COMPARATIVE ANALYSIS OF MPPT ALGORITHMS FOR PHOTOVOLTAIC SYSTEMS

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Submitted by

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DECLARATION

I, Anishma Singh, Roll No. – 2K20/PES/03 student of M.Tech (Power Electronics and Systems), hereby declare that the project Dissertation titled "**Comparative analysis of MPPT algorithms for photovoltaic systems**" which is submittedby me to the Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillmentof the requirement for the award of the degree of Masters of Technology is original and notcopied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship, or other similartitle or recognition.

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Date: 31 May 2022

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CERTIFICATE

I hereby certify that the Project Dissertation titled "**Comparative analysis of MPPT algorithms for photovoltaic systems**" which is submitted by Anishma Singh, Roll No. – 2K20/PES/03, Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Bachelor of Technology, is a record of the project work carried out by the students undermy supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi
Date: 31 May 2022

Supervisor
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Abstract

One of the most viable renewable energy sources is photovoltaic (PV) energy which serves as an alternative to fossil energy as it is considered less polluted. The PV systems must be operating with high efficiency. However, PV panels have a non-linear voltage-current characteristic, which depends on environmental factors such as solar irradiation and temperature and gives very low efficiency. Therefore, it becomes crucial to harvest the maximum power from the PV panels. Thus, they have to operate at their maximum power point (MPP) despite the inevitable changes in temperature and solar irradiation.

The objective of this thesis is to study and analyze the MPPT techniques. The most common and well known perturb and observe (P&O), and incremental conductance (In Cond) methods were focused on in this thesis, as these algorithms were found easy to implement, low-cost techniques, and suitable for large size and medium-size photovoltaic applications and were compared with intelligence-based techniques that are Particle Swarm Optimization (PSO), Fuzzy logic and Artificial Neural Network (ANN).
All these five techniques were implemented in the MATLAB Simulink environment and their performance was analyzed for variable irradiances at standard temperature.
The proposed MPPT schemes are implemented in the control circuit of the DC-DC boost converter.

Results show an improvement in the tracking of ANN based controller compared to all other controllers. The proposed algorithms minimize the oscillations around MPP, and the power is converging faster compared with the response done by conventional algorithms.

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Place: Delhi
Date: 31 May 2022

Anishma Singh
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Chapter 1: INTRODUCTION

1.1 Photovoltaic systems

The global need for energy is steadily growing. As a result, there has been a significant increase in the usage of fossil fuels, with detrimental environmental effects like global warming, acid rain, and ozone layer exhaustion. Diversification of energy resources is critical for overcoming the negative effects of fossil fuel energy technologies on the earth's ecological stability[1]. Additionally, fuel costs and dwindling fossil fuel supplies may have detrimental implications. In the near future, many countries will face economic and political consequences. The enhancement of energy efficiency and the appropriate utilization of renewable energy resources is critical to long-term growth.

Renewable energy systems could be a solution to this crisis. Various renewable energy technologies that are efficient and cost-effective in comparison with traditional power production have been developed. Costs of energy from renewable sources are currently falling, and additional reductions are anticipated with the increment in production and demand.

To stimulate investment in substitute alternative energy sources such as mini-hydropower, wind, solar, and biomass, many countries have implemented new energy policies several of the most significant renewable energy sources is solar energy, and its share is expected to grow in the not-too-distant future. According to an assessment of worldwide energy use conducted by the International Energy Agency, 30 to 60 Terawatts of solar energy per year would be necessary by 2050.

Photovoltaic cells are one kind of method for harvesting solar energy. The problem with solar energy is it's not constantly accessible, and the intervals when it is available are limited i.e. it rarely coincides with energy demand. Furthermore, photovoltaic plants occasionally experience cloud problems, which reduce the efficiency of the photovoltaic (PV) system by reducing its output power. As a result, it appears prudent to store PV energy acquired during high insolation times not just to maintain power supply during low-irradiation or cloudy periods, but to also provide uninterrupted electrical output. The most common type of solar energy storage device used for this purpose is a battery.

Photovoltaic energy sources may be used in both isolated and grid-connected applications as shown in fig 1.1. Battery charging, Water pumping, refrigeration, residential power supplies, street lighting, and satellite power systems. telecommunications, heating systems, hybrid vehicles, military space, swimming pools, and hydrogen manufacturing are all applications for photovoltaic energy sources [6]

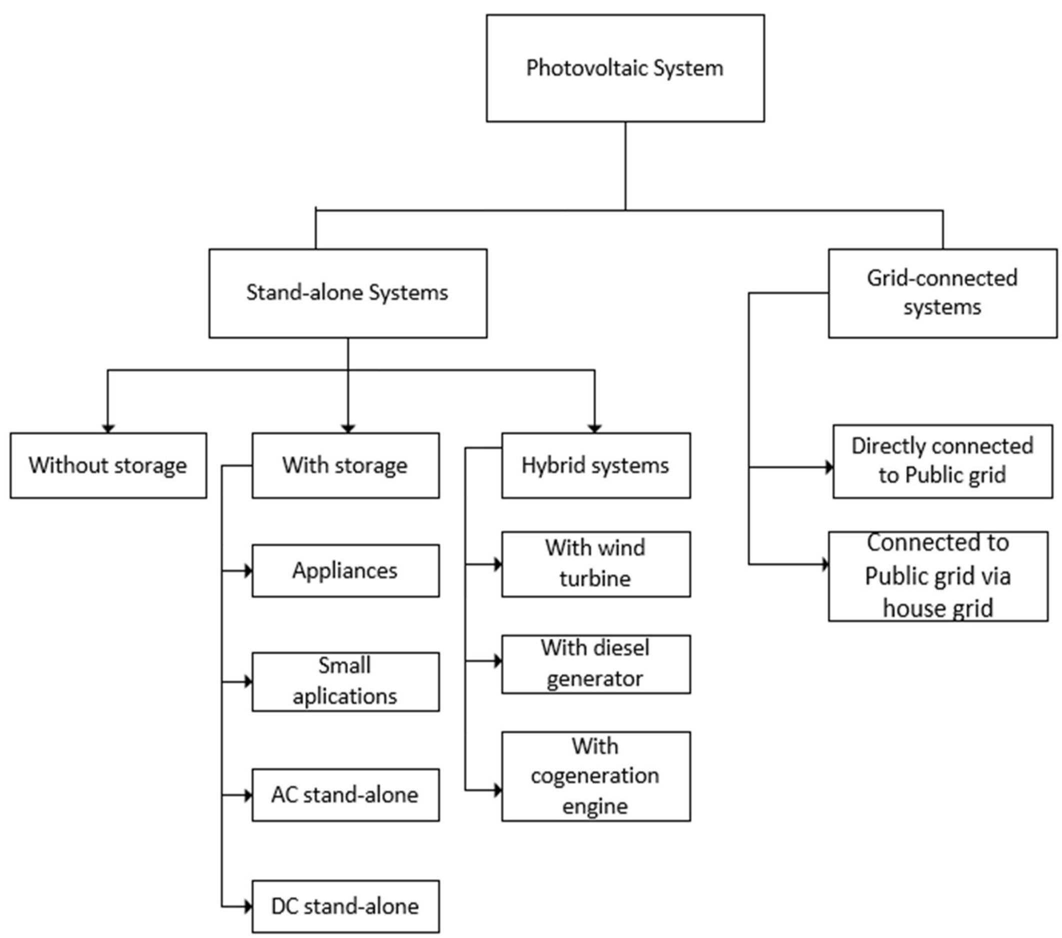


Fig-1.1: Applications for PV Systems

1.2 Background and Motivation

PV systems, for example, have the potential to provide sustained electrical energy in areas where the regular power grid doesn't quite exist. They may be situated near to loads and provide benefits that mass power production cannot. PV energy can be used to power equipment in isolated locations or townships that are not connected to the power grid [3]. Furthermore, PV energy is non-polluting. It requires no upkeep and generates no disturbance. It is possible to create and install it. timely manner. Because of its lightweight, it is extremely mobile and portable. It also offers a good power capacity to weight compared. Peak load demands are well met by PV power production[1].

The following are the limitations of PV energy:

- • A hefty initial investment and a reduction in power conversion efficiency equivalent to 17%.
- The non-linear current-voltage (I-V) relationship of a PV cell as a result of temperature and solar irradiation fluctuations[3].
- The power delivered to the load from the PV generating source in a direct-coupled PV-load system is rarely ideal, which reduces system efficacy.

Trackers for peak powerpoint are used to calculate the value of current required to operate the program at maximum power (MPP). An entire MPPT solar panel system consists of a solar panel, an MPPT algorithm, and a DC-DC converter architecture. Numerous MPPT algorithms for tracking the maximum power of a PV system have been developed in the literature[6] [4]. The Perturb and Observe (PO) approach, Incremental Conductance (IC) method, Constant Voltage (CV) method, and fuzzy logic (FL) methodology are among them. To execute maximum power tracking duties, these MPPT algorithms can be installed into a computer or a microcontroller. They differ, however, in terms of speed, efficacy range, expense, quantity of needed sensors, complication, and recognition [7].

According to the many researchers, current fundamental strategies employed in MPPT approaches can be:

- Rapid response time owing to transitory alterations
- Tracking accurately, but concurrently

Obtaining either of those traits, swift reaction, and precise tracking, at the same concurrently is desirable since they may significantly help to decrease Power losses as a result of dynamic tracking faults that arise when environmental parameters alter rapidly, increasing overall yield.

1.3 Block Diagram

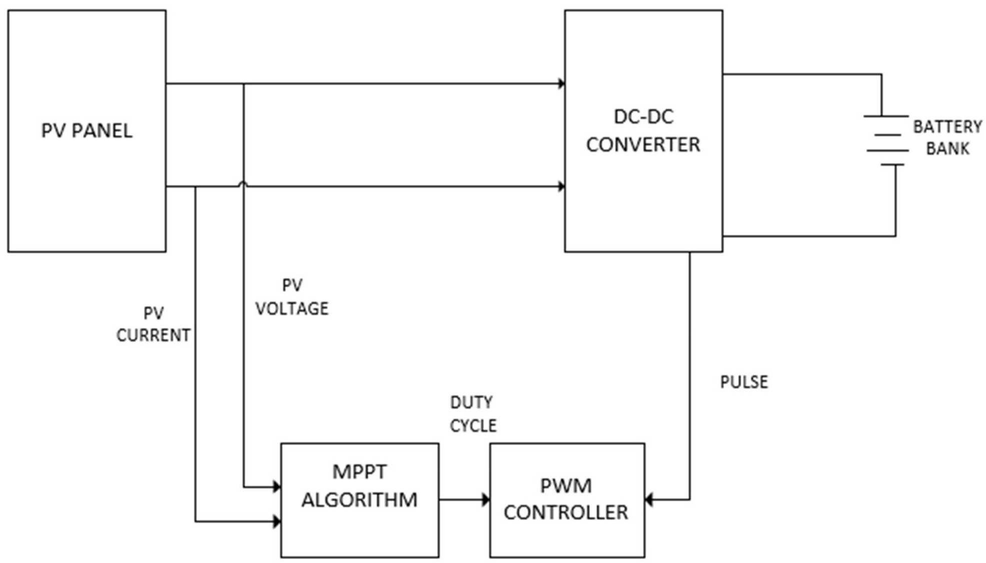


Fig-1.2: Schematic diagram of PV simulation system used

1.4 Objectives, Methodology, and Scope of the Study

In the research of PV solar energy, two approaches are available: a numerical and experimental simulation. Simulations are quantitative experiments that, like experimental simulations, can offer some type of thermal performance information, and they will be the topic of this research project. Modeling, programming, simulation, and evaluation of MPPT approaches were employed in this study.

<u>The following are the dissertation's objectives:</u>

- To find an effective MPPT algorithm appropriate in process of extracting the greatest energy from the panel.

- Under changing environmental operating circumstances, deliver an upgraded MPPT algorithm with benefits such as rapid tracking and reduced power variability

The following is the approach used:

- Through a literature review, analyze and comprehend the merits and disadvantages of certain conventional MPPT algorithms under varied operating circumstances.
- To create a PV prototype and an MPPT prototype with MATLAB and Simulink in order to evaluate the performance of existent MPPT algorithms and correct their shortcomings using various escalation strategies suited for PV domestic applications

The model is of a mercantile available PV panel. In this dissertation, five different types of MPPT algorithms are employed for comparative analysis. They are initially penned in MATLAB m-files and then analyzed through projections. The Perturb and Observe (PO) algorithm, The Incremental Conductance, Particle, and Swarm Optimization, Fuzzy Logic Controller, and Artificial neural network are analyzed. As a result of this analysis, the most optimal One of the five MPPT algorithms is chosen and implemented across the Photovoltaic system.

In a separate MATLAB/Simulink environment, a full Photovoltaic system with an Mppt controller, comprising a solar panel, an MPPT algorithm, and a DC-DC converter architecture, is modelled and simulated computationally. After all, subsystems have been tested individually to guarantee proper operation and coherence, They are linked and integrated with the load to quantify the throughput of this PV application.

The project's goal is not to develop a controller loop for PV voltage control or to conduct a cost-benefit analysis of MPPT approaches; instead, it is to model, program, simulate and evaluate MPPT technique performances for a PV system.

1.5 Outline of the Thesis

The chapters of the dissertation are structured as:

The first chapter includes an overview of the study's background and motivation, as well as a layout design of the MPPT system used. The objectives, methodology, and scope of the study are underlined.

Chapter Two illustrates the modeling of the solar photovoltaic array along with the calculation of required parameters.

Chapter Three includes the designing of the Boost converter required for the controller followed by chapter 4 which discusses the five different maximum power point tracking algorithms. Chapter 5 comprises of Results and discussion of characteristics that are analyzed finally followed by chapter 6 which includes the conclusion.

CHAPTER 2: MODELLING OF SPV ARRAY

2.1 Introduction

Solar cells are the fundamental building blocks of photovoltaic panels. Although substances are utilized, silicon is the most commonly used. Solar cells use photoemission, which is the capacity of certain junction transistors to transform nonparticulate radiation straight into current [1]. The ionized particles produced by incoming radiation are conveniently divided to produce an ion flow by a suitable layout of the solar cell's construction. Solar panels cost expensive. PV modules are constructed by connecting Photovoltaic cells in sequence and collaterally to achieve the necessary voltages and current values. Solar cells are encased because they must be abrasion-resistant and electrical ties must be strong and corrosion-free. Solar panels cost really expensive[1]. Interestingly, photovoltaics producing maximum electricity can compensate for their heavy cost. To get the most out of PVs, a mathematical model that can anticipate their nominal voltage and current should be developed [2]. In this chapter, the structure of the photovoltaic module is reviewed briefly, and the required parameters are calculated.

2.2 Simulation of SPV Theory and Design

2.2.1 Equivalent circuit of Solar cell

Electrical model may be used to represent a solar cell. The following equation describes its current-voltage characteristic[8].

$$I = I_L - \left(e^{\frac{q(V-IR_S)}{AkT}} - 1\right) - \frac{V-IR_S}{R_{SH}} \qquad (2.1)$$

Where V and I are the output voltage and current respectively, an electron's represented as q , I_o is the dark saturation current, Boltzmann constant is represented by k, R_{SH} and R_s are the shunt and series resistance of a cell, and absolute temperature is shown by T. R_S is provided by the solar cell's connections and bulk semiconductor material. The cause of shunt resistance RSH is produced by the atrocious character of the p–n junction as well as the existence of defects along the cell's margins, which give a short-circuit route about the junction. Immaculately, R_S is zero and R_{SH} is limitless. This eventuality, however, isn't achievable, and ms strive to reduce the impact of both resistances to enhance their products.

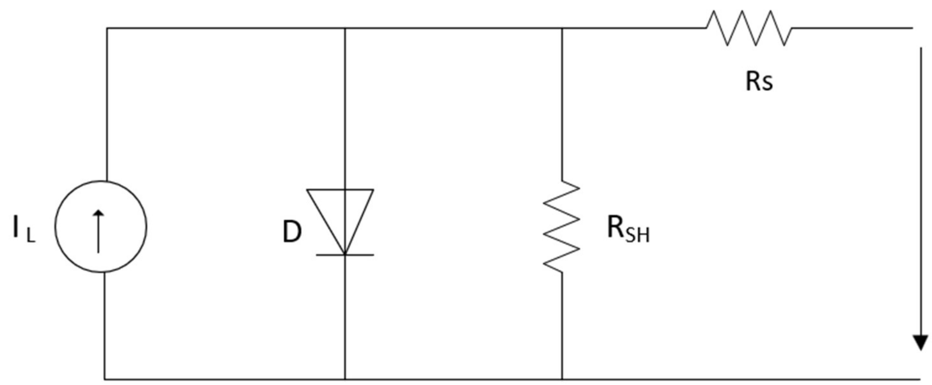


Fig-2.1: Equivalent circuit of a solar cell.

To optimize the design, the influence of shunt resistance is sometimes ignored, i.e., RSH is endless, hence the last component is ignored.

A PV panel is made up of several solar cells linked in parallel or in succession so that the output voltage and current of the PV panel meet the needs of the network or apparatus. Using the above-expressed simplification, the characteristic of output current-voltage of a PV panel expressed by equation 2.2 , Here n_s and n_p are the quantity of solar cells in series and parallel, respectively [8].

$$I \approx n_p I_L - n_p I_o \left(e^{\frac{q(V-IR_S)}{AkTn_S}} - 1 \right) \tag{2.2}$$

2.2.2 Maximum PowerPoint, short circuit current, and Open circuit voltage

Two important facts of the current-voltage characteristic are necessary to be pointed out: the short circuit current I_{SC} and the open circuit voltage V_{OC}. The generated power is 0 at both sites. Whenever I=0 i.e., the cell has zero as the output current, as well as the shunt resistance R_{SH} is not considered, V_{OC} can be calculated by using (1). This approximation is being expressed by equation (3). As indicated in equation(2.4), the short circuit current I_{SC} is the current value when Voltage is zero and is nearly equivalent to produced current I_L [5].

$$V_{OC} \approx \frac{AkT}{q} \ln\left(\frac{I_L}{I_O} + 1\right) \tag{2.3}$$

$$I_{SC} \approx I_L \tag{2.4}$$

The highest power generated by solar cell at the point on the current-voltage. At this point the product of V and I is maximum. This is a unique point, and it is called MPP.

2.2.3 Fill factor

The fill factor (FF) as expressed in eq 2.5 may be calculated using the voltage and current at MPP, V_{MPP} and I_{MPP}, the short circuit current (ISC), and the open-circuit voltage (VOC).

$$FF = \frac{I_{MPP}V_{MPP}}{I_{SC}V_{OC}} \tag{2.5}$$

It is a broadly utilized indicator of the all-inclusive condition of a solar cell. It is the proportion of maximum power ($I_{MPP}V_{MPP}$) to conceptual maximum power ($I_{SC}V_{OC}$), which is not achievable. Due to the general series and shunt resistances, as well as the diode illustrated in diagram 2.1, the MPP voltage and current are less than the open-circuit voltage and short-circuit current, respectively[5].

2.2.4 Irradiance and Temperature effects

The irradiance and temperature are two critical elements that must be considered. They have a significant impact on the features of solar equipment. As an outcome, the MPP changes throughout the day, which is why it must be regularly watched to guarantee that the panel generates the utmost amount of power possible

The photo-generated current, as aforementioned, is directly related to the level of irradiance, hence growing luminescence results in a larger current. In addition, current due to the short circuit is precisely commensurate to the photogenerated current, and hence to the incandescence. Whenever the operative position isn't short-circuited, where neither energy is produced, the photogenerated current is also a critical feature of the PV current. As a result, whenever the irradiation varies, there is fluctuation in the voltage-current characteristic. The influence on open-circuit voltage, is quite minimal since the dependency of the light-produced current is logarithmic.

In application, the voltage reliance on irradiation is frequently overlooked. Because the influence on both voltages and currents is not negative, i.e., each one rise as irradiation increases, the outcome on power is likewise definitive: as irradiation increases, so does power generation.

Temperature, as seen on the other hand, has the most influence on voltage. As illustrated in the following equation, the open-circuit voltage is promptly influenced by temperature[6]:

$$V_{OC}(T) = V_{OC}^{STC} + \frac{K_{V,\%}}{100}(T - 273.15) \quad (2.6)$$

In consonance with(2.6), the temperature doesn't have a positive influence on V_{OC} since Kv is negative, which means that as the warmth increases, the voltage lowers. The current grows with warmth, but only slightly, and it doesn't abrogate for the voltage drop induced by a corresponding hike in temperature. As a result, the power reduces. The temperature variables, that are the specifications indicating by virtue of what the short circuit current, open-circuit voltage, and maximum power fluctuate as the temperature varies, are provided in the datasheets of PV panel manufacturers. Because the influence of temperature on current is so minimal, it's customarily overlooked. As previously stated, temperature and irradiation are affected by the atmospheric conditions which can vary throughout the period, and also within a day they are able to change quickly owing to variable circumstances like clouds. This depending on irradiance and temperature stipulations, causes the MPP to proceed continually. Considerable power loss can occur if the operating point isn't near the MPP. As a result, tracking the MPP in all situations is critical to ensure that the PV panel produces the maximum possible power[7]. This work is delegated to the MPPT algorithms in a contemporary solar power converter.

2.3 Calculation of Parameters

The MATLAB Solar panel block is used to model an SPV array since it integrates this concept and offers an interface to provide critical characteristics that characterize an SPV array.

SPV array current I_{mpp} and voltage V_{mpp} are the specifications that operate at maximum power point and they are picked as 32.24A and 310V in the designed SPV array. SPV module current I_m and V_m are the specifications of operating maximum power point and are specified as 8.06A and 31V in the designed module. The designer selects these values. The designer also selects the module's short circuit current open-circuit voltage and specifications. The short circuit current Isc and open circuit voltage Voc are chosen As 8.55A and 31.6 V. The count of parallel and series modules is calculated based on these values.

The count of solar modules assembled in series.

$$N_S = \frac{V_{mpp}}{V_m} = \frac{310}{31.6} = 10 \tag{2.7}$$

The count of solar modules assembled in parallel

$$N_p = \frac{I_{mpp}}{I_m} = \frac{32.24}{8.55} = 4 \tag{2.8}$$

Generated power by module

$$P_{mpp} = V_{mpp} \times I_{mpp} = 310 \times 32.24 \ = 9994W \tag{2.9}$$

All these are also shown in appendix.

2.4 SPV array characteristics

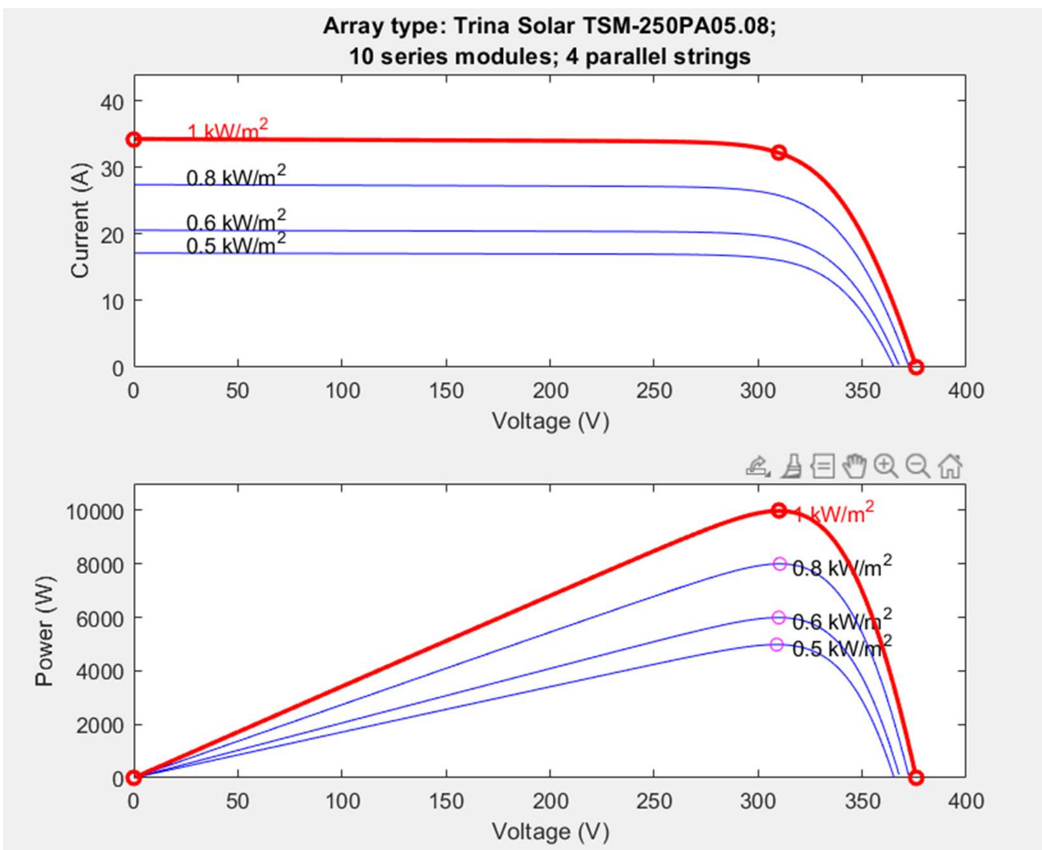


Fig 2.2. IV and PV characteristics of SPV array

2.5 Conclusion

Using MATLAB Simulink, the modeling of the SPV array is performed successfully as the program simplifies module design by providing essential characteristics like MPP current and voltage, open-circuit voltage, short circuit current and the count of systems to be linked side by side and consequently to produce the needed power at a defined load.

CHAPTER 3: BOOST CONVERTER

3.1 Introduction

A DC-DC converter is a critical part of a PV tracking apparatus. Because the voltage level of PV cells varies relying on the location of the desired point, directly providing DC solar power to the electric demand may be inadvisable. A DC-DC converter is utilized in an MPPT system to transform erratic input power into a controlled one with the necessary voltage level. Switch-mode DC-DC converters are now popular due to their compact volume size and strong controllability. The functioning of the DC-DC converter is divided into two modes: Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM)[14,16].

A swapping converter is considered to be in CCM if the current in the inductor can't reach zero within an exchange cycle, or in DCM if the current through the inductor hits null prior to the termination of an exchange cycle and stays in here for a specific amount of time[16]. As the input to the PWM control mechanism, the MPPT algorithm establishes a standard parameter. The converter may then change its operation to determine the ideal optimum voltage of the module using an MPPT technique.

The Basic topologies of switch-mode DC-DC converter include Step-down or step-up converter i.e., Buck or Boost converter respectively which can either result in decrement or increment of dc output voltages. According to the required application of PV, cost, control parameter or design, we may employ a specific converter topology [13,16].

3.2 Theory and schematic diagram

A boost converter is also seen as an electrical power DC-DC tool to achieve good synchronization between the battery load and solar panel [14,15]. It takes the solar module's output voltage as an input variable and adjusts it to the required reach while maintaining the output voltage constant. A boost chopper's output voltage is always larger than or the same as its input voltage. It employs the same constituents as the buck converter for ease of comparison. The steady-state and dynamic evaluations for ideal and non-ideal circuits are included in the boost converter research.

A boost DC-DC converter's job is to upgrade the input voltage of the DC power. A switching device, an input capacitor, an inductor, an output capacitor, a diode, and an electric load are typical components of a boost DC-DC converter [14]. The boost converter is shown below:

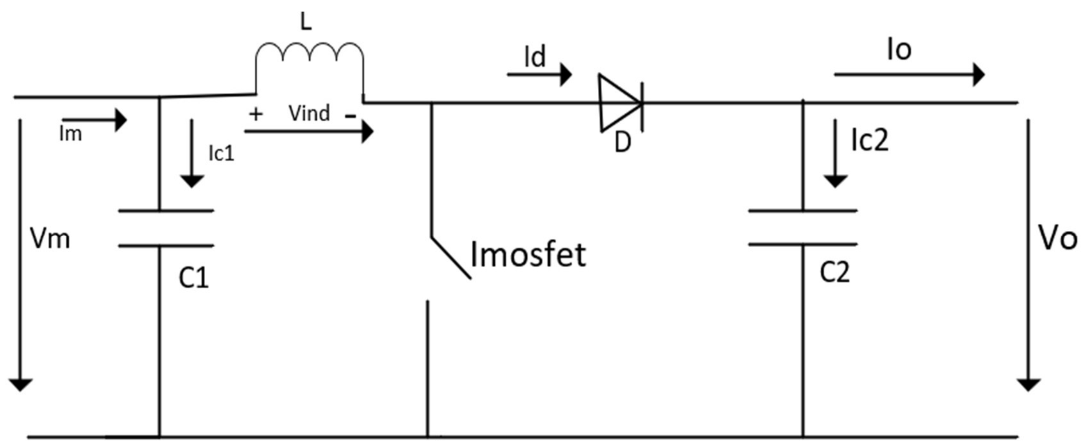


Fig. 3.1 schematic circuit diagram of the boost converter

3.3 Design

In this project, the employed DC-DC converter is the Boost converter which is made to use the optimum power of the SPV array by running at the maximum power point independent of solar insolation or ambient temperature. The maximum voltage of a solar panel is 310V at a peak insulation of 1000W/m^2. The chosen switching frequency of Boost converter is 10KHZ. MPPT module uses all the five algorithms which are P&O, INC, PSO, Fuzzy, and ANN which are used for maximum power extraction . Computation for all components is performed with a 10% ripple of current and 2% voltage ripple. The voltage ripple at panel is taken to be as 2%. The figure of the constituents utilized in Boost converter are determined by the output side of the system using the MPPT algorithm and the input side SPV array configurations specified in the appendix.

$$D = 1 - \frac{V_{IN}}{V_O} = 1 - \frac{275}{280} = 0.018 \tag{3.1}$$

$$C_1 = \frac{\Delta i_L}{8\Delta v_m f_s} = \frac{3.5}{8\times5.5\times10\times1000} = 7.9\mu F \tag{3.2}$$

$$C_2 = \frac{DI_o}{8\Delta v f_s} = \frac{0.018\times35}{8\times5.6\times10000} = 1.4\mu F \tag{3.3}$$

$$\mathrm{L} = \frac{V_m\times D}{f_s\Delta i_L} = \frac{275\times0.018}{10000\times3.5} = 141\mu H \tag{3.4}$$

3.4 Block diagram of simulation

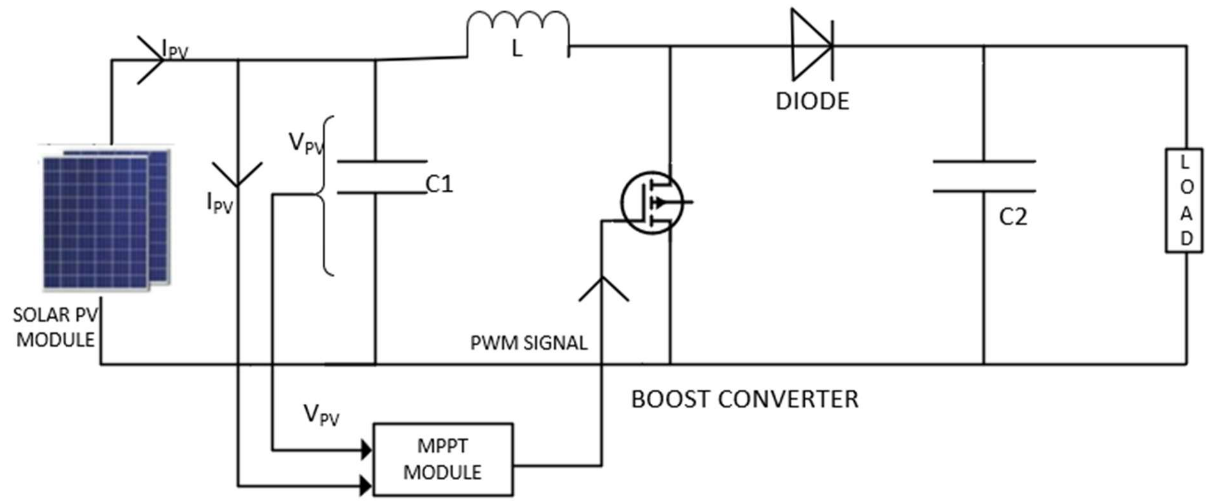


Fig 3.2 Block diagram of simulation using Boost converter

3.5 Conclusion

The boost converter has been efficiently modelled in the MATLAB Simulink and tested throughout the simulation. MPPT algorithms and their implementations are analyzed in further chapters

CHAPTER 4 : MAXIMUM POWER POINT TRACKING ALGORITHMS

4.1 Introduction

Specific ways prevail to get the devices to work at their maximum points as specified without knowing these points beforehand, and without understanding when they were changed or why were they changed. Tracking Point of Maximum Power is the name given to this form of control (MPPT). The goal of these directives is to locate the maximum power point (MPP) while guaranteeing a perfect match between the generator and the demand in order to transmit the most power. Few algorithms have been analyzed in [5].
Several devised MPP tracking techniques can be presented in the literature.
These systems differ in numerous ways, including expense, efficacy, monitoring precision whenever temperature or irradiation changes, and complication. A thorough examination of 19 distinct MPPT algorithms available in [4]
As a result, we may conclude that harvested power of a solar panel module relies on temperature, lighting, and panel location. It is also affected by the voltage-current product (VCELL x ICELL). Power might also be maximized by altering one of these two factors, voltage and/or current.[5],[6]
In a PV system, reaching the operational peak of a PV cell to MPP is critical. A vast variety of current approaches may make it difficult to determine the optimal algorithm to utilize when developing a PV system difficult[19]. Algorithm parameters vary in terms of criticality, the total count of sensors required, digital or analog integration, convergence speed, accurate tracking capabilities, and cost efficiency. MPPT algorithms are classified into several groups. The division in this project is done on the basis of measurement, calculation, smart schemes and combination schemes which are further split up in several procedure .

4.1.1 Measurement based MPPT algorithms

These approaches work by presuming that the cells' parameters (voltage and current) and sun-produced light characteristics are measured. The techniques in this category function by performing computations and comparing the results to prior estimates or a predefined MPP parameter.

4.1.2 Calculation based MPPT Algorithms

The MPP may be calculated using the equation computations of each method in this category.

4.1.3 Intelligent schemes based MPPT Algorithms

MPP can also be discovered using new optimization strategies based on intelligence algorithms.

4.1.4 Hybrid schemes based MPPT Algorithm

In these methods, the combination of traditional and intelligent algorithms is used.

This work involves, Five MPPT algorithms have been analyzed and verified that are namely Perturb and Observe (P&O), Incremental conductance (IC), particle swarm Optimization (PSO), Fuzzy and Artificial neural network(ANN).

4.2 Measurement based MPPT Algorithms

4.2.1 Perturb And Observe Method

4.2.1.1 Theory

The perturb and observe approach is a traditional MPPT methodology that is commonly utilized due to its simplicity and lack of antecedent understanding of PV power attribute or the monitoring of solar potency and cell temperature [7], [8]. As the name implies, the technology works by regularly enraging the PV array boundary voltage and contrasting the PV output power in comparison to the preceding disturbance loop [4]. Incase power enhances as a result of these alterations; the perturbation is maintained in this direction. If not, the perturbation is flipped. It is the method through which maximum power point is obtained in time-varying atmospheric circumstances[7]. The essential aspect of P&O is to compare the latest PV power P(k) to past PV power P. (k-1). The photovoltaic power is calculated by monitoring current (I) and voltage (V). When the variance between the latest and prior power is more than zero, this technique will try to identify the ideal point towards the left or right of the current position. When P equals 0, the maximum power is obtained. The point of operation hovers throughout the maximum power point after it is attained [8]. This issue is equally prevalent in the incremental conductance approach.

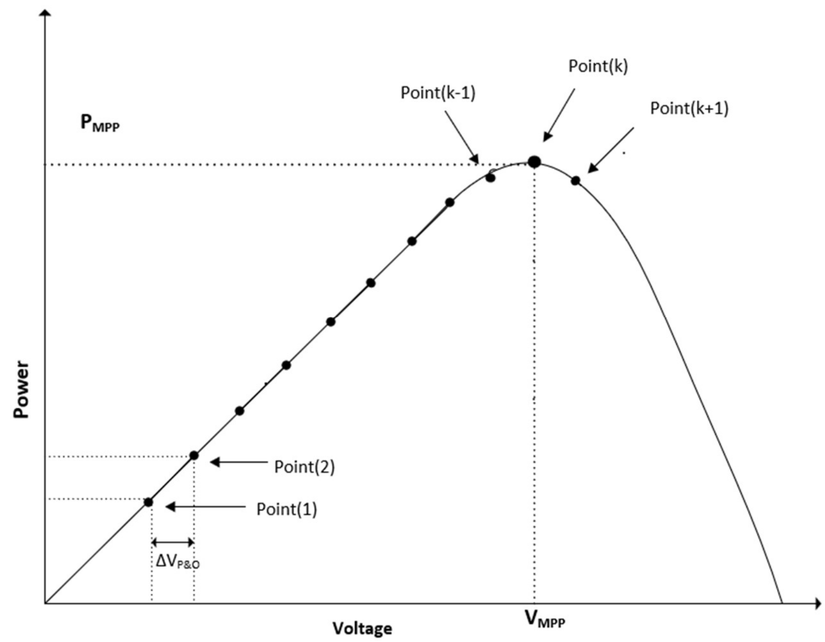


Fig 4.1 P&O algorithm

4.2.1.2 Flow Graph

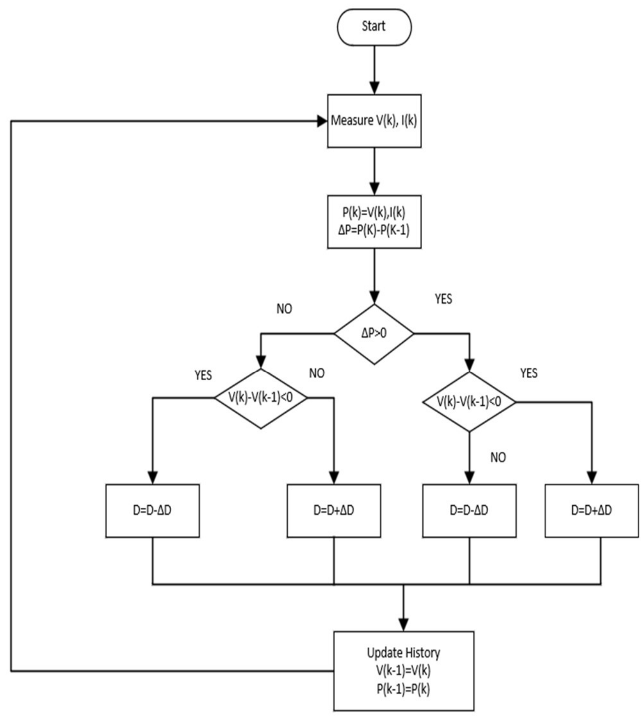


Fig 4.2. PO MPPT flow graph

4.2.1.3 MATLAB Simulation

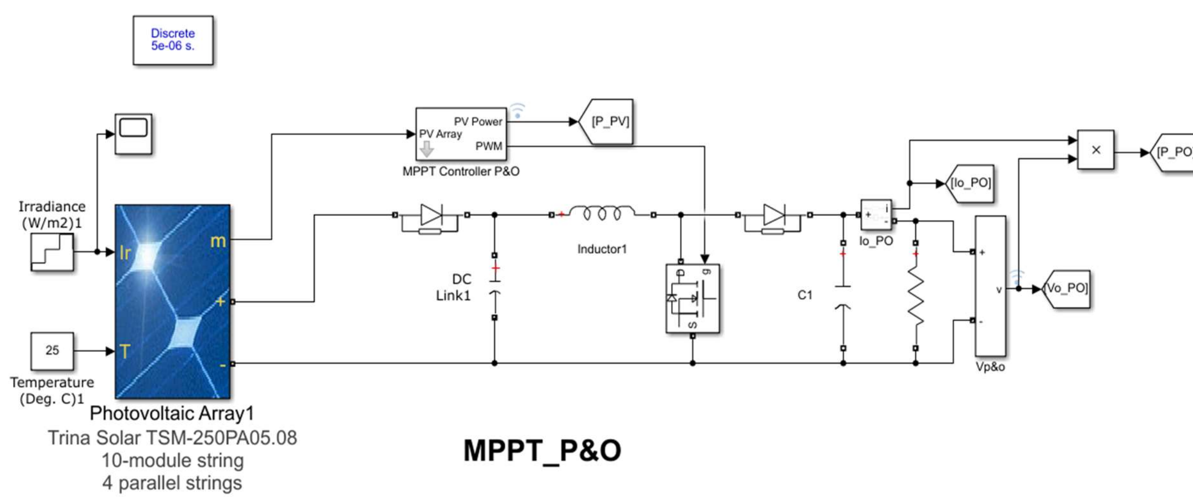


Fig 4.3. MATLAB simulation using P&O algorithm

4.3 Calculation Based MPPT Algorithms

4.3.1 Incremental Conductance

4.3.1.1 Theory

The IC approach compensates for the deficiencies of the perturbation and observation technique for monitoring peak power under fast shifting climatic circulation. When the MPP is achieved, the IC can discontinue perturbing the operational point. If this requirement is not fulfilled, the perturbation the MPPT functioning point's orientation may be computed leveraging correlation between dl/dV . This relationship is obtained because when MPPT is used towards the left of MPP, dP/dV is positive and when towards the right of MPP, dP/dV is negative. Contrasting P&O, this algorithm can detect whenever the MPP has been attained by the MPPT, whereas P&O vibrates about the MPP[27,26]. Furthermore, incremental conductance can monitor quickly rising and declining irradiance set up more precisely than perturb and observe. One downside of this process is that it is more complicated than P&O.

The incremental conductance (IC) approach works by differentiating PV power depending on voltage. When the differential result of this division is 0, MPP is attained. The powerpoint at the top of the curve is calculated and compared by assessing and evaluating the two portions that are incremental conductance(dI_{pv}/dV_{pv}) and conductance (I_{pv}/V_{pv})[27,26].

$$\frac{dP_{PV}}{dV_{PV}} = \frac{d(V_{PV}I_{PV})}{dV_{PV}} = I_{PV} + V_{PV}\frac{dI_{PV}}{dV_{PV}} = 0 \tag{4.1}$$

This implies that:

$$\frac{I_{PV}}{V_{PV}} + \frac{dI_{PV}}{dV_{PV}} = 0 \tag{4.2}$$

in simple words, the incremental changes (dVPV and dIPV) may be estimated by increasing both parameters (VPV and IPV) using observed VPV and IPV values at different instants. The following are the parameters:

$$dV_{PV}(t_2) \approx \Delta V_{PV}(t_2) = V_{PV}(t_2) - V_{PV}(t_1) \tag{4.3}$$

$$dI(t_2) \approx \Delta I_{PV}(t_2) = I_{PV}(t_2) - I_{PV}(t_1) \tag{4.4}$$

This approach is driven by the fact that when the MPP is achieved, the inclination The power curve of the PV array is nonexistent. It is greater than zero on the MPP's left side and less than zero on the MPP's right side. The following are the mathematical relationships of IC[11, 27]:

$$\frac{\Delta I_{PV}}{\Delta V_{PV}} = -\frac{I_{PV}}{V_{PV}} \quad \text{at MPP} \tag{4.5}$$

$$\frac{\Delta I_{PV}}{\Delta V_{PV}} > -\frac{I_{PV}}{V_{PV}} \quad \text{left to MPP} \tag{4.6}$$

$$\frac{\Delta I_{PV}}{\Delta V_{PV}} < -\frac{I_{PV}}{V_{PV}} \quad \text{right to MPP} \tag{4.7}$$

4.3.1.2 Flow Graph

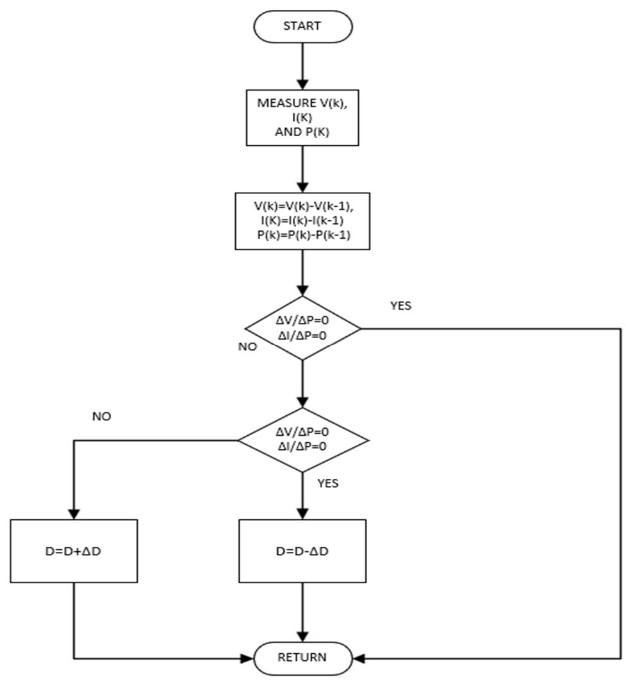


Fig 4.4. INC MPPT flow graph

4.3.1.3 MATLAB Simulation

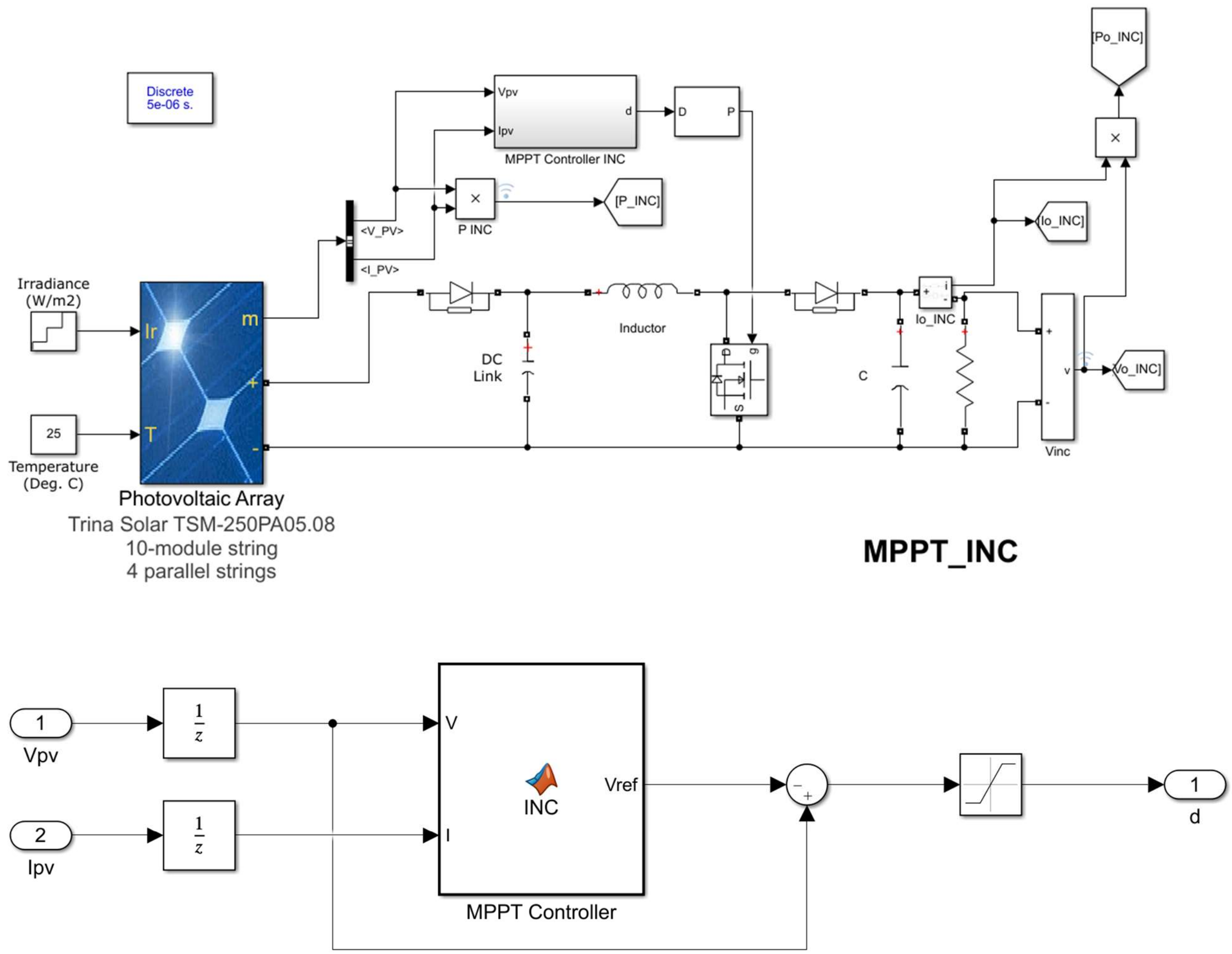


Fig 4.5. MATLAB Simulation using INC algorithm

4.4 Intelligent Schemes Based MPPT Algortihms

4.4.1 Particle Swarm Optimization

4.4.1.1 Theory

Particle Swarm Optimization is a simple and effective thematic technique for nonconventional smart optimization. It was created in 1995 by Eberhart and Kennedy.

PSO is an evolutionary algorithm (EA) search optimization technique based on population. Its concept was adopted by the behavior of bird flocks in order to overcome the challenges associated with the search process and optimization[12,19]. In the PSO approach, every particle of the postulated swarm evaluates itself at multiple spots in a D-dimensional search space and advances at a speed determined by its individualized perfect position (Pbest) and the right place of his group (Gbest). Every particle in the population exchanges information gained throughout the search process.

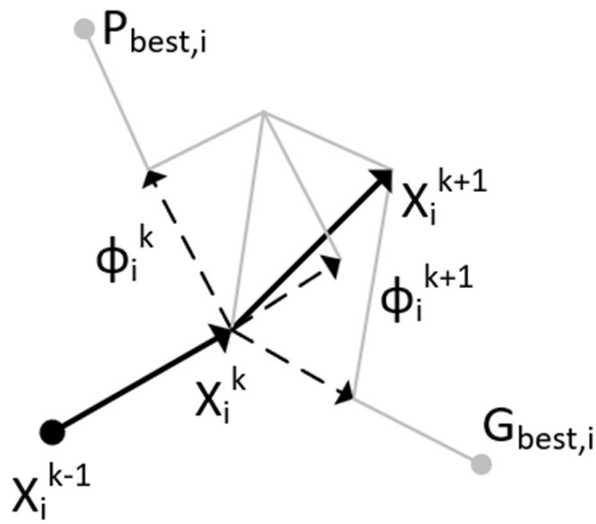


Fig 4.6. Particles movement during PSO

During the search phase, each component in the swarm communicates with its neighbors and quickly accumulates on the global optimal location in the search space[12].

As a result, each particle's location is influenced by her best neighbor particle P_{best} and also the global best position discovered by all particles in the whole community G_{best}.

Indeed, the I th location x_i of each particle is modified in accordance with the following equation:

$$x_i^{k+1} = x_i^k + \varphi_i^{k+1} \tag{4.8}$$

where k denotes the repetitive counter. The step size is also represented by the velocity component, φi. Recursively, particles are rendered capable of possibly exploring any region of the search space. The velocity is changed as

following:

$$\varphi_i^{k+1} = w\varphi_i^k + c_1 r_1\{P_{best} - x_j^k\} + c_2 r_2\{G_{best} - x_j^k\} \tag{4.9}$$

Here w is the inertia weight that governs the influence of prior particle velocity on subsequent particle velocity. Consider c1 and c2 as acceleration variables. r1, r2 are random coefficients that are distributed evenly within the range [0, 1], $P_{best,i}$ is the personalized perfect location of particle i and G_{best} is the strongest spot of the fragment for whole swarm population.

Assume the particle location as the real duty cycle and speed as the aberration of original duty cycle, and afterwards change the equation as follows[12].

$$d_i^{k+1} = d_i^k + \varphi_i^{k+1} \tag{4.10}$$

Indeed, the resultant impact on the actual duty cycle is dependent on P_{best} and G_{best}, As per above equation.

The process for PSO is as follows:

Step 1. Set the PSO settings (swarm size, beginning location, initial velocity, and iteration counter) to their default values.

Step 2. Determine the fitness of every particle

Step 3. Assess and modify the optimum location of each particle.

Step 4. Assess and modify the optimum location of global particles.

Step 5. Using equation (5)(6), adjust the location and velocity of each swarm particle.

Step 6. If the convergence requirement is fulfilled, the iterations counter will be incremented by one and the process will proceed to step 2.

4.4.1.2 Flow Graph

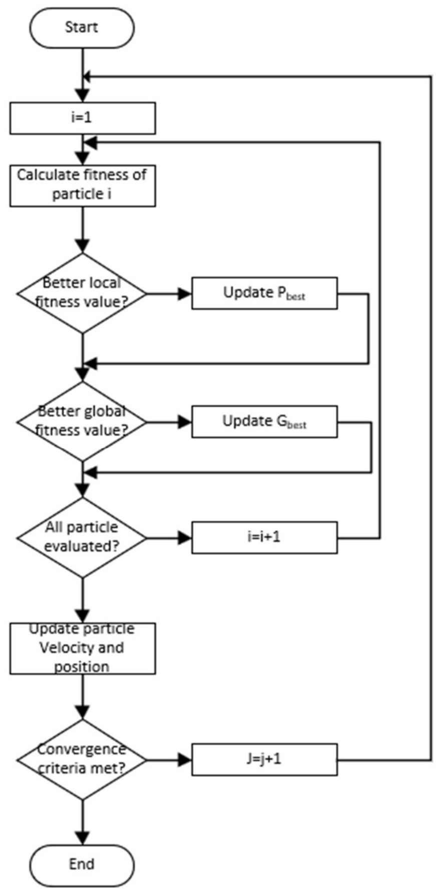


Fig 4.7. PSO MPPT flow graph

4.4.1.3 MATLAB Simulation

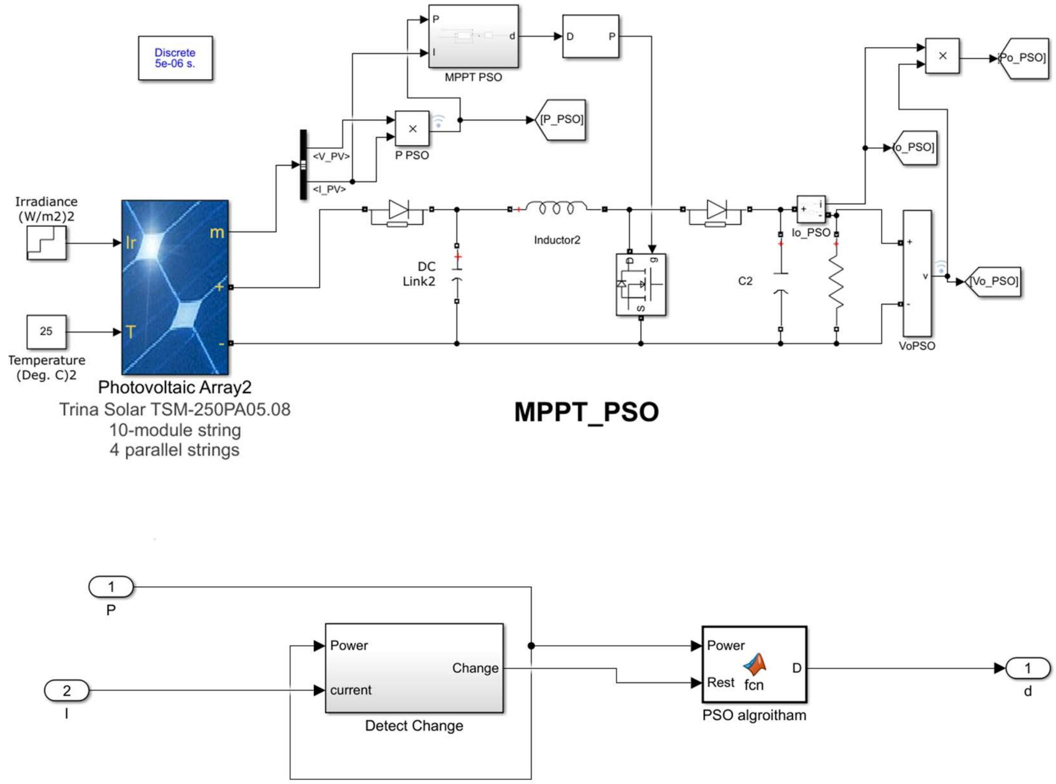


Fig 4.8. MATLAB simulation using PSO algorithm

4.4.2 Fuzzy Logic Control

4.4.2.1 Theory

Human decision-making is based on fuzzy logic. It works with imperfect and ambiguous data and offers important adaptability. In the Boolean system, 1 denotes utter truth and 0 denotes absolute false, however there is no reasoning for the absolute truth and false in fuzzy logic. Nevertheless, there will be an intermediary significance to display that is both true and false. It is shown in figure below[17]:

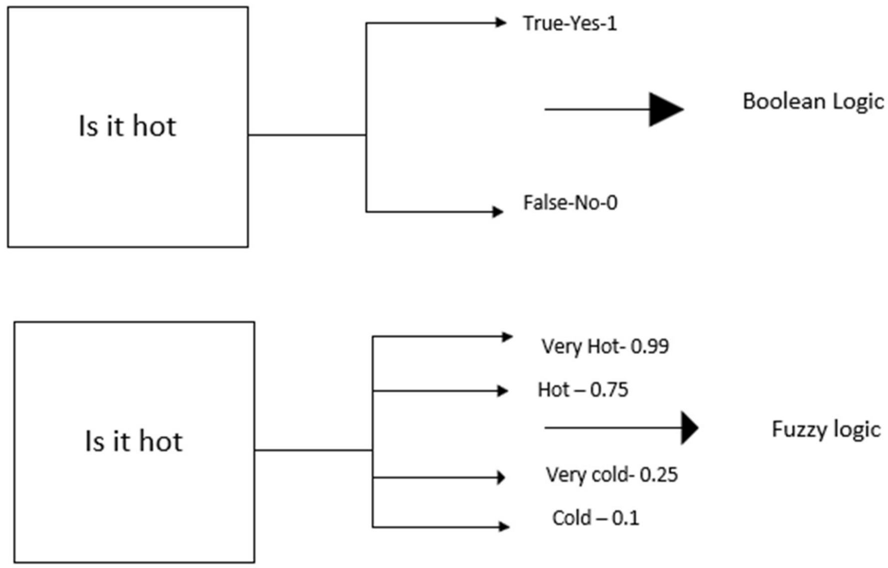


Fig 4.9 . Fuzzy logic example

The fuzzy logic controller has several uses. It was implemented in PV systems to enforce PV to function about MPP. They have the benefits of coping with inaccurate input, managing non-linearity to be resilient, and being relatively straightforward to develop as they don't demand exact model expertise. Fuzzification, fuzzy inference system, rule base, and defuzzification are the core components of the FLC.

To begin, fuzzification[18] relates to the procedure of converting sharp inputs into linguistic terms based on their degree of membership in specific fuzzy sets. Figure "Y" depicts an instance of a membership function. They are employed to give each linguistic phrase a value.

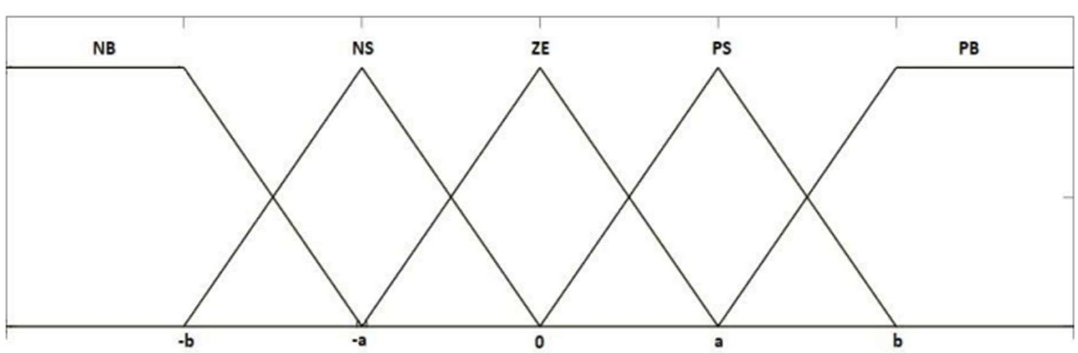


Fig 4.10. Fuzzy logic example

As inputs, the MPPT fuzzy logic controller typically receives an error E and a modification in error ΔE. Individuals have the opportunity of determining how to estimate E and ΔE. However, since it is zero at MPP, the fault is usually selected as ΔP/ΔV. After this E and ΔE can be written as

$$E(n) = \frac{P(n)-p(n-1)}{V(n)-V(n-1)} \quad (4.11)$$

When E and E are computed and transformed into linguistic terms, the fuzzy logic controller output, which is generally a modification in the duty cycle of the power converter, D, may be searched up in a rule base[20]. Depending on the power converter, the rule base or fuzzy rule algorithm connects the fuzzy output to the fuzzy inputs. Table below depicts an example of a rule base.

TABLE 4.1 – BASE RULES OF FUZZY

E \ ΔE	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	BS	ZE	ZE	ZE	PS
PS	PS	PS	ZE	ZE	ZE
PB	PB	PB	PB	ZE	ZE

The rhetorical variables allocated to D for various E and E configurations are determined by the type of power converter employed as well as the user's understanding. As an instance, suppose the operating point is much more to the right of the MPP, that is E is NB and E is ZE, it can be shown in Table I that the duty cycle of the power converter should be considerably enhanced, that is D should be PB, to achieve the MPP[22].

The final level of fuzzy logic system is defuzzification. At this point, the fuzzy logic controller output is changed transforming a parameter into an arithmetical crisp using the membership functions shown below several defuzzification techniques are available. The approach based on the area's center (COA), The most commonly used defuzzification method, furthermore, recognized as the centroid method[17,18].

The benefits of fuzzy logic control include the fact that It is not necessary to have a correct predictive model. and can manage system non-linearity in addition to coping with imprecise inputs. Furthermore, it creates very minor oscillations about the MPP. The fundamental drawback of fuzzy logic control is that its efficacy is dependent on user expertise, as well as selecting the suitable error calculation and establishing the appropriate rule base.

4.4.2.2 Flow Graph

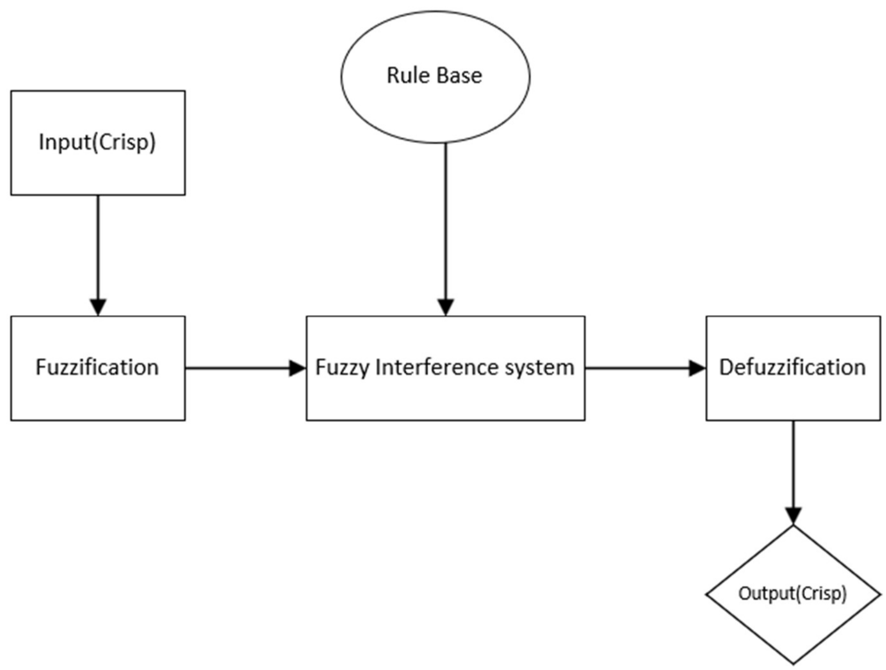
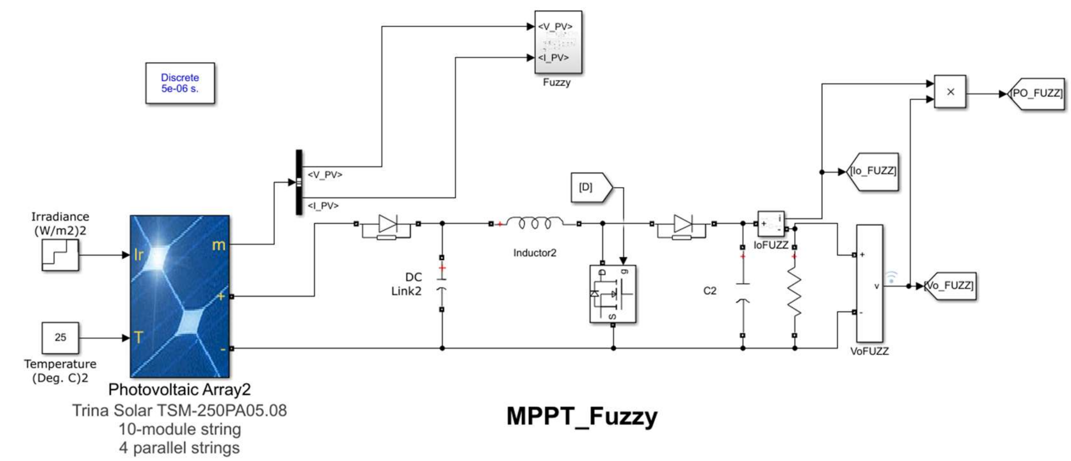


Fig 4.11. Flow chart of fuzzy logic algorithm

4.4.2.3 MATLAB Simulation



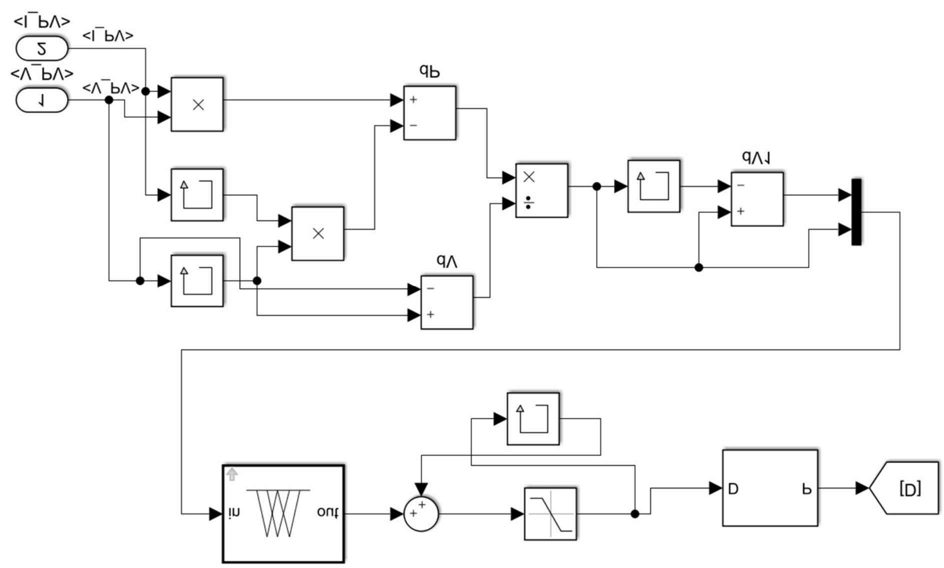


Fig 4.12. MATLAB Simulation using Fuzzy logic algorithm

4.4.3 Artificial Neural Network

4.4.3.1 Theory

Artificial neural networks (ANNs) are a class of demographic learning models that are influenced by biological neural networks (the autonomic nervous systems of animals, specifically the brain) and have been used to predict or quantify aspects that can rely on a huge set of inputs and are pretty much unknown. Artificial neural networks are commonly shown as systems of interconnected "neurons" swapping signals. The linkages include numeric weights that may be adjusted depending on experience, allowing neural nets to modify to inputs and learn[23, 21].

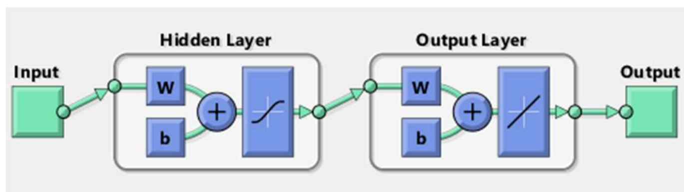


Fig. 4.13 Neural Network Structure

In MPP, the Neural Network is employed to make the system operate. The suggested technique is based on monitoring the most critical power-influencing parameters (irradiance and temperature) and managing the mechanism by adjusting the duty cycle. So, Irradiance and temperature are the inputs and duty cycle is the output[21].

Figure 4.6 depicts the suggested method's design.

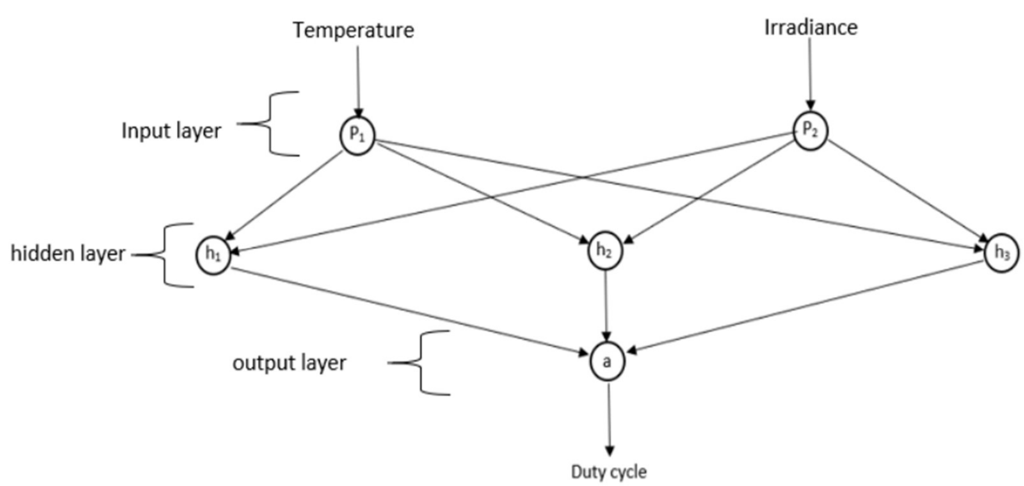


Fig 4.14. Neural Network algorithm

Before being used, the network must be thoroughly trained (through offline training). The following are the steps to obtaining the network:

1) Collection of Data

   The initial step in creating an ANN is gathering data (inputs, outputs). Increasing the amount of data available improves the efficiency of NN.

2) Network structure selection

   The outcomes are influenced by the network's architecture. The selection of a NN structure entails configuring all of the Network's characteristics, including the kind of network, layer count, the quantity of neurons in every layer, and activation function. Furthermore, because it is differentiable, the LogSigmoid Transfer Function is commonly employed in back-propagation networks.

   There are currently no recommendations to compute the value of layers and neurons required; instead, they must be varied until the best results are obtained[23,21]].

3) Training the network

   Following the establishment of the NN design, data collection is made available for training. The weights of the training algorithms are adjusted and updated using the training function. The associated method has a minimal MSE, indicating that the forecast duty cycle cumulates to the real duty cycle of MPP[23].

4) Testing the network

   The final stage before using the network is to test it. During this step, the weights are fixed (no changes to the network topology), and the network performance is measured.If the network produces inaccurate results or performs poorly, it should be retrained. The performance of NN may be altered by raising the number of samples, modifying the training procedure, and increasing the number of neurons . In the event of outliers, which are data points whose fit is much worse than the bulk of data, it is necessary to examine the quality of those data, and if they are good data, it is necessary to expand the network by obtaining more data compared to them. In the alternative, they will be erased[23].

Solar temperature and irradiance are sent into the neural network.

The count of concealed layers is determined through experimentation. The duty cycle to the boost converter is produced outcome. To begin working with any ANN algorithm, training points must be gathered. The training sets are acquired by adjusting the irradiance and temperature inputs towards the PV array and obtaining parameter of duty ratios to used converter to monitor optimum energy from panel for varied temperature and irradiance circumstances. After tutoring , certain training counts are saved as test points to put network to the test. The "nntool" in MATLAB m-FILE is used for training the system. The network is created by training it with the Levenberg-Marquardt algorithm. ANN's execution function is mean squared error (MSE). 1000 data sets are collected to train a neural network. Range of temperature is from 20 degree Celsius to 45 degree Celsius. And irradiance varies from 0 to 1000w/m^2. The activation functions of the hidden and output are "tansig" and "purelin," correspondingly.

Input : : Irr and T

Output: D

Count of samples: 1000

Count of hidden neurons: 10

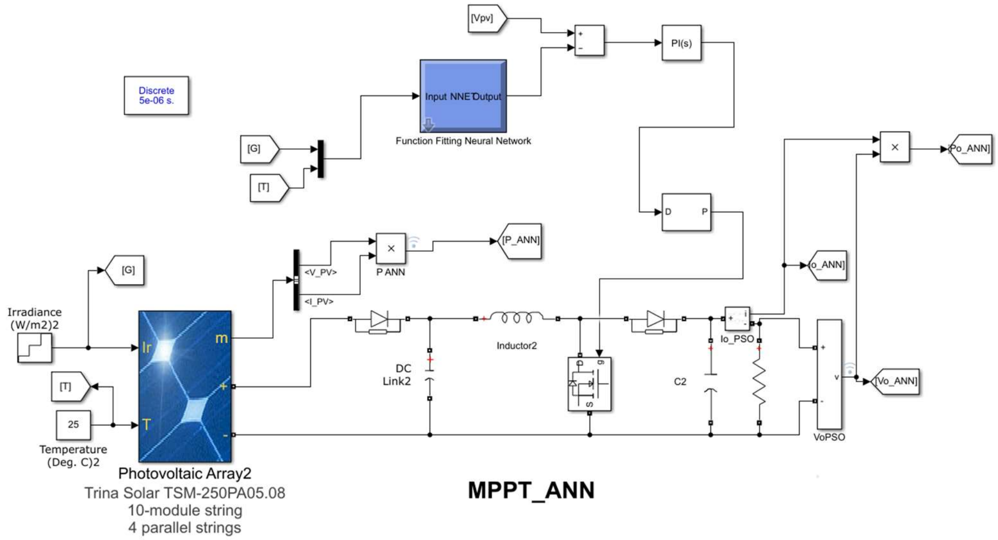
Number of epochs:100

Method: Feed forward

4.4.3.2 ANN M File

```
clear all
Iscs=8.55;
IMPS=8.06;
Vocs=37.6;
VMPS=31;
alpha=0.06;
beta=-0.35;
Gs=1000;
Ts=25;
for i=1:1000
    Tmin=15;
    Tmax=35;
    T=(Tmax-Tmin)*rand+Tmin;
    Gmin=0;
    Gmax=1000;
    G=(Gmax-Gmin)*rand+Gmin;
    IMP(i)=IMPS*(G/Gs)*(1+(alpha*(T-Ts)));
    VMP(i)=VMPS+(beta*(T-Ts));
    PMP(i)=VMP(i)*IMP(i);
    input(i,:)=[G T];
    output(i,1)=VMP(i);
    output1(i,1)=IMP(i);
    output2(i,1)=PMP(i);
end
```

4.4.3.3 MATLAB Simulation



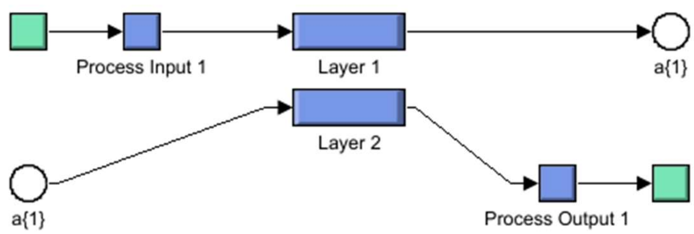


Fig 4.15. MATLAB Simulation using ANN algorithm

4.5 Conclusion

All the five algorithms that are Perturb and Observe, Incremental conductance, Particle swarm optimization, Fuzzy logic and Artificial Neural Network are successfully implemented in the MATLAB Simulink environment and their parameters are properly taken care of.

CHAPTER 5 : RESULTS AND DISCUSSION

5.1 SPV Array

The selected PV array is Trina Solar TSM-250PA05.08 which is take from the reference paper[]. Same PV array is taken for all the five MPPT controllers.

The no of strings in parallel are 4 and number of strings in parallel are 10. The maximum power of the

panel is 249.86 watt and the cells per module is 60. The Irradiance provided to the solar panel is variable i.e 500, 600, 800, 1000 kw/m^2 and the temperature is fixed at standard value i.e., 25˚C. The final output is taken at 1000kw/m^2 irradiance.

The parameters of this array are as follows:

TABLE 5.1 . Parameters of solar array

Max. Power	249.86 Watt	Current at Max. power	8.06
Isc	8.55 A	Voltage at Max. Power	31V
Voc	37.6 V	Series connected String	10
Cell/Module	60	Parallel string	4

5.1.1 PV Voltage And Variable Irradiance Of Array For Different Algorithms

PV voltage for all the five MPPT algorithm controllers is measured from SPV array at a standard temperature of 25 degree Celsius and it is observed that the highest voltage is for Artificial neural network based controllers whereas the lowest voltage level is for Perturb and observe based MPPT controller.

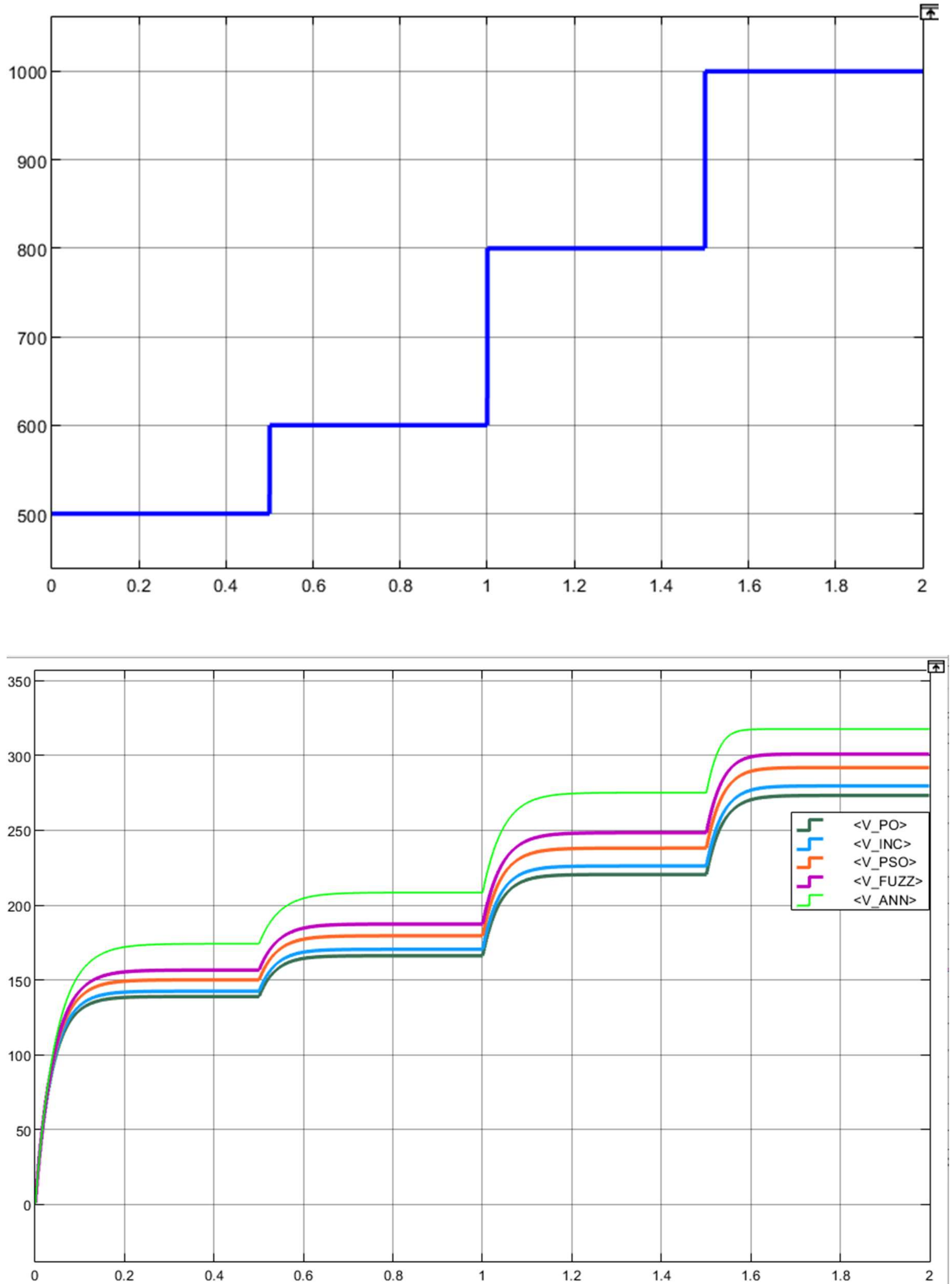


Fig 5.1. PV voltage for different algorithms at variable Irradiance

5.1.2 PV Current For Different Algorithms

PV current for all the five mppt controller is measured from SPV array for variable irradiance levels that are 500, 600, 800 and 1000KW/m^2 at standard temperature. It is observed that there isn't much difference in the current values for all the controllers as shown in the fig.

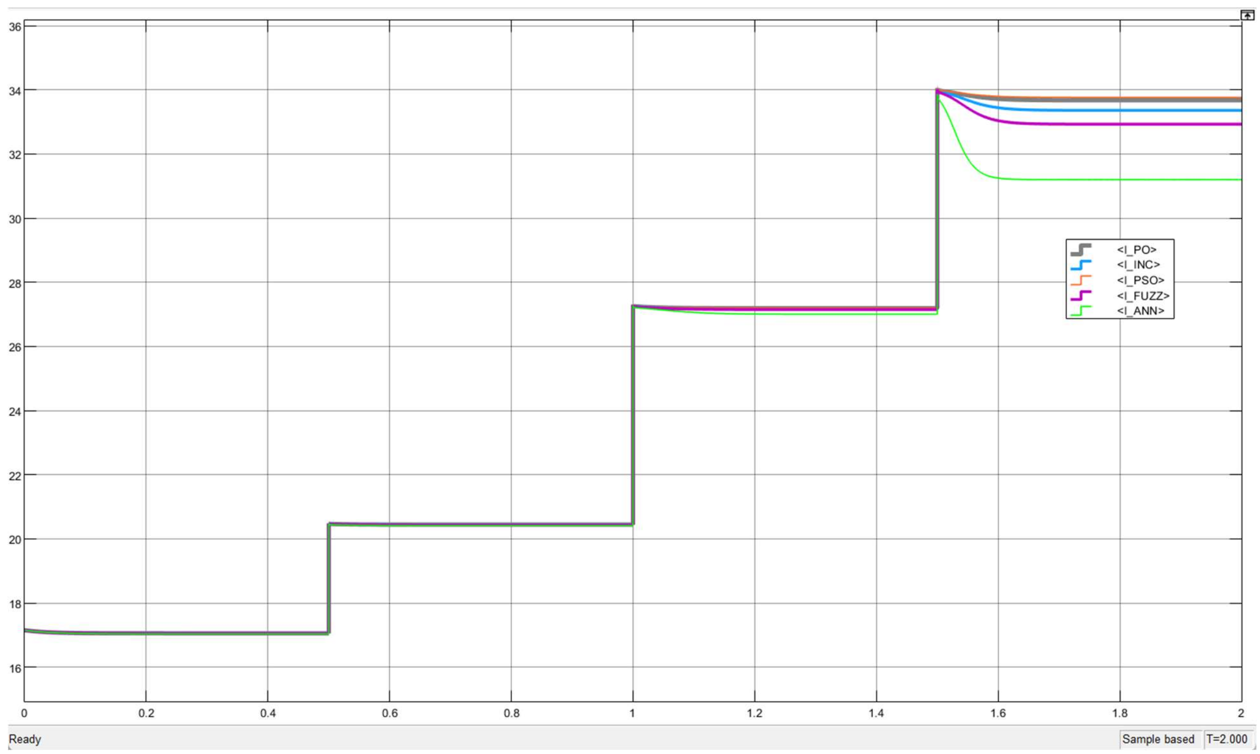


Fig 5.2. PV current for different algorithms at variable Irradiance

5.1.3 PV Power For Different Algorithms

The SPV array characteristic of Power for different algorithms is shown in the figure given below. It is plotted for variable Irradiance at a specific temperature . The max output power is 9994 at 1000kw/m^2 irradiance and the best performance is being showed by ANN based controller.

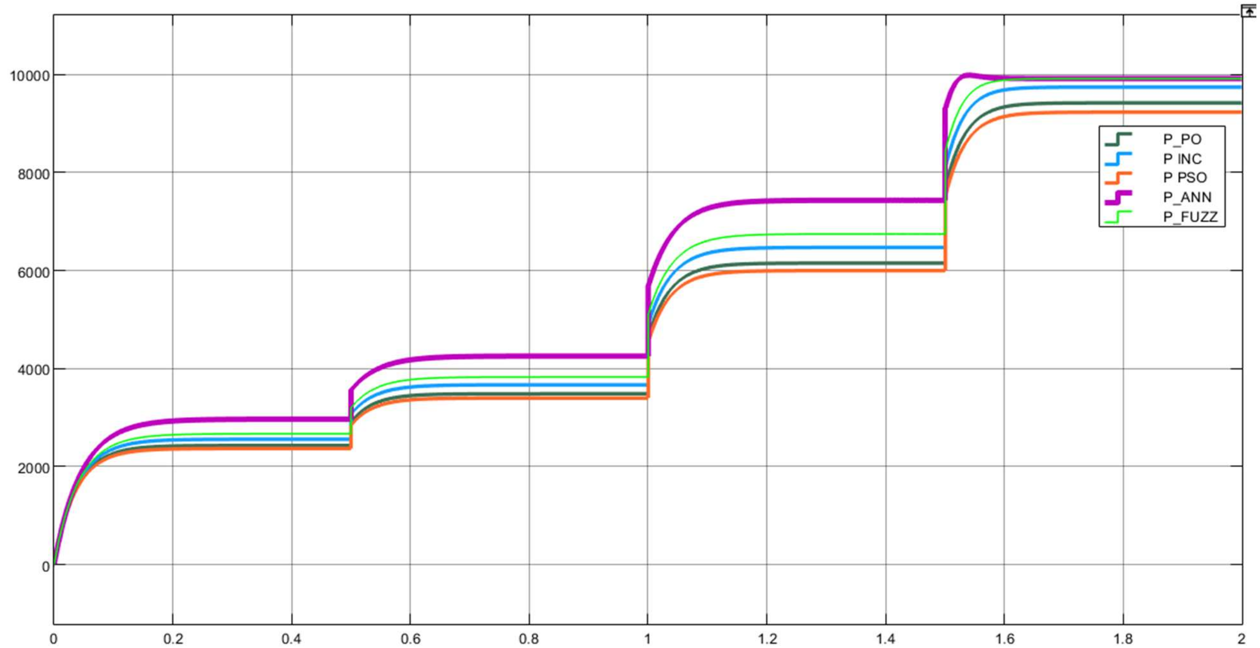


Fig 5.3. PV power for different algorithms at variable Irradiance

5.2 Output Characteristics Of Different MPPT

ALGORTIHMS

In the figures given below , the output characteristics for all the five algorithms is shown for variable Irradiances of 500,600,800 and 1000Kw/m^2 . Since the DC-DC converter used is Boost converter therefor the output voltage increases. The PV panel output which is power has a maximum value of 9994 Watt and the comparison of the parameters is done on the basis of maximum output power and maximum dc output voltage.

5.2.1 OUTPUT VOLTAGE

After the being processed by different algorithms, the figure shows the output voltage of the boost converter for variable irradiance . As the Figure shows, the maximum output voltage is being represented by the ANN based controller which is more than 350 volts at the highest peak whereas for PO based controller the output voltage is just near 280 volts at the peak. Fuzzy logic controller shows similar characteristics as ANN but the time taken by fuzzy is comparatively more than ANN. Because there are memory elements present in Fuzzy logic controller.

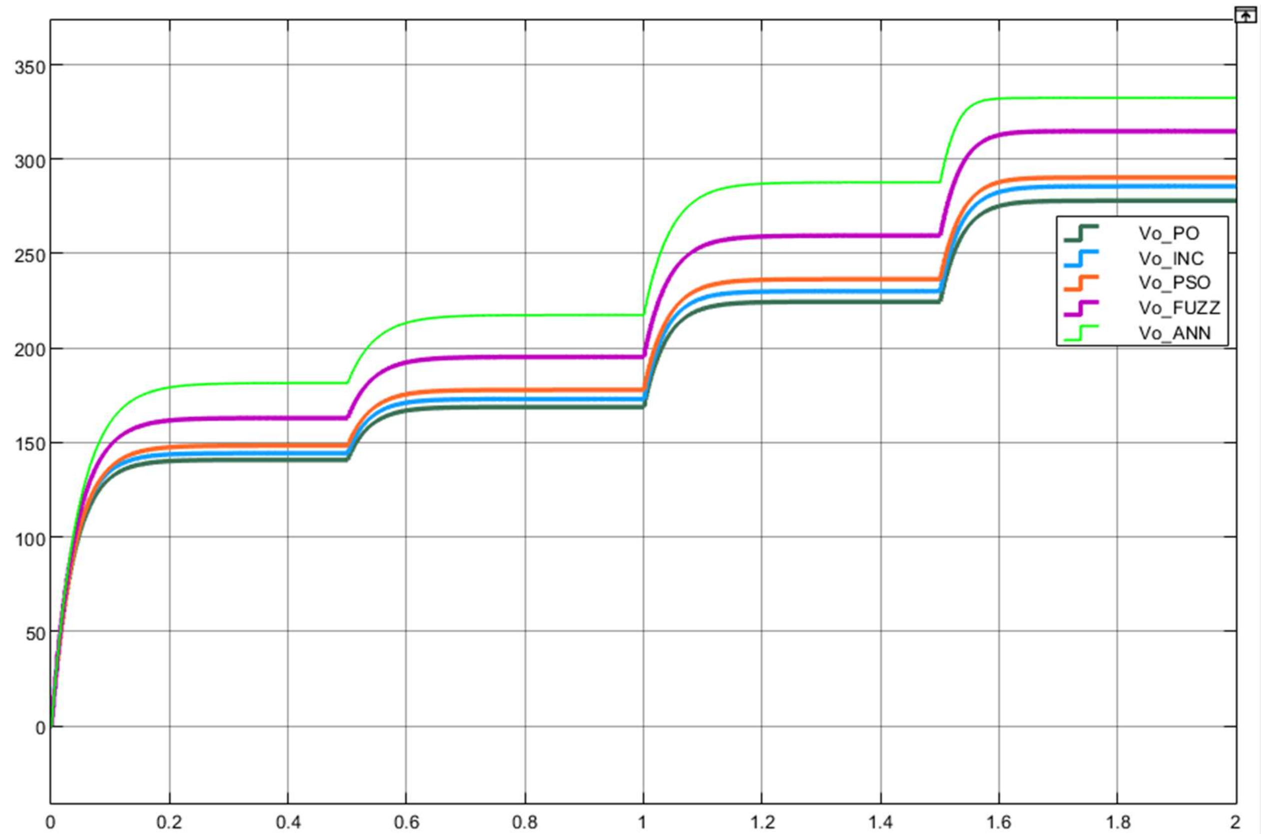


Fig 5.3. Boost output voltage for different algorithms at variable Irradiance

5.2.2 Output Current

The figure shows the output current of boost converter after the application of different mppt controllers . There is just minute difference in the current levels of different algorithms but comparatively P&O shows highest value of output current whereas ANN based controller shows lowest value of output current.

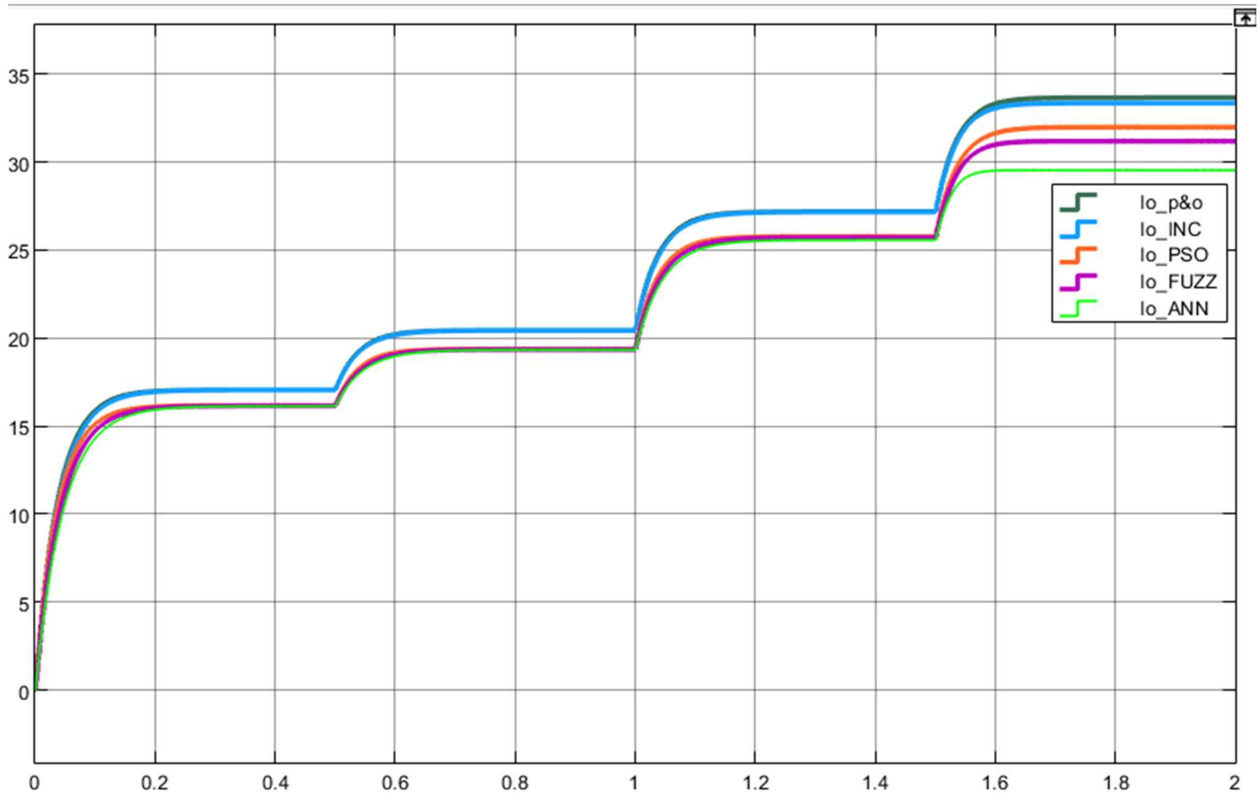


Fig 5.4. Boost output current for different algorithms at variable Irradiance

5.2.3 Output Power

The graph given below shows the comparative study of output power of all the five controllers for 4 different levels of Irradiance that are 500, 600, 800, 1000 kw/m^2 . The output power is obtained below is the product of the output current and output voltage of the boost converter. The Maximum power point calculate at 1000kw/m^2 is 9994watt and it is observed that the ANN based controller shows the nearest level to 9994 watt. P&O is the farthest from the MPP. Fuzzy also shows close enough to MPP but comparatively takes more time than ANN because of the presence of memory elements in fuzzy logic controller.

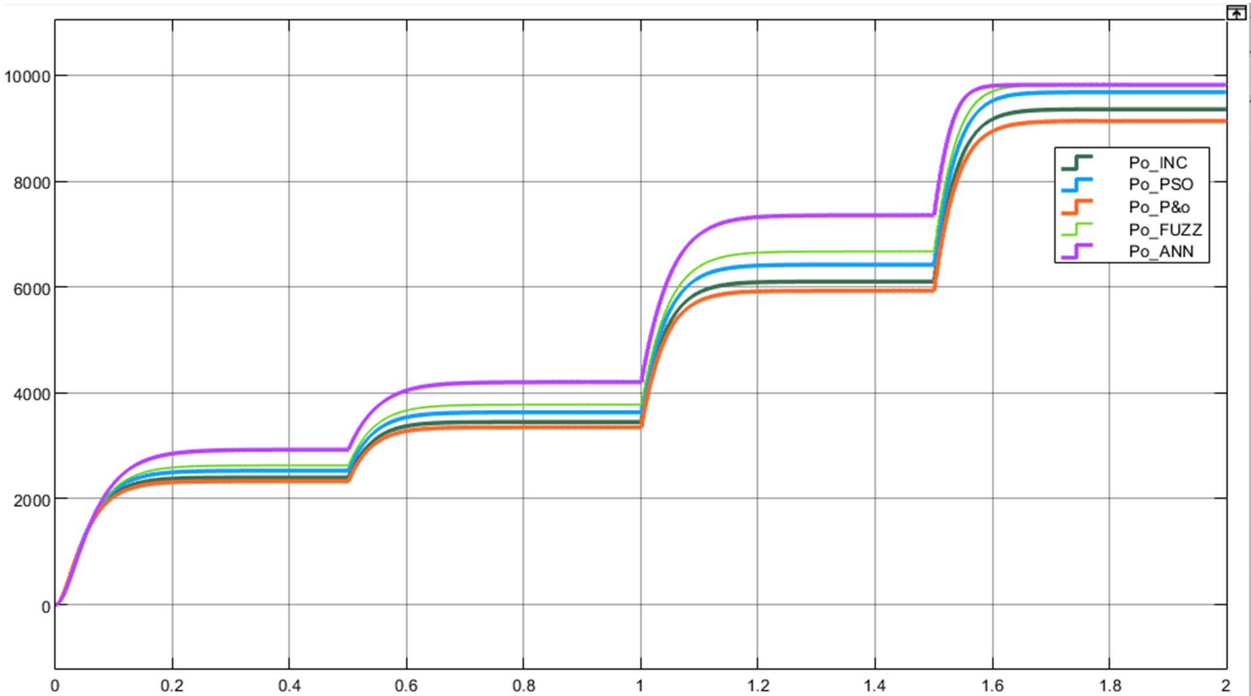


Fig 5.5. Boost output power for different algorithms at variable Irradiance

5.3 Result

The table given below displays the overall analogy of the Parameters of Different algorithms based solar MPPT controller. It shows the parity of Panel voltage, panel Power with the Output voltage and output power of the boost converter for different algorithms.

Table 5.2 . Comparative Analysis

S.No	Parameters	P&O	INC	PSO	FUZZY	ANN
1	Panel voltage Vpv(v)	273.3	279.7	298.3	303.5	317.7
2	Panel Current Ipv(A)	33.67	33.76	33.36	32.76	31.2
3	Temperature(oC)	25	25	25	25	25
4	PV MPPT	9227	9416	9738	9912	9942
5	Boost Converter Output voltage (V)	278	285.9	290.9	317.6	332.6
6	Boost Converter Output current (A)	33.57	33.35	32.02	31.06	29.57

7	Boost Converter Output Power (W)	9154	9360	9686	9865	9901

CHAPTER 6 : CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

In this research work, Mostly the taken MPPT algorithms were the ones which can find the maximum power point. There were five MPPT algorithms take out of which two were the most fundamental ones namely Perturb and Observe and Incremental conductance and rest all belong the Intelligent ones namely Particle swarm optimization, Fuzzy logic controller and the most advanced one was Artificial Neural network based. The controllers based on these Algorithms were prepared and analyzed in MATLAB Simulink environment and therefore implemented successfully.

The preferred SPV array module was Trina Solar TSM-250PA05.08 which was taken from the reference paper and the Preferred DC-DC converter was the Boost converter or step up converter. The Temperature taken for SPV array was standard one i.e., 25˚celcius and the controller is simulated for different irradiance level that are 500 , 600, 800 and 1000KW/m^2 . The comparison is made on the basis of final output values of different parameters when the simulation stops at 2 second for 1000KW/m^2. At this Irradiance the Output power for ANN based controller is highest that is 9942watt and for fuzzy it is 9912watt whereas for PO it is 9227 watt. Rest of the controllers output power lie this range . The maximum Power generated by the SPV module is 9994 watt and, in this respect, the MPP of ANN based controllers is the closest. The output voltage shown by the ANN controller is also highest i.e., 317.7 volts whereas for P&O it is just 273.3 V.

Overall, the best performance is shown by the ANN based controller whereas the lowest output range is shown by the basic controller P&O. Though the Fuzzy logic based controller shows outputs close enough to ANN based controller, but it takes comparatively longer time to reach same level whereas ANN shows faster response.

6.2 Future Scope

Scope for future work for Solar MPPT controller is really assorted with respect to the different algorithms of MPPT. Since Solar Energy is available abundantly and the industrial as well as residential applications are gaining huge importance therefore it is necessary to find efficient systems and that can be done by using different MPPT techniques. Designing of the controller should be extended in terms of input parameters, converters, load and should be tested with a motto of getting accurate results taking into consideration various factors such as cost, location etc.

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APPENDIX

PARAMETERS OF SPV ARRAY

S.NO	PARAMETER	VALUE
1	VMPP	310
2	VM	31V
3	IMPP	32.4
4	IM	8.06A
5	ISC	8.55 A
6	VOC	37.6 V
7	NS	10
8	CELL/MODULE	60
9	NP	4
10	PMPP	249.86 WATT

PARAMETERS OF BOOST CONVERTER

S.NO.	**PARAMETER**	**VALUE**
1	D	0.018
2	C1	7.9 μF
3	C2	1.4 μF
4	L	141 μH
5	ΔI_L	10%
6	ΔV_C	2%