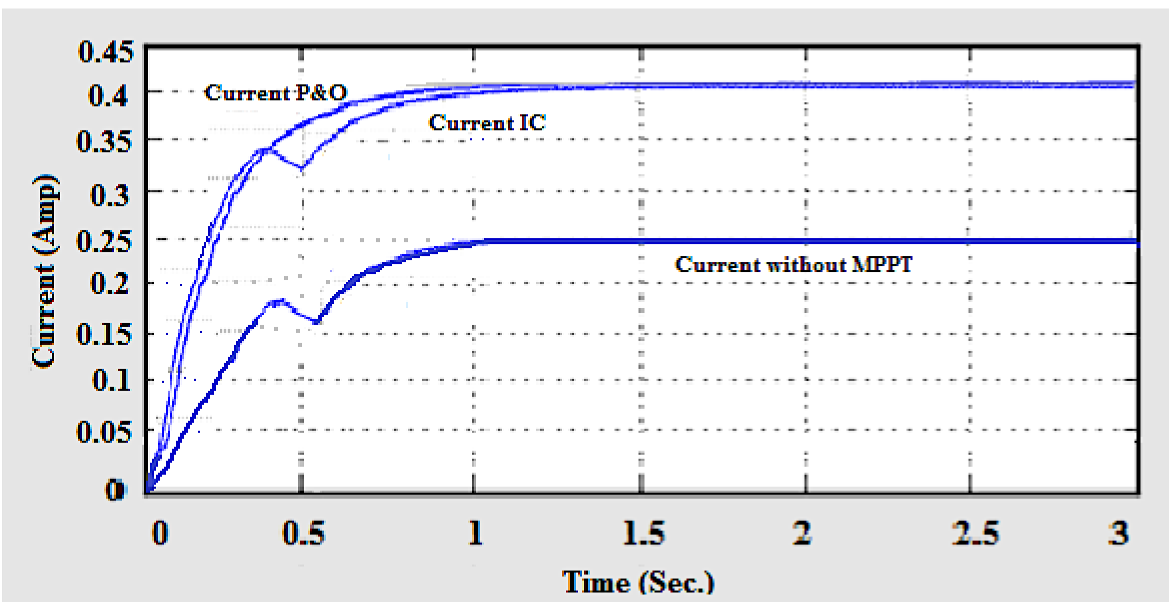


Fig. 6.4(b): Output Current in P&O and IC Method

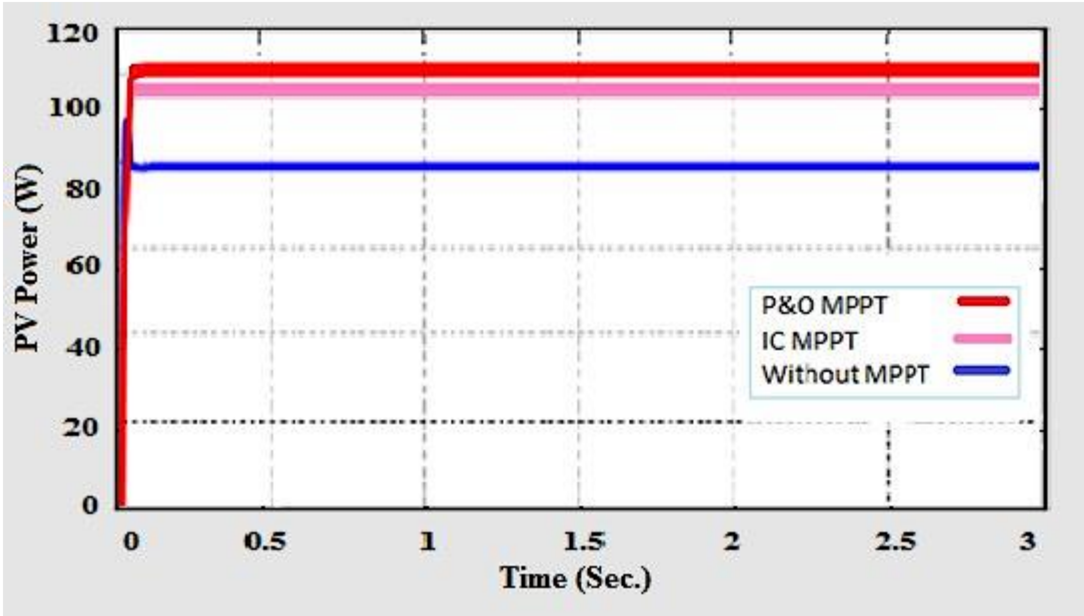


Fig. 6.4(c): Comparative Output Power with and without MPPT Method

The P&O algorithm exhibits a more gradual fluctuation of outputs in comparison to IC algorithms during the initial transient period. The P&O techniques have been observed to exhibit limitations in low irradiance levels in response to irradiance variation. The incremental conductance (IC) technique exhibits inferior efficiency in comparison to the perturb and observe (P&O) methods. However, the response time of the IC approach remains unaffected by variations in irradiation levels, and its irradiance efficiency increases. In scenarios where there are frequent and rapid fluctuations in radiance levels, this methodology may serve as a viable substitute for traditional IC techniques.

Table 6.1: Comparative Table of P&O and IC MPPT Algorithm

MPPT	**Output Power**	**Output Voltage**	**Output current**	**Response Time**	**Accuracy**
IC MPPT	90W	110 V	0.35 A	1.2 Sec	Less
P&O MPPT	100W	118 V	0.40 A	0.97ec	Accurate

6.3. MATLAB Simulation of FLC based MPPT Controller

The depicted circuit comprises a DC-DC converter that facilitates the transmission of solar panel-generated power to the load side. The circuit employs an FLC-based model circuit to achieve maximum power transfer through MPPT. The primary objective of this system is to maintain the operating point in close proximity to the maximum power point. The attainment of the highest power output is contingent upon the utilisation of the Maximum Power Point Tracking (MPPT) algorithm, which facilitates the alteration and adjustment of the duty cycle (D) of the DC-DC boost converter. The DC-DC converter's boost circuit exhibits a voltage (Vo) that is either equivalent to or surpasses the input voltage Vs (voltage generated by the photovoltaic generator). The diagram depicted in Figure 6.5 illustrates the manner in which a fuzzy logic control (FLC) based maximum power point tracking (MPPT) algorithm alters the duty cycle of a metal-oxide-semiconductor field-effect transistor (MOSFET) based boost direct current-direct current (dc-dc) converter.

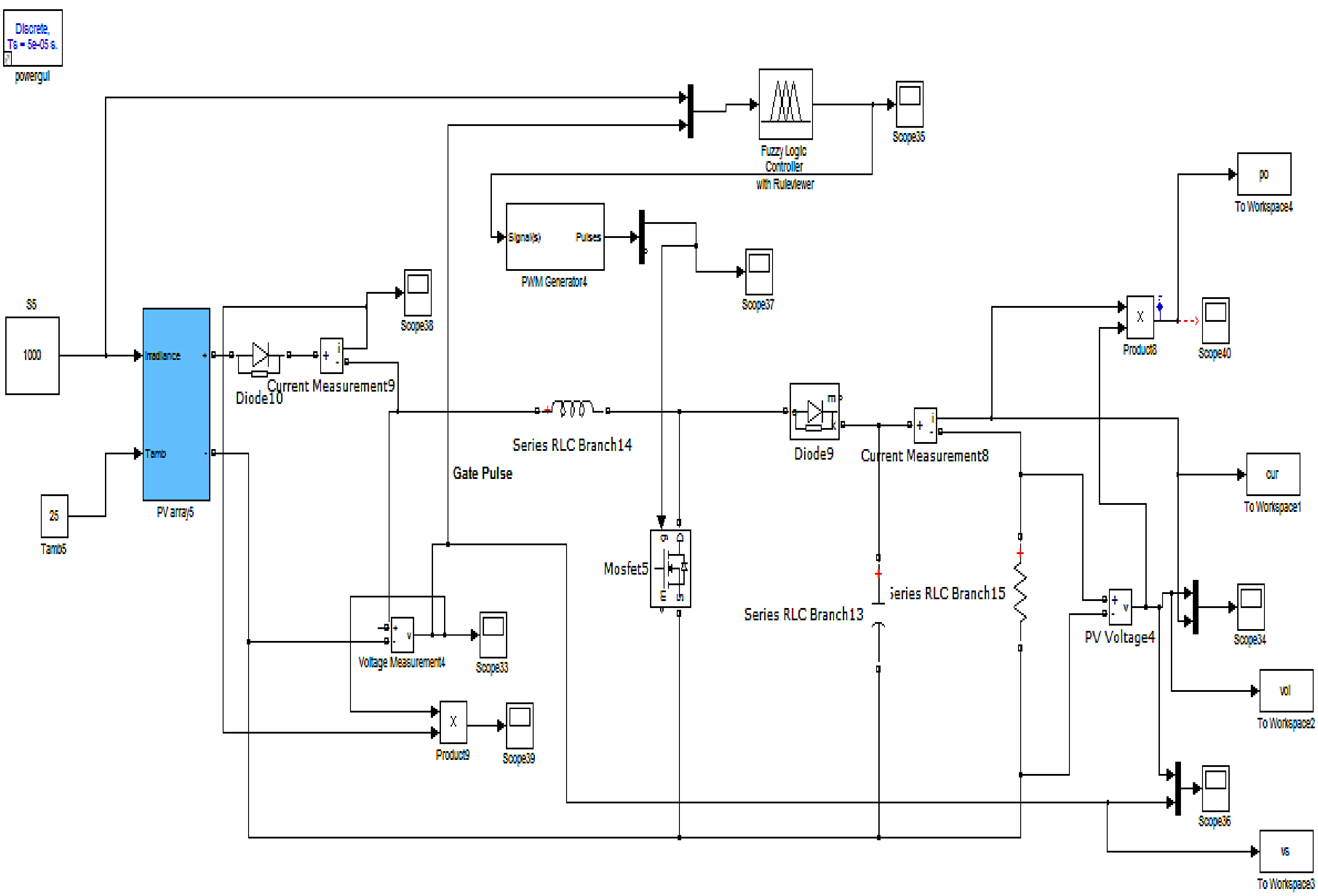


Fig 6.5: Simulation Model of FLC based MPPT Controller

6.4. Simulation Results of FLC based MPPT Controller

The PV system simulation was conducted utilising the simpower and fuzzy toolbox systems available in MATLAB/Simulink. “The photovoltaic (PV) module exhibits a power output of 100 watts and is composed of a series connection of 10 cells and a parallel connection of 6 cells. The utilisation of a DC-DC boost converter is employed in the MPPT controlled duty cycle for the purpose of converting low DC input voltage to high voltage. “The findings indicate an elevation in irradiance, a surge in power, and a boost in efficiency of the photovoltaic (PV) system while maintaining a consistent cell temperature of 25°C. The temperature of the cell was raised from 25°C to 50°C under constant irradiance of 1000W/m2 within a time frame of 0.2 seconds. Elevated cellular temperature is associated with a decrease in output voltage, current, and power. “The inclusion of an MPPT controller in a PV system is observed to enhance its effectiveness in comparison to a PV system that lacks an MPPT controller. Figure 6.5(a) depicts the output voltage and output current of the Fuzzy Logic Controller (FLC) based Maximum Power Point Tracking (MPPT) controller. On the other hand, Figure 6.5(b) illustrates the output power and duty cycles over time.”

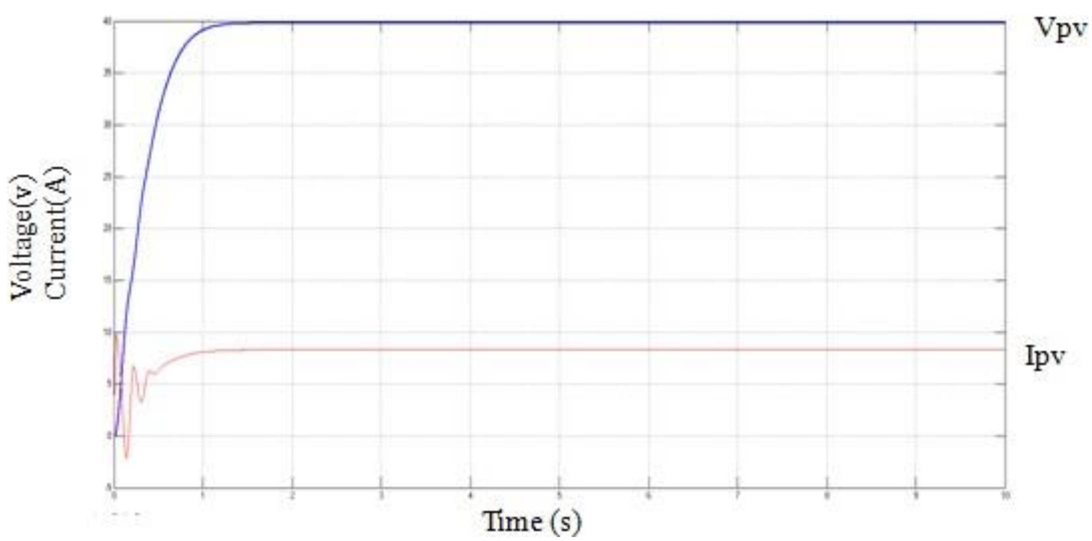


Fig 6.6(a): PV Module Output Voltage and Current response by FLC controller

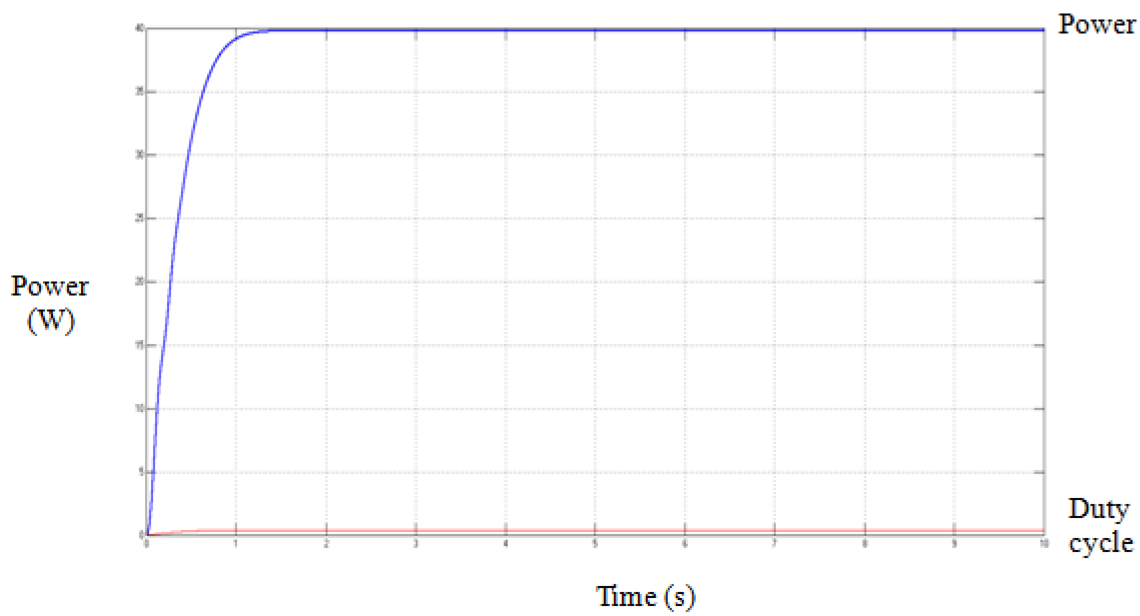


Fig 6.6(b): MPPT with FLC Output Power

The findings suggest that "the FLC-MPPT exhibits a faster convergence time compared to conventional P&O and IC controllers". It exhibits superior aptitude in accurately responding to abrupt changes in solar irradiance. Table 6.2 presents "a comparison of the output voltage, output current, output power, and accuracy of the device". It is evident that the FLC-MPPT exhibits a superior performance in terms of both convergence time and output power when compared to conventional methods. Furthermore, it is the most precise method for monitoring the maximum power point (MPP) within a shorter duration.

Table 6.2: Comparative Table of Conventional method and FLC based MPPT controller

MPPT	**Output Power**	**Output Voltage**	**Output current**	**Response Time**	**Accuracy**
IC MPPT	90W	110 V	0.35 A	1.2 Sec	Less
P&O MPPT	100W	118 V	0.40 A	0.97ec	Accurate
FLC MPPT	110W	122V	0.52A	0.086 sec	Accurate

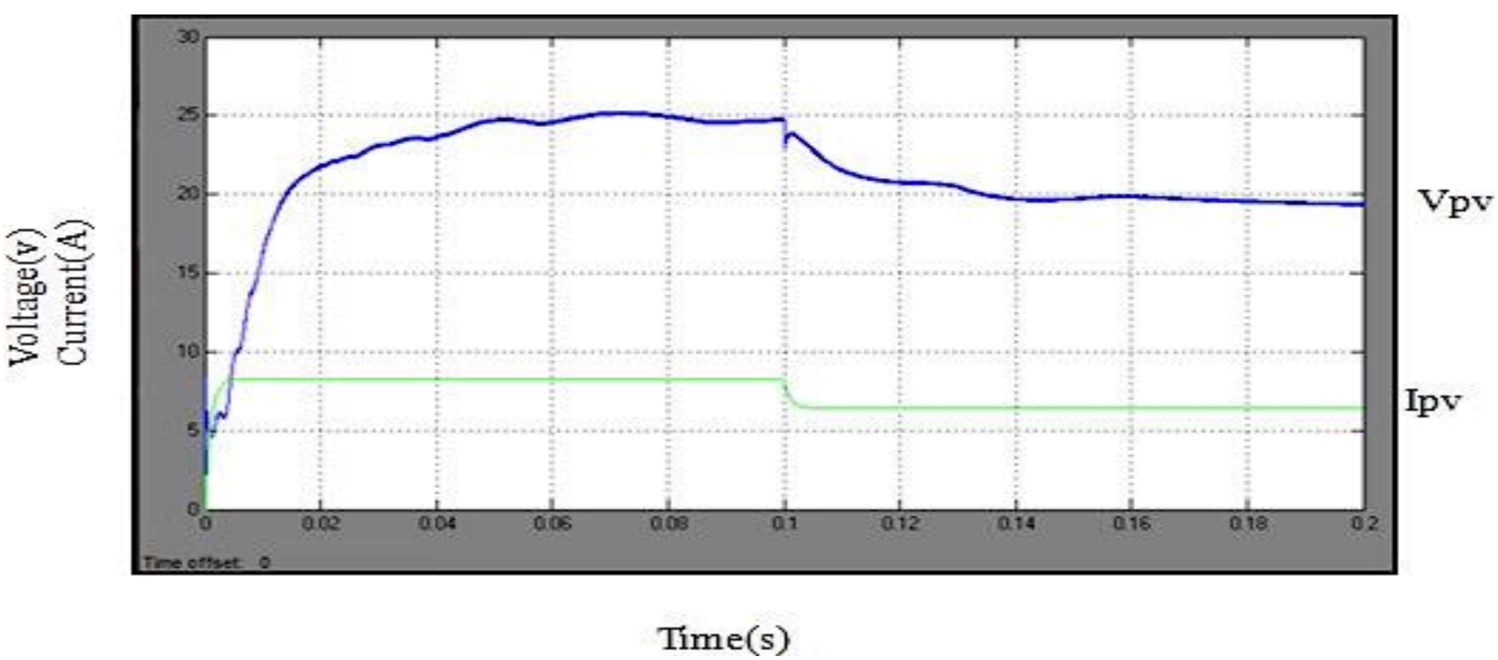
6.5.MATLAB Simulation of ANN based MPPT Controller

The construction of the simulation model using MATLAB/SIMULINK has been completed. The simulation model of the proposed method is depicted in Figure 6.6. "The circuit under consideration is powered by a photovoltaic module and requires a self-sufficient direct current source. The photovoltaic (PV) terminal voltage and current serve as the inputs, while the duty cycle is fed to the DC-DC Boost converter via the output." The implementation of frequency control is deemed essential, as it is imperative to effectuate the requisite adjustments to align with the maximum power point. It is imperative to have a switch frequency control. The simulation was conducted in two modes, initially involving irradiation to maintain a constant level of 1000 W/m^2 while varying the temperature. Under the second mode, the temperature is to be consistently maintained at 25 degrees Celsius while the solar irradiance is allowed to fluctuate.

6.6. Simulation Results of ANN based MPPT Controller

The performance of the ANN controller is evaluated by subjecting the system to a constant solar irradiation of 1000 W/m^2 and a temperature of 25^{o}C. The voltage and current output of the PV module are depicted in Figure 5.7(a), while Figure 6.7(b) illustrates the steady state of the PV output power and its oscillation. The findings confirm the efficacy of this approach in swiftly tracking the maximum power point (MPP) and maintaining minimal oscillation around the MPP during steady-state.

Fig 6.7(a): PV Module Output Voltage and Current response by ANN controller



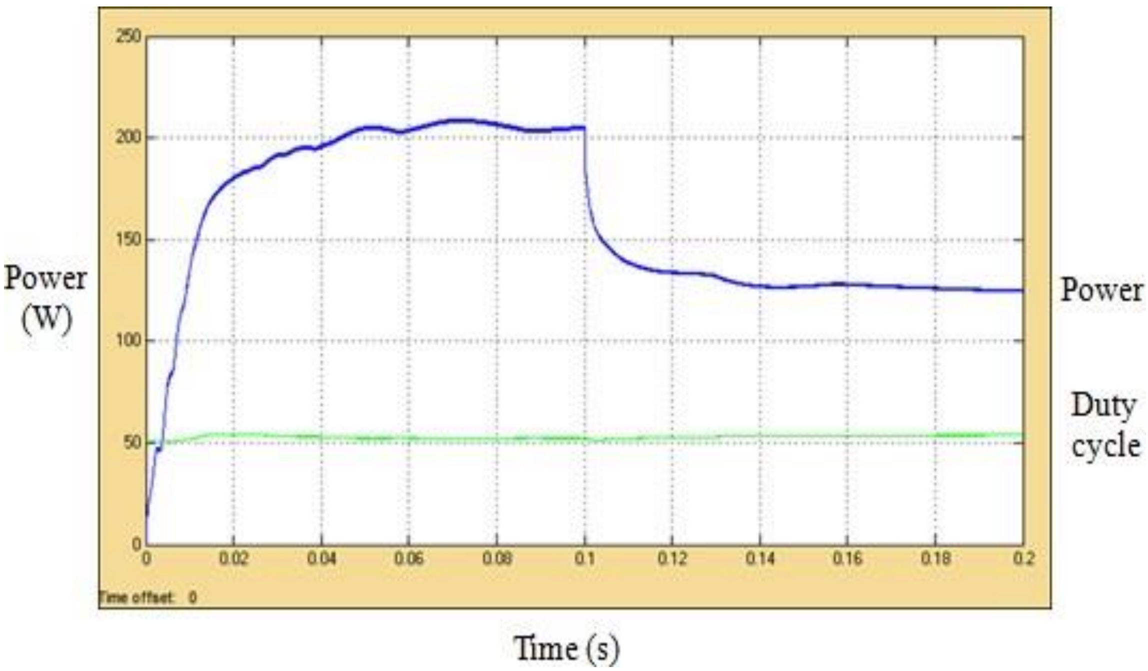


Fig 6.7(b): MPPT with ANN Output Power

6.7. MATLAB Results of CNN algorithm based MPPT Controller

The investigation of Convolutional Neural Networks reveals their capacity for achieving high levels of accuracy and robustness in predicting I-V and P-V curves for photovoltaic modules. This feature renders them superior to conventional Maximum Power Point Tracking techniques when applied in complex environmental conditions. The neural network has undergone training to optimise the selection of the most effective training algorithm. Figure 6.8 (a) presents the outcomes of the test set validation of the optimal training model, including the forecast accuracy, error escalation, and the challenge of ascertaining the maximum power of photovoltaic modules. The neural network undergoes training via the Rectified Linear Unit (ReLU) layer. The training procedure was executed in accordance with the flowchart and algorithm outlined in the preceding chapter. The learning parameters are configured to adapt the learning rate of the biases or weights within the layer. "The evaluation of I-V curves involves the utilisation of Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) parameters. The output denotes the precision and errors computed subsequent to the execution of the algorithm. Figure 5.8(b) illustrates the relationship between output current and voltage, while Figure 5.8(c) depicts the correlation between power and voltage.The graphical data suggests that the CNN algorithm provides accurate measurements of the maximum power value."

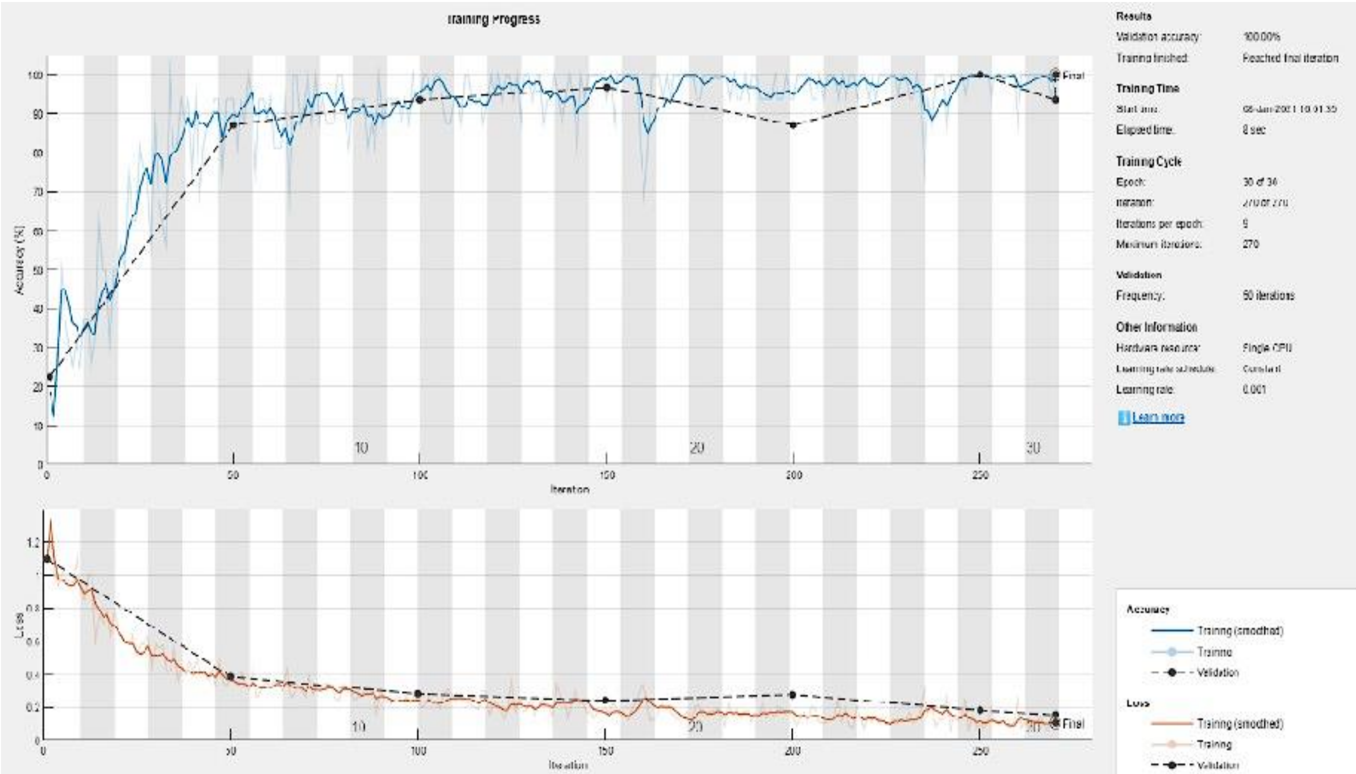


Fig. 6.8 (a): Represent accuracy and loss function of CNN Algorithm

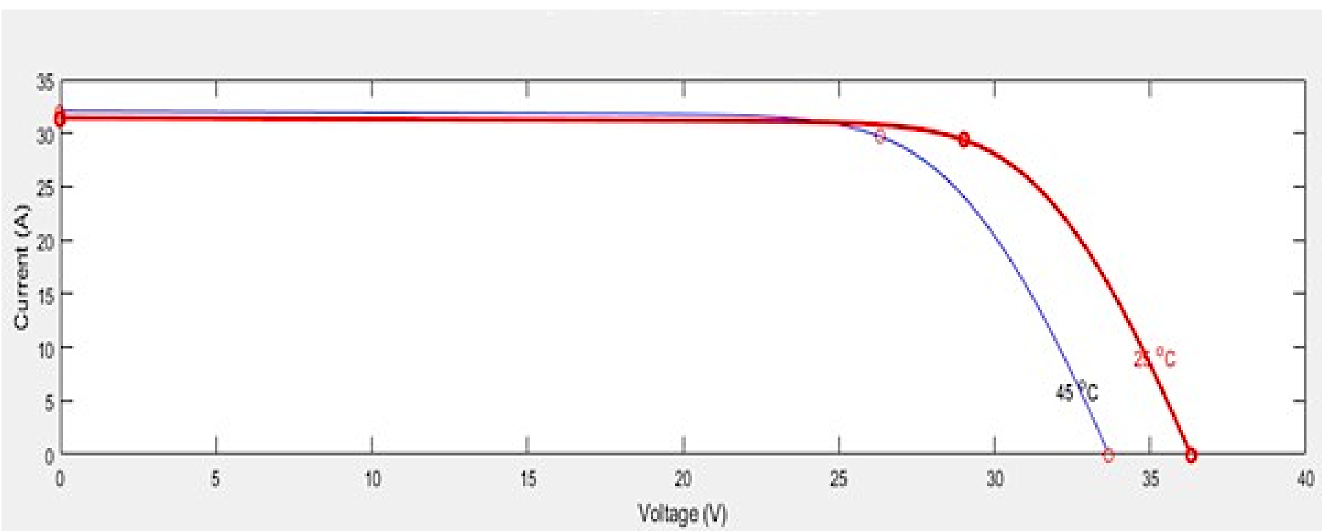


Fig.6.8 (b): Comparative between the Current and voltage

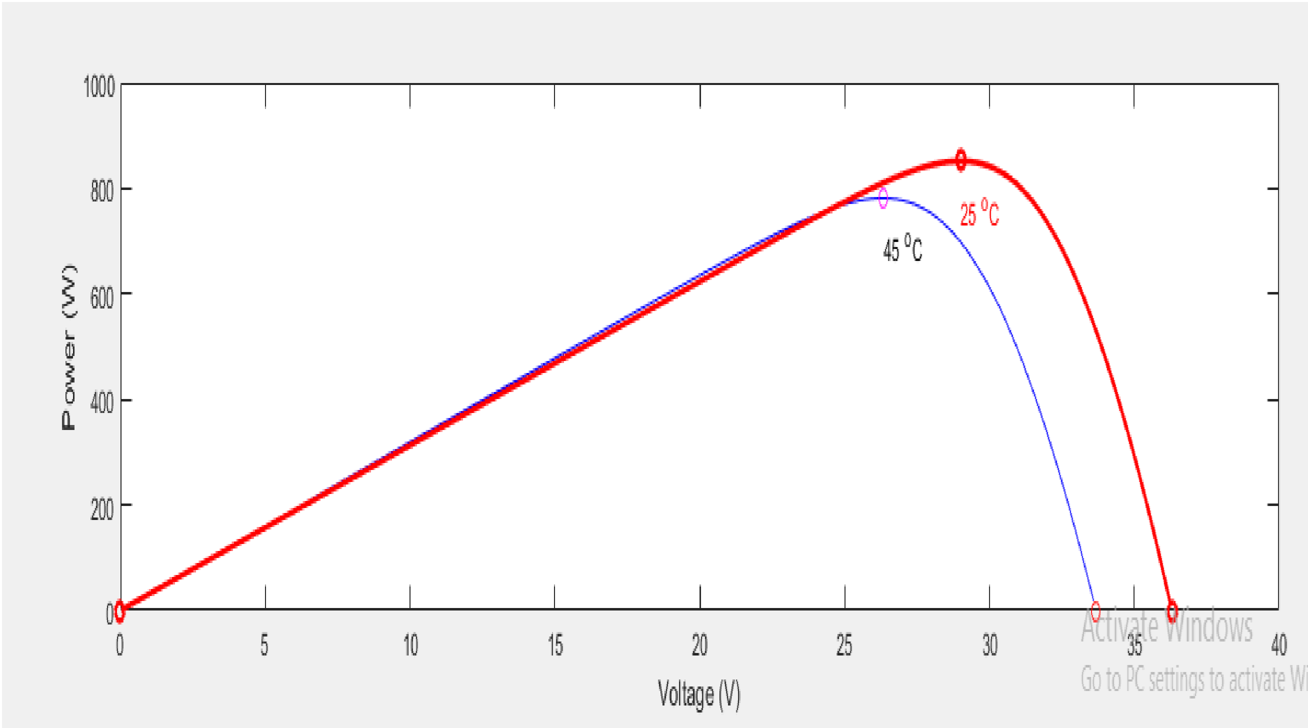


Fig.6.8 (c): Comparative between the Power and voltage

6.8. MATLAB Simulation of DBN-BPNN compound algorithm based MPPT Controller with results

The present investigation introduces a novel approach for controlling neural networks and DBNs. The PI controller was responsible for controlling the converter switch function with respect to the reference voltage. During this phase, the Backpropagation Neural Network (BPNN) was utilised to determine the optimised deep learning data for Vmpp supply under varying atmospheric conditions. The simulation findings indicate that the DBN-BPNN composite algorithm exhibits satisfactory and accurate efficacy in the monitoring of the maximum power point. The advantages of this compound method can be succinctly summarised as follows: The utilisation of DBN-optimized neural network training has resulted in a reduction of tracking time, minimal constant ripples in output power, and accurate monitoring of the maximum power point with variations in atmospheric conditions or load conversion. This has ultimately led to improved performance of the MPPT-controller.A novel deep belief network (DBN) compound algorithm has been simulated utilising the Matlab/Simulink environment with the aid of the sim-power toolbox. Figure 6.9 depicts the cumulative block diagram of a Deep Belief Network (DBN) that incorporates a photovoltaic (PV) system, a DC-DC boost converter, and a load. The PI controller was responsible for controlling the converter switch function with respect to the reference voltage. During this phase, the BPNN was utilised to determine the optimised deep learning (offline) data for Vmpp supply under varying atmospheric conditions. "The simulation outcomes indicate that the compound algorithm of DBN-BPNN exhibits satisfactory and accurate performance in the monitoring of MPP. The benefits of this compound approach can be succinctly summarised as follows: The utilisation of DBN-optimized neural network training has resulted in a reduction in tracking time, minimal constant ripples in output power, and accurate monitoring of the maximum power point with variations in atmospheric conditions or load conversion. This has ultimately led to improved performance of the MPPT-controller. Figure 6.9 (a), (b), and (c) depict the output voltage, output current, and output power, respectively."

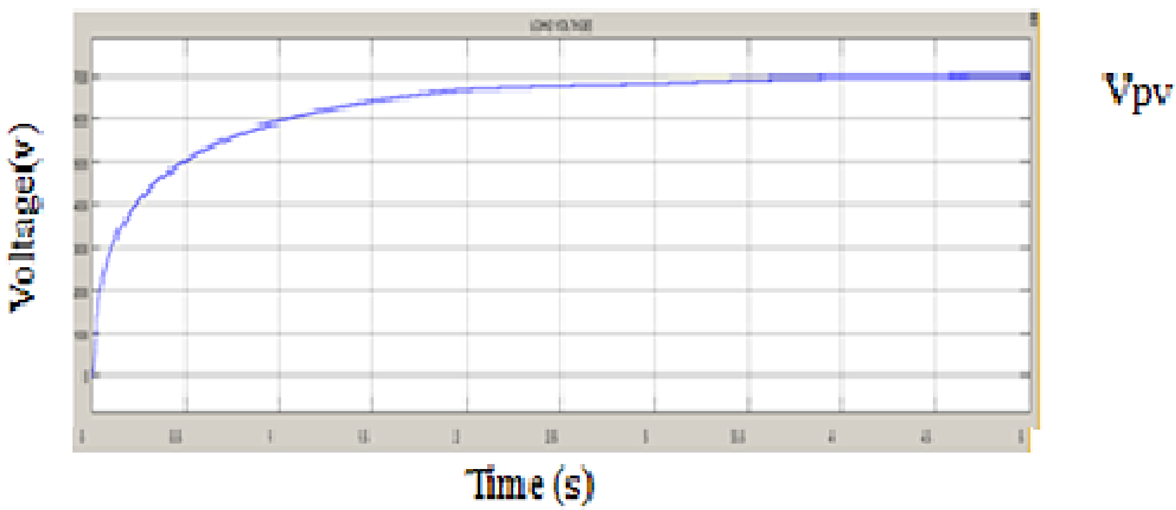


Fig .6.9(a): PV Module output Voltage of DBN-BPNN controller

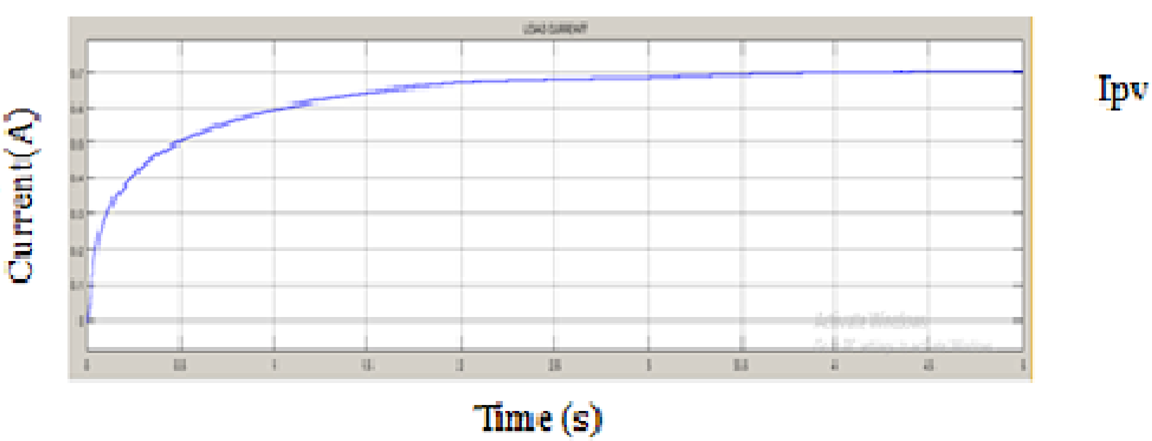


Fig 6.9(b): Output Current response of DBN-BPNN controller

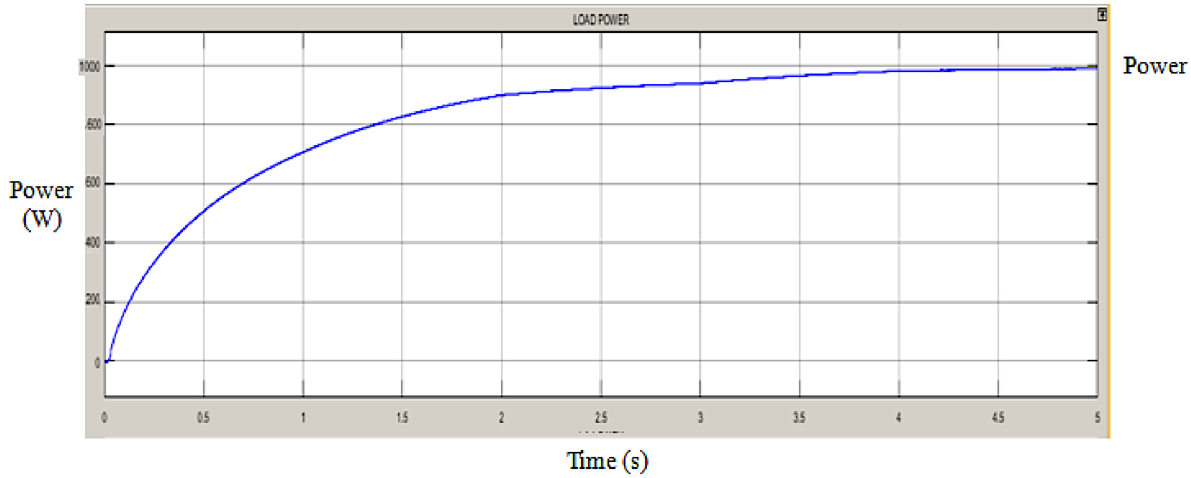


Fig 6.9(c): Output Power with DBN-BPNN MPPT Controller

The present study introduces a novel approach for controlling neural networks and DBNs through a newly developed control method. The PI controller was responsible for controlling the converter switch function with respect to the reference voltage. During this phase, "the Backpropagation Neural Network (BPNN) was utilised to determine the optimised deep learning data for Vmpp supply under varying atmospheric conditions. The simulation outcomes indicate that the DBN-BPNN composite algorithm exhibits satisfactory and accurate efficacy in the monitoring of the maximum power point. The benefits of this compound approach can be succinctly outlined as follows: the utilisation of a DBN-optimized neural network for training purposes resulted in a reduction in tracking time, the output power exhibited negligible constant ripples, the maximum power point (MPP) was accurately monitored in response to changes in atmospheric conditions or load conversion, and ultimately, the performance of the MPPT-controller was enhanced."

6.9.Comparative results of different MPPT Controller

Maximum Power Point Tracking (MPPT) is a method utilised to obtain optimal power output from photovoltaic (PV) systems. The present research conducts a comparative analysis of various Maximum Power Point Tracking (MPPT) techniques and recommends the most effective one in terms of MPPT efficiency, while also assessing their suitability for deployment in systems that operate across a diverse range of conditions. Consequently, it is apparent that every Maximum Power Point Tracking (MPPT) technique possesses its distinct advantages and disadvantages. Moreover, it is imperative that the Maximum Power Point Tracking (MPPT) system has the capability to minimise the oscillation in the vicinity of the Maximum Power Point (MPP). This study investigates various MPPT methodologies with regards to the dynamic response of photovoltaic (PV) systems, efficiency, and implementation considerations through simulations conducted in the MATLAB/Simulink platform. The findings suggest that traditional techniques such as incremental conductance and P&O algorithms are relatively uncomplicated to construct, yet exhibit a sluggish response in achieving peak performance. Fuzzy Logic control and artificial neural network are recognised as intelligent techniques that exhibit superior performance compared to conventional methods. These techniques demonstrate faster convergence to the maximum peak point, accompanied by reduced ripple and a shorter time to reach the peak value. The efficacy of each methodology has been assessed across a range of irradiation and temperature conditions. The utilisation of convolution neural network, a more sophisticated approach, has been found to be both more time-efficient and accurate when compared to conventional techniques. The utilisation of various conventional and intelligent Maximum Power Point Tracking (MPPT) techniques has been shown to effectively optimise the power output of solar photovoltaic (PV) panels. The proposed implementation of a deep belief network system has been found to consistently achieve the maximum power extraction potential from the solar PV panels. Figure 6.10 illustrates a comparison of output power response among various techniques, indicating that DBN exhibits the highest power response. Figures 6.11 (a) and 5.12 (b) depict the comparative P-V and I-V curves of various MPPT controllers.

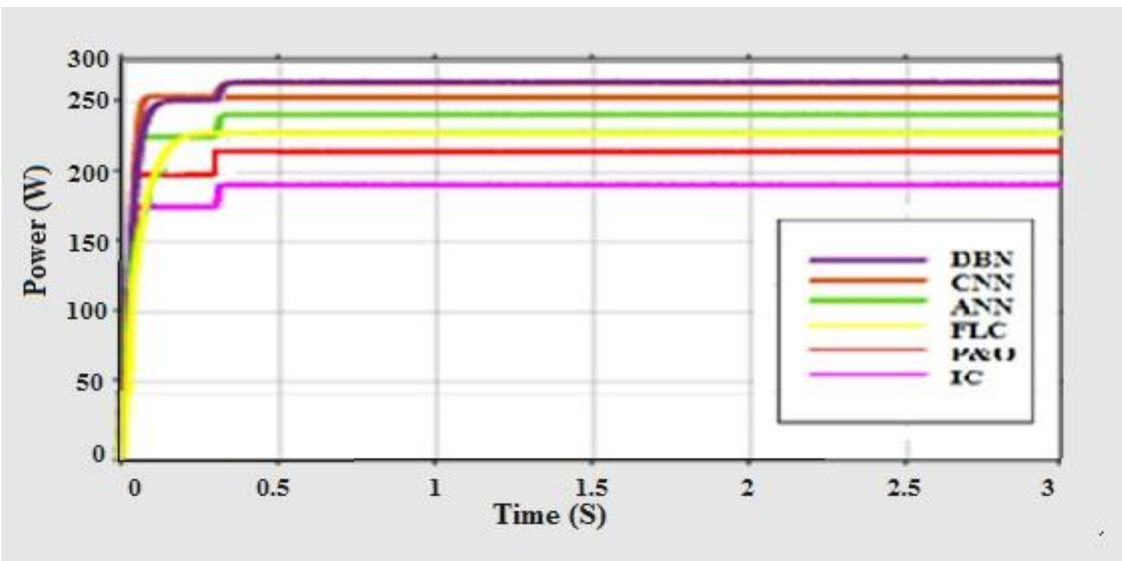


Figure 6.10: Comparative output power of different MPPT controller

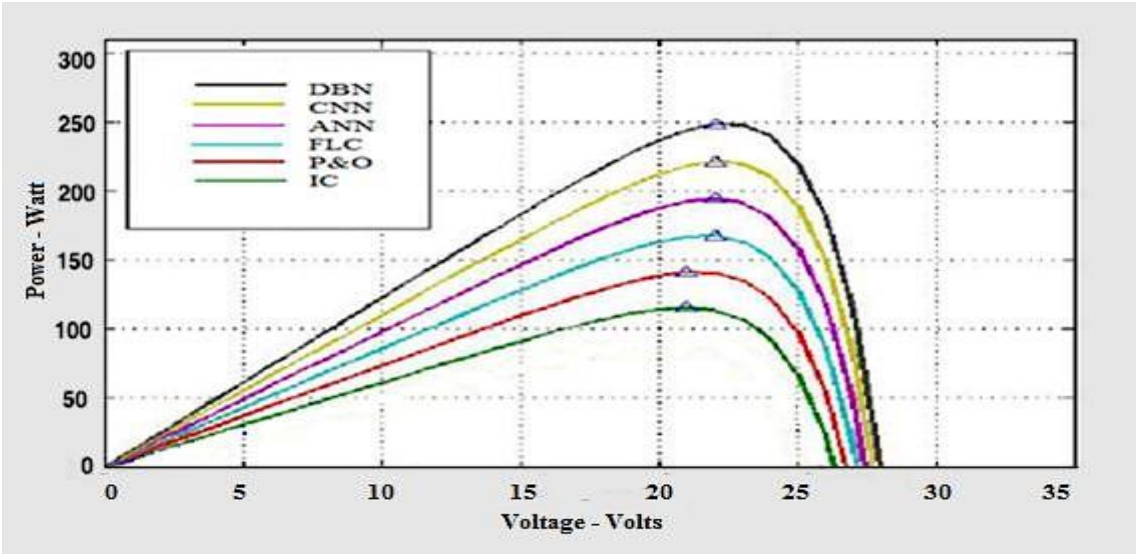


Figure 6.11(a): Comparative P-V Curve of different MPPT controller

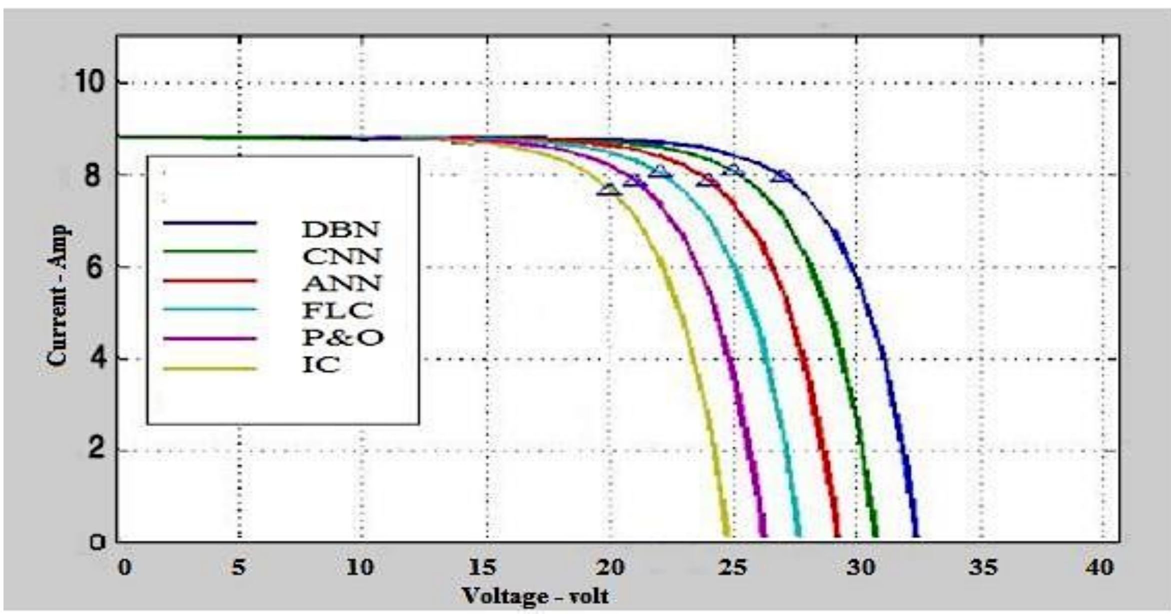


Figure 6.11(b): Comparative I-V Curve of different MPPT controller

"MATLAB/Simulink has been used to implement the various models and techniques. This was based on a data base which has been measured and taken on the system in advance. This database includes several values of T cell PV, G solar radiation and a separate test model measured duty cycle. Table 5.3 to Table 5.5 shows optimum findings".

Table 6.3: Varying Irradiation and Constant Temperature at 25^{0}C

Irradiation w/m^2	With-out MPPT (w)	With MPPT P&O (w)	MPPT using FLC (w)	MPPT using ANN (w)	MPPT using CNN (w)	MPPT using DBN (w)	Reference Power (w)
1000	175	234	246.2	247	251.5	251.6	251.8
800	161	215.2	226.5	227.2	231.2	231.4	231.6
600	151.3	202.2	212.9	213.5	217.3	217.5	217.7
400	145	194	204.3	204.9	208.6	208.8	208.9
200	142	190	200.2	200.8	204.4	204.6	204.7

Table 6.4: Constant irradiation 1000 w/ sq.m and varying temperature at different deg.celcius

Irradiation w/m^2	Temp ^{o}C	With-out MPPT (w)	With MPPT P&O (w)	MPPT using FLC (w)	MPPT using ANN (w)	MPPT using CNN (w)	MPPT using DBN (w)	Reference Power (w)
1000	15^{o}C	175	234	246.2	247	251.5	251.6	251.8
1000	25^{o}C	167	226	238.2	239	243.2	243.3	243.7
1000	35^{o}C	163	222.1	234.1	235	239.6	239.7	239.8
1000	45^{o}C	160	219	231.4	232	236.1	236.2	236.3
1000	55^{o}C	158	217	229.5	230	207.2	207.3	234.4

Table 6.5: Power Comparison for Different MPPT Techniques (at Constant temperature 25^0 C)

Irradiation w/m^2	With MPPT P&O (w)	MPPT using FLC (w)	MPPT using ANN (w)	MPPT using CNN (w)	MPPT using DBN (w)	Reference Power (w)
1000	234	246.2	247	251.5	251.6	251.8
800	215.2	226.5	227.2	231.2	231.4	231.6
600	202.2	212.9	213.5	217.3	217.5	217.7
400	194	204.3	204.9	208.6	208.8	208.9
200	190	200.2	200.8	204.4	204.6	204.7
Total Power (w)	1035.4	1090.1	1093.4	1113	1113.9	1114.7
Efficiency (%)	92.88	97.79	98.08	99.84	99.92	

6.10.Results analysis

This chapter presents findings pertaining to the diverse development of uncomplicated and efficient Maximum Power Point Tracking (MPPT) techniques for solar systems operating under fluctuating environmental circumstances. The study involved the development of simulation models for both conventional and intelligent control maximum power point tracking (MPPT) techniques. The analysis and discussion of the waveform of the output voltage, output current, and output power are conducted across all scenarios. Intelligent control-based techniques have been found to exhibit greater accuracy in identifying the maximum power point with reduced time consumption, as compared to conventional MPPT controllers. The proposed method exhibited an efficiency ratio that was nearly equivalent to 100 percent. The utilisation of DBN-optimized neural network training has resulted in a reduction in tracking time, minimal constant ripples in output power, accurate monitoring of the maximum power point with variations in atmospheric conditions or load conversion, and ultimately an enhancement in the performance of the maximum power point tracking controller. Consequently, the techniques that have been suggested render the MPPT controller appropriate for utilisation in both autonomous and interconnected load.

CONCLUSION

In summary, the utilisation of artificial intelligence-based MPPT techniques offers advantages in terms of tracking accuracy, adaptability, and potential for improvement in complex operational environments. The implementation of Maximum Power Point Tracking (MPPT) algorithms based on Artificial Intelligence (AI) involves a greater level of intricacy, which requires sufficient computational resources for both training and execution. The development of artificial intelligence models, including neural networks and fuzzy logic systems, involves the collection of data, training, and careful refinement. The complexity of this phenomenon may require specialised expertise, additional tools, and advanced computational resources. Artificial intelligence (AI) algorithms possess the ability to autonomously refine and optimise the maximum power point tracking (MPPT) process, thereby eliminating the requirement for manual intervention upon deployment. In summary, while traditional maximum power point tracking (MPPT) methods have been extensively employed in solar photovoltaic (PV) systems, MPPT algorithms powered by artificial intelligence (AI) provide significant advantages in terms of adaptability, accuracy, and effectiveness. The aforementioned systems exhibit the ability to adjust to diverse circumstances, augmenting the extraction of power in dynamic scenarios, and providing accelerated and accurate tracking. However, the utilisation of artificial intelligence-based MPPT techniques involves increased complexity and resource requirements during their development and implementation.

Future Research Directions

Future research directions in the field of MPPT for solar PV systems can focus on several areas to further improve the efficiency and performance of these systems. Here are some potential future research directions:

Advanced AI-Based MPPT Algorithms: There is potential for further exploration and optimisation of AI-based Maximum Power Point Tracking (MPPT) algorithms. The present study involves the investigation of novel machine learning methodologies, such as deep learning, reinforcement learning, or hybrid techniques, with the aim of improving the precision, flexibility, and responsiveness of the algorithms. Scholars may conduct an inquiry into the utilisation of sophisticated neural network structures or alternative artificial intelligence models to enhance the tracking efficacy across diverse operational circumstances.

Integration of Big Data and Predictive Analytics: The employment of big data analytics and predictive modelling methodologies has the potential to enhance the precision of Maximum Power

Point Tracking (MPPT). Through the amalgamation of diverse data sources, including historical solar irradiation data, weather forecasts, and real-time performance data from the photovoltaic (PV) system, scholars can construct sophisticated predictive models. The optimisation of the Maximum Power Point Tracking (MPPT) process can be achieved through the incorporation of long-term patterns, environmental trends, and real-time conditions into the models.

Hybrid MPPT Techniques: Investigating hybrid Maximum Power Point Tracking (MPPT) methods that integrate the advantages of various algorithms has the potential to be a fruitful area of inquiry in the future. Hybrid methodologies can exploit the benefits of diverse Maximum Power Point Tracking (MPPT) techniques to attain enhanced tracking precision, flexibility, and robustness. Scholars may explore the most effective amalgamation and synchronisation of conventional and artificial intelligence-driven algorithms to optimise their advantages and alleviate their drawbacks.

Robustness and Fault Tolerance: It is imperative to improve the resilience and error tolerance of Maximum Power Point Tracking (MPPT) algorithms to guarantee dependable functioning of photovoltaic (PV) solar systems. Subsequent studies may concentrate on the advancement of algorithms capable of managing system malfunctions, such as incomplete shading, module breakdowns, or grid disruptions, through the dynamic reconfiguration of the Maximum Power Point Tracking (MPPT) approach.

Optimization of Power Electronics Interfaces: One potential area of research is the optimisation of power electronics interfaces, including DC-DC converters and inverters, in conjunction with maximum power point tracking (MPPT) algorithms. Exploring innovative converter topologies, control methodologies, and circuit optimisation techniques has the potential to improve the efficiency, dependability, and overall efficacy of photovoltaic systems. The incorporation of Maximum Power Point Tracking (MPPT) capability into power electronics interfaces has the potential to simplify system design and enhance system efficiency.

Experimental Validation and Field Testing: The validation of MPPT algorithms through extensive experimentation and field testing is imperative for the evaluation of their real-world application and performance. Subsequent investigations may concentrate on performing extensive field investigations to authenticate the efficacy of artificial intelligence-driven maximum power point tracking (MPPT) algorithms across a range of operational circumstances and system arrangements. The implementation of AI-based maximum power point tracking (MPPT) systems on a large scale and the subsequent extended monitoring to assess their effectiveness, dependability, and financial feasibility is a potential course of action.

Economic and Techno-Economic Analysis: Undertaking economic and techno-economic evaluations of AI-driven Maximum Power Point Tracking (MPPT) systems can yield significant insights into the cost-benefit and financial feasibility of deploying these sophisticated algorithms. Prospective studies may explore the plausible economic advantages, ROI, and LCOE linked with MPPT systems based on AI. This can aid in assessing the economic viability and informing decision-making regarding the implementation of these sophisticated technologies.

Through the investigation of these research avenues, the domain of maximum power point tracking (MPPT) for photovoltaic (PV) solar systems can progress further, resulting in enhanced efficacy, adaptability, and dependability of systems that effectively capture the highest possible power output from solar energy sources.

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ANNEXURE-. RESEARCH PUBLICATION PAPER COPY

A Qualitative Review of Artificial Intelligence Based MPPT Techniques

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Abstract- *Artificial Intelligence (AI) is becoming increasingly popular in many areas, including the field of maximum power point tracking (MPPT), where it is used to optimize the power output from a photovoltaic (PV) system. There are several methods for AI based MPPT, each with their own advantages and disadvantages, as well as different levels of complexity. In this article, we will discuss the most popular AI based MPPT techniques, their advantages and disadvantages, and the complexity associated with each.*

Keywords- Solar Cells, MPPT, Fuzzy logic, Particle swarm optimization (PSO), Ant Colony Optimization, Unscented Kalman filters (UKFs).

I. INTRODUCTION

To begin, it is important to understand how a solar cell works. Solar cells are devices that capture energy from sunlight and convert it into electrical energy. The amount of electrical energy they produce is determined by the amount of sunlight they are exposed to, as well as their efficiency. When the sunlight is strong and the cell is working efficiently, the MPP is at its maximum. Thus, it is important for solar cells to be able to accurately track their MPP to ensure that they are running as efficiently as possible.[1]Maximizing power point tracking (MPPT) is a technique used to maximize the power output from a photovoltaic (PV) system. Traditional MPPT techniques include fuzzy logic, perturb and observe (P&O), incremental conductance (IC), and hill climbing. These methods rely on iterative adjustment of duty cycles to achieve accurate power tracking. While these methods are effective, they are slow and require dedicated hardware. Whereas, AI based MPP tracking is a way of using artificial intelligence algorithms to accurately track and optimize the MPP of solar cells. This is done by employing various machine learning and deep learning techniques to monitor the performance of the solar cell and adjust its performance accordingly. By doing so, the solar cell can be made to run more efficiently and produce more energy. In this review, we examine the use of AI-based MPPT techniques to improve the performance of a PV system.

II. AI-BASED MPPT TECHNIQUES

AI-based MPPT techniques offer an alternative to traditional methods. These methods rely on data-driven models and use machine learning algorithms to learn the optimal duty cycle settings which result in maximum power output. AI-based MPPT techniques are faster and more accurate than traditional methods, and they can be implemented on existing PV systems with minimal modifications.

- **Advantages of AI-Based MPPT Techniques**

AI-based MPPT techniques have several advantages over traditional methods. First, they are faster and more accurate, resulting in more efficient and reliable power tracking. Second, they require minimal modifications and can be implemented on existing PV systems. Finally, as the machine learning algorithms learn the optimal duty cycle settings, the system performance can be improved over time without manual intervention. The main benefit of using AI based MPP tracking is that it can significantly improve the efficiency of solar cells. By using AI algorithms to analyze the performance of the solar cell and adjust it accordingly, the cell can achieve its maximum power output more quickly and accurately.[2] This can lead to significant cost savings and increased energy production. However, there are also some limitations to using AI based MPP tracking. For example, the algorithms used by AI based MPP tracking are often computationally intensive and require significant amounts of data to accurately track the MPP. This can be difficult and costly to obtain in some cases. In addition, AI algorithms can be difficult to implement in real-world applications due to their complexity.

- **AI Methods to Enhance Performance of Solar Power Cells**

Artificial intelligence methods can be used to enhance overall performance in scaling solar power systems, especially when powerful computer systems are used. AI can also be used to develop algorithms that can make point tracking for maximum power more efficient. Hybrid systems that use synergy of AI and other technologies are also being studied in order to lessen the environmental effect of solar photovoltaic systems.AI is used to enhance power conversion efficiency and ensure MPPT controller in PV panels and PV arrays. Traditional PV systems use charge controllers to obtain continuous maximum power but AI can help optimize the system's charge. AI also helps in tracking technologies to ensure the maximum power point under varying climatic conditions. This helps in optimizing the system's charge while ensuring that the point tracking order is met under varying ecological conditions. Theapplication of Artificial Intelligence (AI) in tracking Maximum Power Point for Solar Cell is an effective way to maximize the system's power output. AI-based MPPT systems can be used in PV systems to self-optimize power output by selecting the optimized algorithm. This helps in reducing the need for a relatively complex control circuit. The AI-based MPPT control algorithm is designed to detect and track the point of maximum power from a PV source in real time, regardless of environmental factors such as temperature or installation method. It helps optimize the system's operating point and maximize its power output with improved efficiency than other methods without requiring any user input or manual adjustments.[3]

II. DIFFERENT AI BASED MPPT TECHNIQUES

Modern maximum power point tracking (MPPT) systems use several types of artificial intelligence (AI) techniques to optimize the performance and efficiency of photovoltaic (PV) systems. The most commonly used AI techniques are fuzzy logic, neural networks, and genetic algorithms.

III. ARTIFICIAL NEURAL NETWORK

The biological neural networks in animal brains inspired the ANN or connectionist system. It is used to train and test the I-V and P-V nonlinearity relationship. ANN gathers inputs ranging from input current, input voltage, irradiance, temperature, and metrological data and constantly learns to adapt the behaviour of the solar power system for maximum power. FLC design may be simulated using ANN for more accuracy and simpler converter implementation.

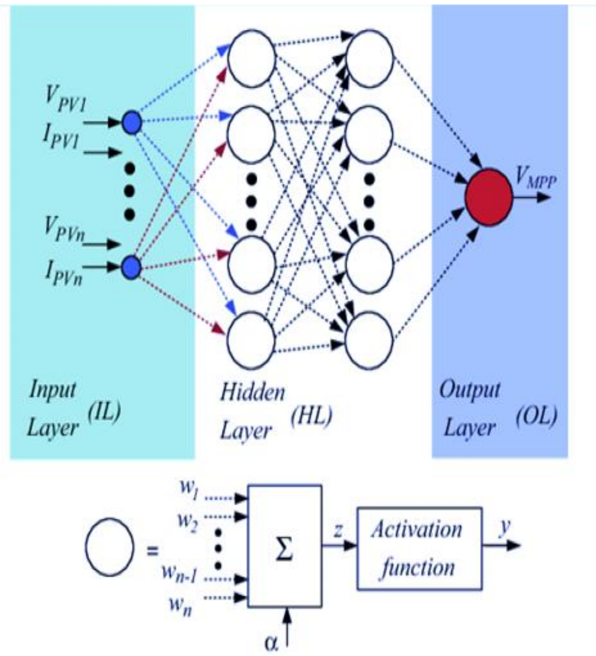

Figure1: Multilayer Feed Forward Neural Network[4]

The dataset is obtained from the simulation or hardware setup by feeding solar irradiances, temperatures, solar power system voltage or current to ANN in order to discover the relevant P_{max} or V_{max} output, as seen in the Figure below. After being transformed into training data, these data are sent into the artificial neural network (ANN) being developed. Test datasets are used to assess the trained ANN's effectiveness, with the resulting mistakes feeding back into the ANN to fine-tune the design. It may be used to supplement state estimate using sequential Monte Carlo (SMC) filtering and MPP prediction. The IC MPPT method's architecture may accommodate a state-space model for sequential MPP estimation, and the ANN model uses voltage and current or irradiance data to enhance SMC's calculation of GMPP.[5]
ANN's benefits include, among others, the ability to model non-linear relationships with high precision and to solve issues with little to no input from the user.

IV. PARTICLESWARM OPTIMIZATION (PSO)

It is a meta-heuristic algorithm based on the collective social behaviour of a group of birds or insects. It has been widely used in various fields such as engineering optimization, machine learning, and finance. In the field of maximum power point tracking (MPPT), PSO has been used to optimize the performance of solar cells by minimizing the non-linearity between the temperature and the output current of the photovoltaic system. In this process, PSO is used to find the optimal operating point for the solar cell by iteratively searching for the values of various parameters such as the bus voltage, open circuit voltage (Voc), and maximum power point (MPP).[6]

To achieve the optimal output, the algorithm first identifies the location of the MPP by calculating the gradient of the power-voltage curve. Then, the parameters of the system are adjusted according to the gradient values and the output is compared with the expected output. This process is repeated until the desired accuracy is achieved. ThePSO algorithm maintains a swarm of individuals (called particles), where each particle represents a candidate solution. Particles follow a simple behaviour: emulate the success of neighbouring particles and its own achieved successes. The position of a particle is therefore influenced by the best particle in a neighbourhood, p_{best} as well as the best solution found by all the particles in the entire population, g_{best}The particle position,χ_i ,is adjusted using where the velocity component, , represents the step size.

$$\chi_i^{t+1}=\chi_i^t+\nu_i^{t+1}$$

The velocity is calculated by[7]

$$\nu_i^{t+1}=\omega\nu_i^t+c_1r_1.(p_{best},\ i-x_i^t)+c_2r_2.(g_{best}-x_i^t),$$

$i=1,2,\ldots.N$,

whereχ_i denote the particle position for i; the velocity of the particle at i is represented byν_i ; the number of iteration is denoted by t ; the inertia weight is represented byω and r_1 and r_2 are uniformly distributed random variables within[0,1]; and the cognitive and social coefficient are, respectively, denoted by $c_1 c_2$. The best position for the storage of the ith particle that has been found so far is denoted by variable $p_{best,\ i}$and the storage of the best position of all the particles is represented by g_{best} . [8]

V. FUZZY LOGIC CONTROL SYSTEM

The fuzzy logic control system works by tracking the maximum power point (MPP) of the PV module. It does this by taking into account the environmental parameters such as temperature, irradiance, and voltage levels to adjust the PV module's operating voltage to ensure optimal performance. The fuzzy logic control system also takes into account the changes in the PV module's operating voltage and subsequently adjusts the current and voltage levels to maintain the MPP. The fuzzy logic control system has been developed to provide reliable and efficient power tracking, even under varying environmental conditions. It is also capable of providing a robust and reliable system by taking into account the power characteristics of the PV module. Furthermore, the fuzzy logic control system can be tuned to the specific characteristics of the PV module to ensure optimal performance under all environmental conditions.

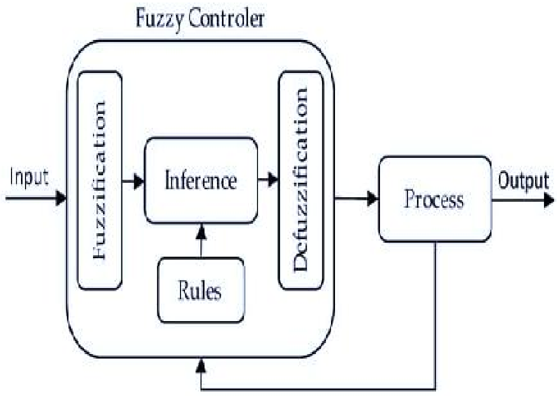

Figure 3: Block Diagram of FLC [9]

The FLC comprise in three steps fuzzification, inference rule base and defuzzification. Fig Block diagram shows these techniques. The input variable of the fuzzification but these variables are generally known as an error ‘e(k)’ and variation in error (Δe(k)). The main work of fuzzification is using membership function converts crips value to linguistics value. The triangular membership is highly popular show in fig. and table .

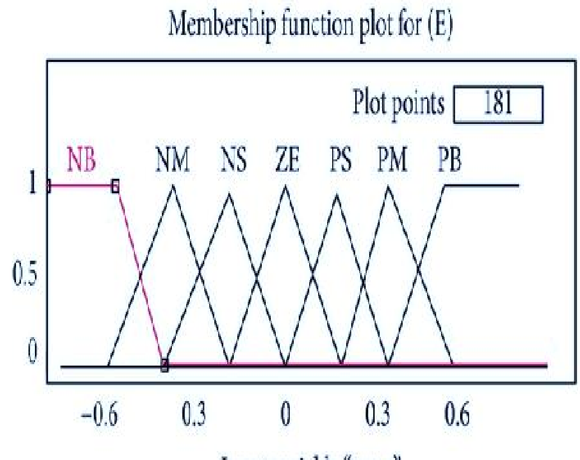

Figure 4: Membership Function [10]

Rule Table of FLC [11]

$\Delta P_p v \Delta I_p v$	**P**	**Z**	**N**
PB	PB	PB	NB
PM	PM	PM	NM
PS	PS	PS	NS

ZZ	PS	ZZ	NS
NS	NS	NS	PS
NM	NM	NM	PM
NB	NB	NB	PB

Output variables are control according to rule inference engine. Using a rule base table the membership function base inference engine applies rules. In defuzzification convert output linguistic to relevant crisp & numerical value[12] . In MPPT application input variable calculate using this equations:

$$(e(t)) = \frac{\Delta p(t)}{\Delta v(t)} = \frac{p(t)-p(t-1)}{v(t)-v(t-1)} \text{.................. (1)}$$

$$\Delta e(t) = e(t)- e(t-1) \text{..............................(2)}$$

In FLCP(t) power value and V(t) voltage value are the operating point, respective; t is the sampling time; next step of the operation direction of the operating point define by the Δe(t), and position e(t) of the operating point in the P-V. Then, the MPP is calculated using the fuzzy rules from the above table, with the logic being "THEN Changes applied AND power increased THEN- continue the direction," which is used to describe the DC-DC converter's necessary change in operation cycle. [13]

VII. ANTCOLONY OPTIMIZATION BASED MAXIMUM POWER POINT TRACKING (MPPT)

Ant Colony Optimization based Maximum Power Point Tracking (MPPT) is a meta-heuristic approach to optimize the power output of a photovoltaic (PV) system. It is inspired by the foraging behaviour of ant colonies and allows the PV system to operate at its optimal power point (OPP) for maximum power extraction.

The main idea of the ACO based MPPT is to use an artificial ant colony to search for the global optimum of the PV system's performance. The artificial ants will search the PV system's power-voltage curve to find the OPP. To achieve this, the artificial ants are allowed to move along the power-voltage curve and adjust their movement according to their current power input and voltage output. The movement of the ants is guided by a heuristic algorithm which takes into account the current power input and voltage output of the PV system.[14]

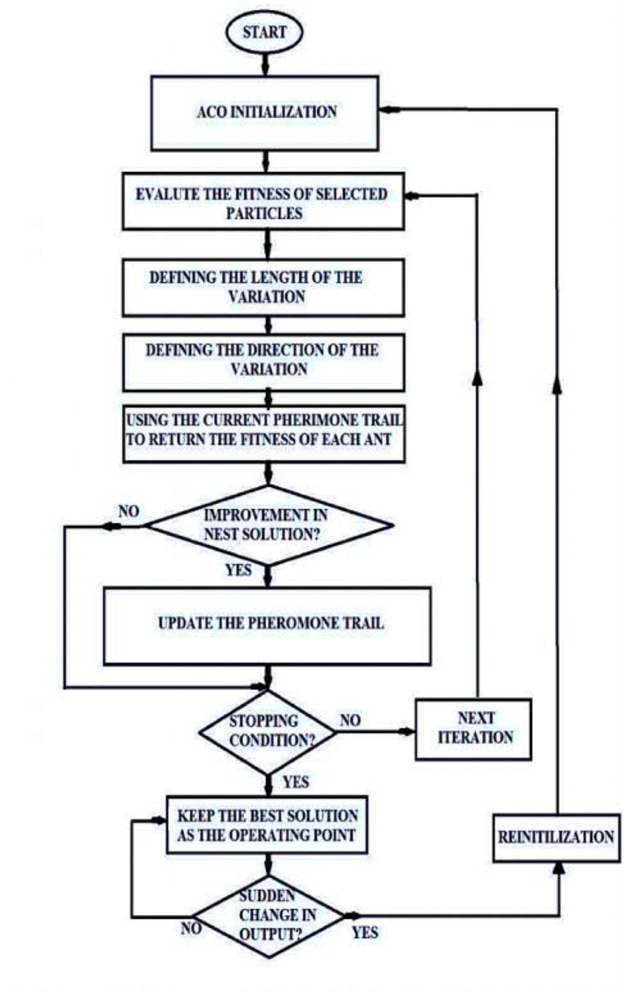

Figure 6 :ACO based MPPT flow chart [14]

The ACO-based MPPT uses a grid-based representation of the PV array's voltage at each point. Each ant's optimal fitness value, represented by the F(x) objective function, is ranked by its voltage score. The following equation displays the 1st iteration of the location matrix, assuming n ants are involved.[15]

$$X_l^i=[X_l^1,X_l^2,\ldots..X_l^N]$$

The ACO based MPPT is a reliable and efficient method for tracking the OPP of the PV system. It has been used to achieve up to 30% more power output compared to traditional MPPT algorithms. Furthermore, the ACO based MPPT algorithm is relatively easy to implement, does not require any complicated mathematical calculations, and can be implemented in any type of system. Additionally, the ACO based MPPT algorithm requires very little energy and can be deployed remotely by wireless communication.

VIII. UNSCENTED KALMAN FILTERS (UKFS)

Unscented Kalman filters (UKFs) are a powerful tool used in the Maximum Power Point Tracking (MPPT) of solar cells. UKFs have been shown to be successful in tracking the optimal power output of solar cells, and in this guide we will discuss their use and implementation. The UKF approach utilizes a set of non-linear equations to track the optimal power output of a solar cell by using statistical methods to account for noise and irregularities in the cell's output. The UKF is based on the Bayesian filtering technique, which estimates the current state of a system by using past measurements and a process model. In the UKF approach, a set of sigma points are used to represent the system's uncertainty.[16] These sigma points are generated by perturbing the system's mean state vector with a sequence of Gaussian noises. The sigma points capture the relative uncertainty of different components of the system and allow for a more accurate tracking of the MPPT of the solar cell. Once the sigma points are generated, they are propagated through the system dynamics to get the predicted state vector. The process model is then used to update the expected error covariance matrix, which is used to compute the Kalman gain and the optimal prediction of the solar cell's power output.
The UKF approach has been proven to be a successful and accurate tool for tracking the optimal power output of a solar cell.

IX. APPLICATION OF HILL CLIMBING (HC) TECHNIQUE IN SOLAR CELL MAXIMUM POWER POINT TRACKING

Solar energy is an abundant and clean renewable energy source which is receiving increasing attention from researchers due to its sustainable benefits. Maximum Power Point Tracking (MPPT) is the process of continuously optimizing the output of a photovoltaic (PV) system to capture the maximum available energy from a PV module. The application of HC technique in MPPT has been studied by several researchers due to its capability to effectively search and track the maximum power point as quickly as possible.[17]

The HC technique is a local search algorithm which is applied to find the maximum power point of a PV system by repeatedly iterating to find the next possible point with increased power output. The HC technique used in MPPT is defined as an optimization process in which the PV system is driven by a current-voltage curve and the corresponding power output is monitored. The HC technique rapidly navigates the PV system to efficiently track the maximum power point by gradually increasing the current and voltage of the system until the maximum point is reached. The HC technique is based on two principles, namely the ‘ascent’ and the ‘descent’ principle. The ascent principle is applied when the power output is increased by increasing the current and voltage, and the descent principle is applied when the power output is decreased by decreasing the current and voltage. The HC technique is based on the principle of ‘one-step-ahead search’ and it does not require any prior knowledge of the system’s PV characteristics.

X. EVOLUTIONARY ALGORITHM (EA)

Evolutionary Algorithm (EA) based Maximum Power Point Tracking (MPPT) is a method of solar power optimization that uses evolutionary algorithms to identify the optimal combination of parameters to maximize the amount of energy captured from a given solar panel. EA based MPPT can be used to identify the optimal amount of power output, given a specific solar panel, ambient temperature, and other environmental conditions. The EA based MPPT method is also beneficial in tracking changing environmental conditions, and can adjust the parameters accordingly. The application of EA based MPPT is beneficial for increasing the efficiency of any solar panel system. By using the EA based optimization approach, the system is able to identify the combination of parameters that will produce the highest amount of energy from the given solar panel. This means that the system can identify the best combination of parameters for a given solar panel, even when the environmental conditions or the solar panel itself change. The EA based MPPT approach is also advantageous for reducing the cost of solar power systems. By being able to identify the optimal combination of parameters, the overall cost of the system can be minimized, as the system will not be wasting energy. By utilizing the EA based MPPT, solar panel systems are able to make the most of their available energy, and optimize their performance.[18]

XI. COMPARING DIFFERENT AI-BASED MPPT TECHNIQUES

Modern solar installations make use of Maximum Power Point Tracking (MPPT) technology to optimize energy output from the solar array. AI-based MPPT algorithms offer a distinct advantage over traditional methods, such as the Perturb and Observe algorithm, as they are able to respond faster to fluctuations in environmental conditions. In this article, we will compare the performance of several AI-based MPPT techniques, including Fuzzy Logic, Unscented Kalman Filters, and Neural Networks, to assess their suitability for different applications.

Fuzzy Logic

Fuzzy Logic-based MPPT techniques allow for the optimization of a solar array's power output through the use of fuzzy rules. Fuzzy logic allows for the definition of a system's performance in terms of qualitative parameters, such as "low", "medium" and "high". By leveraging fuzzy logic, the power output of a solar array can be optimized by adjusting the system's operating parameters in accordance with those fuzzy rules. So, the fuzzy logic system uses a set of rules to determine the best parameters, which makes it simpler than neural network or evolutionary algorithm based approaches. The main advantage of this approach is its simplicity and cost-effectiveness. However, it is not as accurate or as fast as other AI based approaches.[19]

Unscented Kalman Filters

Unscented Kalman filters (UKF) are a type of AI-based MPPT algorithm that uses a combination of statistical and probabilistic methods to optimize power output. UKF works by calculating the expectation values of a system's parameters, then using those values to calculate optimal operating parameters. This technique is particularly useful in environments with rapidly changing environmental conditions, as UKF is able to respond quickly to sudden changes.

Hill Climbing (HC) Algorithm

The Hill Climbing (HC) algorithm is one of the simplest and most widely used AI based MPPT techniques. The main purpose of the HC algorithm is to maximize the output power of a PV system by modifying its operating point. The algorithm works by incrementally adjusting the system's operating point until it finds the point that maximizes the output power. HC algorithms are relatively easy to implement and require minimal computational resources, making them a viable solution for small-scale PV systems. The main advantage of the HC algorithm is its simplicity; however, it can also suffer from local minima, meaning that the algorithm may not always find the global maximum. Additionally, HC algorithms may take a long time to find the optimal solution if the parameters vary drastically from one iteration to the next.

Particle Swarm Optimization (PSO) Algorithm

The Particle Swarm Optimization (PSO) algorithm is another popular AI based MPPT technique. Like the HC algorithm, it is used to maximize the output power of a PV system. The main difference between the two is that PSO uses a population of points, known as particles, which move around in search of the optimal solution. Each particle is associated with a fitness value, which guides the algorithm towards the optimal solution. The main advantage of PSO is that it is relatively fast and can avoid local minima. Additionally, the algorithm does not require a large amount of computational resources, making it suitable for small-scale PV systems. The main disadvantage of PSO is that it can require a large number of particles to find the optimal solution, which can lead to high computational costs.

Neural Network Based MPPT

Neural Network based MPPT is a type of AI based MPPT technique which uses a neural network to learn the best parameters for maximum power point extraction. The neural network is trained with a large set of experimental data and can provide highly accurate results. The main advantage of this approach is its high accuracy and fast response time. However, it can also be complex, time-consuming, and expensive to build and train the neural network.

Evolutionary Algorithm Based MPPT

Evolutionary Algorithm based MPPT is another AI based MPPT technique which uses evolutionary algorithms to determine the optimal solution. This approach is simpler than Neural Network based MPPT, since evolutionary algorithms are already implemented in most programming languages. Additionally, this approach is usually more cost-effective, since it does not require the use of expensive hardware for training. However, the accuracy and response time of this approach is lower than Neural Network based MPPT.

XII. CONCLUSION

It can be concluded that the current AI-based methods have faster convergence speed, higher efficiency and better accuracy than conventional ones. Furthermore, the various AI-based MPPT algorithms in terms of oscillation, current accuracy, and fast response to changing environmental conditions when compared with the traditional methods.

Artificial intelligence-based MPPT techniques are able to achieve improved maximum possible energy from a solar cell or solar power system when compared to conventional methods. The paper provides a review of the various new methods and novel mechanisms used in artificial intelligence based MPPT techniques for efficient point tracking. Finally, it can be concluded that AI-based MPPTs can outperform conventional methods in terms of tracking accuracy, response speed and overall system efficiency.[20] The realistic MPPT approach has been identified as a better option for achieving maximum power point tracking with less time and effort. In addition, the significant instalment cost of such a system is justified by its effectiveness in life implementation. In conclusion, the different AI based MPPT techniques have different advantages and drawbacks. Neural Network based MPPT is the most accurate and fastest approach, but it is also the most complex and expensive. Evolutionary Algorithm based MPPT is simpler and more cost-effective, but is not as accurate or fast. Finally, Fuzzy Logic based MPPT is the simplest approach, but is not as accurate or as fast as other AI based approach. In order to select the most suitable AI-based MPPT technique, it is important to consider the environmental conditions of the installation and the desired performance of the system. Fuzzy logic is best suited to relatively stable environments, as the system's performance can be defined in terms of qualitative parameters. Unscented Kalman filters are ideal for rapidly changing environments, as the system is able to respond quickly to sudden changes in conditions.

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