ISSN 2277 – 8322

# MPPT TECHNIQUES FOR GRID-INTEGRATED HYBRID SOLAR PV–WIND ENERGY SYSTEMS: A COMPREHENSIVE REVIEW

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**Abstract:** The increasing demand for reliable, sustainable, and environmentally friendly electricity has accelerated the integration of renewable energy sources into modern power systems. Among the available renewable resources, solar PV and wind energy have gained significant attention due to their abundance, low environmental impact, and suitability for distributed and grid-connected power generation. However, the intermittent and variable nature of solar irradiance and wind speed presents significant challenges in extracting maximum available power from these sources. Maximum Power Point Tracking (MPPT) techniques are therefore essential for improving the energy conversion efficiency of hybrid solar PV–wind energy systems. This review paper presents a comprehensive study of MPPT techniques used in grid-integrated hybrid solar PV–wind energy systems. Various conventional and advanced MPPT methods, including Perturb and Observe (P&O), Incremental Conductance (I&C), Hill Climbing, fuzzy logic control, artificial neural network (ANN)-based methods, and other intelligent and optimization-based techniques, are reviewed and compared. The operating principles, tracking accuracy, convergence speed, computational complexity, sensor requirements, cost, and performance under rapidly changing irradiance and wind conditions are discussed. Particular attention is given to the challenges associated with multiple maximum power points, partial shading, fluctuating wind conditions, and dynamic grid operating conditions. The review also examines the role of MPPT controllers in improving the overall efficiency, stability, and power quality of grid-integrated hybrid renewable energy systems. Finally, the comparative analysis identifies the major advantages and limitations of different MPPT approaches and highlights potential research directions for developing faster, more accurate, robust, and computationally efficient MPPT techniques for future hybrid solar PV–wind energy applications.

**Keywords:** Maximum Power Point Tracking (MPPT), Solar Photovoltaic (PV), Wind Energy, Hybrid Renewable Energy System, Grid Integration, Perturb and Observe (P&O), Incremental Conductance (I&C), Intelligent MPPT Control.

## I. INTRODUCTION

The continuous growth in global energy demand, coupled with the depletion of conventional fossil fuel resources and increasing environmental concerns, has accelerated the transition toward renewable energy sources (RES). Conventional energy resources such as coal, oil, and natural gas are finite and their extensive utilization contributes significantly to greenhouse gas emissions, air pollution, and other environmental impacts. Consequently, solar and wind energy have emerged as two of the most promising renewable energy resources because of their widespread availability, sustainability, and potential for clean electricity generation [1], [2]. The increasing penetration of renewable energy into modern power systems has created a need for efficient utilization and reliable integration of these variable energy resources. Solar photovoltaic (PV) systems convert solar radiation directly into electrical energy, whereas wind energy conversion systems (WECS) utilize the kinetic energy of wind to generate electricity. However, both resources are inherently intermittent and highly dependent on environmental conditions such as solar irradiance, temperature, and wind speed. Therefore, effective energy management and appropriate power conversion technologies are required to extract the maximum available power from these sources and improve the overall efficiency and reliability of renewable energy systems [3]. A conventional electrical grid consists of generation, transmission, and distribution networks that deliver electricity from generating stations to consumers. Electricity may be produced from conventional or renewable energy sources and is subsequently transferred through transmission networks before being supplied to end users through distribution systems [4]. With the increasing integration of distributed renewable energy sources, modern grids are evolving toward more flexible and decentralized architectures. Grid-connected hybrid solar PV–wind systems can contribute to improved utilization of renewable resources by combining two complementary energy sources and reducing the dependence on conventional power generation [5].

The rapid development of renewable energy technologies has resulted in substantial growth in their contribution to global electricity generation. Solar PV and wind energy have experienced particularly significant expansion because of technological advancements, declining system costs, improved conversion efficiency, and supportive government policies. Countries such as Germany and Spain have played important roles in the early development and large-scale deployment of solar PV technology, contributing to the expansion of the global PV market [6], [7]. In addition, an increasing number of countries have established renewable energy targets and policies aimed at increasing the share of renewable sources in their national energy mix [8].

Despite these developments, the variable nature of solar irradiance and wind speed remains a major challenge in achieving efficient power extraction from hybrid renewable energy systems. Maximum Power Point Tracking (MPPT) techniques are therefore essential for ensuring that solar PV and wind energy conversion systems operate near their maximum power-producing conditions under varying environmental and operating conditions. In grid-integrated hybrid solar PV–wind systems, the selection and implementation of an appropriate MPPT strategy can significantly influence energy conversion efficiency, dynamic response, system stability, and overall power quality. Therefore, a comprehensive assessment of conventional, intelligent, and advanced MPPT techniques is essential

ISSN 2277 – 8322

for understanding their suitability for modern grid-integrated hybrid renewable energy applications.

## II. GRID CONNECTED POWER SYSTEM

Renewable energy refers to energy obtained from naturally replenishing resources such as solar radiation, wind, hydropower, biomass, and geothermal heat. Unlike conventional fossil fuels, which are finite and subject to depletion, renewable energy resources can be continuously replenished through natural processes [9]. The increasing global demand for electricity, depletion of conventional energy resources, and growing concerns regarding environmental pollution and greenhouse gas emissions have accelerated the development and adoption of renewable energy technologies [10]. The utilization of renewable energy can reduce dependence on fossil fuels and contribute to the development of cleaner and more sustainable power systems [11]. A grid-connected renewable energy system is integrated with the utility grid through appropriate power electronic converters and control systems. Such systems enable renewable energy sources to supply electricity to local loads and, when sufficient power is available, export excess electricity to the grid [12]. In modern power systems, solar photovoltaic (PV) and wind energy are among the most widely deployed renewable technologies. A hybrid solar PV–wind system combines these two variable energy sources to improve renewable energy utilization and enhance the continuity of power generation. Since solar irradiance and wind speed vary with time and environmental conditions, appropriate energy management, power conversion, and Maximum Power Point Tracking (MPPT) techniques are required to extract the maximum available power from each source [13].

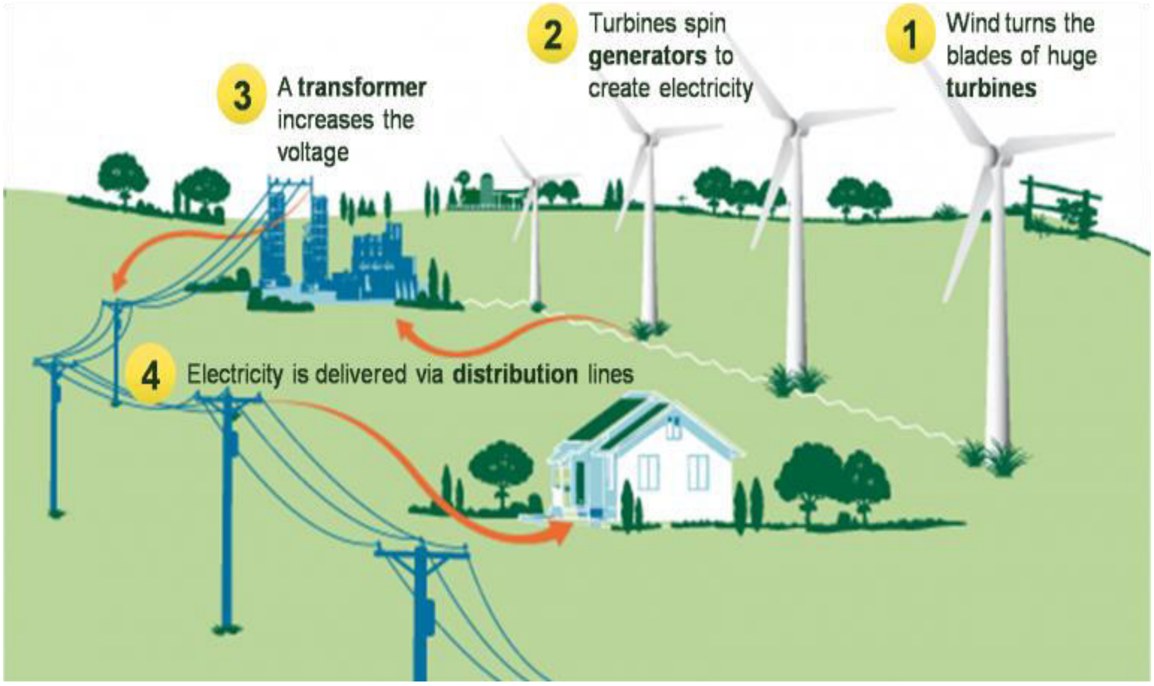


**Figure 1.: Solar and Wind Power Hybrid Energy Plant**

## III. DIFFERENT SOURCES OF RENEWABLE ENERGY

**Wind Power:** Wind energy is obtained by converting the kinetic energy of moving air into mechanical and subsequently electrical energy using wind turbines. The power generated by a wind turbine is strongly dependent on wind speed, and even a relatively small change in wind velocity can result in a significant variation in power output [14], [15]. Modern wind turbines incorporate improved aerodynamic blade designs, efficient generators, and advanced control systems to enhance energy conversion efficiency. In variable-speed wind energy conversion systems, MPPT techniques are employed to maintain the turbine operation near its optimum operating point under changing wind conditions. Consequently, wind energy is an important component of hybrid renewable energy systems and can complement solar PV generation, particularly during periods of low solar availability.

**Solar Power:** Solar energy is one of the most abundant renewable energy resources and can be utilized through both thermal and photovoltaic conversion technologies. Solar thermal systems convert solar radiation into heat, which can subsequently be used for heating applications or electricity generation. In contrast, solar photovoltaic (PV) systems directly convert sunlight into electrical energy using semiconductor-based photovoltaic cells [16]. Solar PV technology has become increasingly important because of its modular structure, scalability, low operating requirements, and suitability for both distributed and grid-connected applications. However, PV power generation varies with solar irradiance and cell temperature. Therefore, MPPT controllers are commonly employed in PV systems to continuously track the operating point corresponding to maximum available power.

**Small Hydropower:** Small hydropower systems generate electricity by utilizing the potential and kinetic energy of flowing or stored water. Depending on the classification adopted by a particular country or standard, small hydropower plants generally refer to systems with relatively low installed capacities, with classifications commonly extending up to several megawatts [7]. Hydraulic turbines convert the energy of water into mechanical energy, which is then converted into electrical energy by a generator. Run-of-river systems can generate electricity from the natural flow of water with limited or no large-scale storage requirements. Small hydropower is considered a reliable renewable energy technology because its generation can be more predictable than some other variable renewable sources.

**Biomass Energy:** Biomass energy is derived from organic materials such as agricultural residues, forestry products, animal waste, and dedicated energy crops. Plants capture and store solar energy through photosynthesis, and this stored chemical energy can subsequently be converted into useful heat, fuels, or electricity. Biomass can therefore serve as an energy-storage medium in the broader renewable energy system because the accumulated chemical energy can be utilized when required. Depending on the conversion technology, biomass can be used for direct combustion, gasification, anaerobic digestion, or the production of biofuels. Its effective utilization can also contribute to waste management and reduction of dependence on conventional fuels.

**Geothermal Energy:** Geothermal energy is the thermal energy stored within the Earth's interior [11]. Heat from the Earth's subsurface can be extracted and utilized for direct heating applications or electricity generation. In geothermal power plants, underground heat is used to produce steam or a working fluid with suitable thermodynamic properties, which drives a turbine connected to an electrical generator. Geothermal resources are particularly attractive because they can provide relatively continuous power generation compared with weather-dependent renewable sources. However, their development is geographically constrained by the availability of suitable geothermal reservoirs, which are often associated with tectonic and volcanic regions [17]. Advances in drilling, reservoir engineering, and geothermal conversion technologies have expanded the potential for geothermal energy utilization.

Among these renewable resources, solar PV and wind energy are particularly suitable for hybridization because their generation profiles can complement each other under certain environmental conditions. Their integration with the utility grid, supported by power electronic converters and appropriate MPPT algorithms, can improve renewable energy utilization and facilitate reliable power delivery. This makes hybrid solar PV–wind systems an important area of research for modern grid-connected renewable energy applications.

## IV. MPPT TECHNIQUES

In Maximum Power Point Tracking (MPPT) is an essential control technique used in renewable energy conversion systems to extract the maximum available power from variable energy sources. In solar photovoltaic (PV) systems, the maximum power point varies primarily with solar irradiance and temperature, whereas in wind energy conversion systems (WECS), it varies with wind speed and turbine operating conditions. An appropriate MPPT algorithm continuously adjusts the operating point of the energy conversion system to maximize power extraction and improve overall conversion efficiency. Several MPPT techniques have been developed, ranging from simple conventional methods to advanced intelligent and optimization-based approaches. The most commonly used techniques include Perturb and Observe (P&O), Incremental Conductance (I&C), fuzzy logic control, and artificial neural network (ANN)-based methods. Their performance differs in terms of tracking accuracy, convergence speed, computational complexity, sensor requirements, steady-state oscillations, and response to rapidly changing environmental conditions.

### A. Perturb and Observe (P&O)

The Perturb and Observe (P&O) method, also known as the hill-climbing method in certain applications, is one of the most widely used MPPT techniques because of its simple structure and relatively low computational requirement. The basic principle is to introduce a small perturbation in the operating voltage or converter duty cycle and observe the resulting change in output power. Based on the direction of the power variation, the controller determines whether the operating point should be moved toward or away from the Maximum Power Point (MPP).

For a solar PV system, the PV voltage and current are measured at successive sampling intervals, and the corresponding power is calculated. The variation in power with respect to voltage can be expressed in terms of the slope of the power-voltage characteristic. When the operating point is located to the left of the MPP, an increase in voltage generally results in an increase in power. Conversely, when the operating point is located to the right of the MPP, an increase in voltage causes the power to decrease. At the MPP, the slope of the power-voltage curve approaches zero.

The controller therefore modifies the converter duty cycle according to the observed change in power. This process is continuously repeated so that the operating point remains close to the MPP. In a DC-DC converter-based PV system, the duty cycle controls the effective input impedance of the converter and consequently regulates the operating voltage of the PV array.

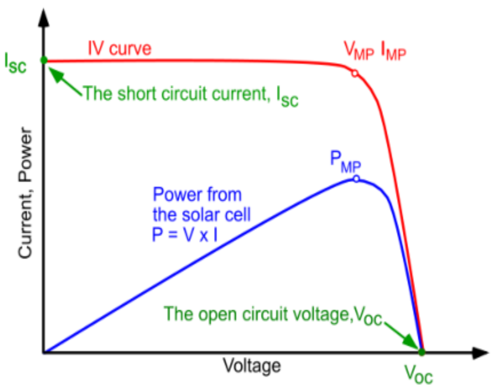


**Figure 2: PV Panel Characteristic Curves[18]**

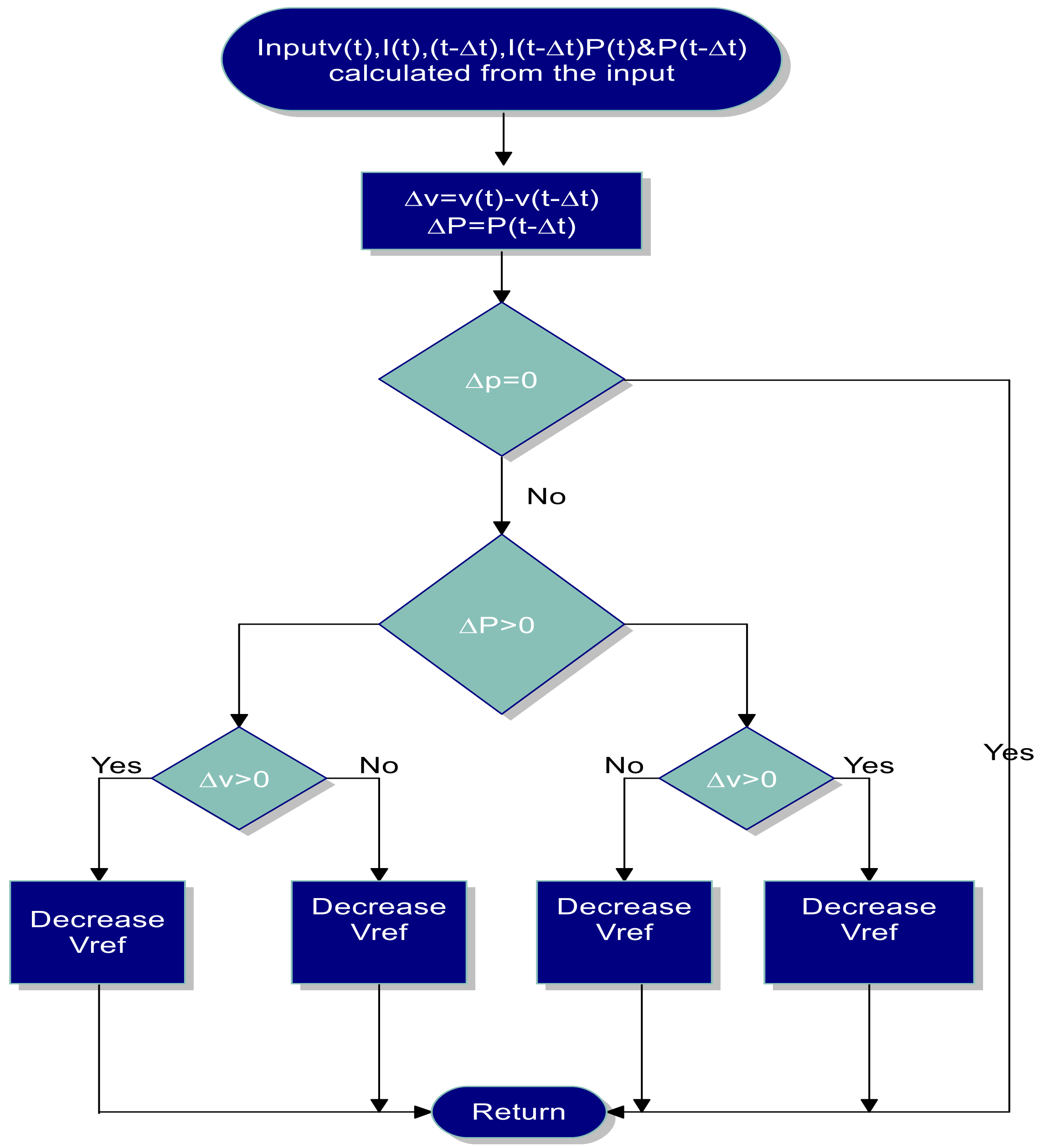


**Figure 3: The Flowchart of the P&O Algorithm**

**Algorithmic Steps**

Step 1: Measure the PV voltage and current at the present sampling instant.

Step 2: Calculate the instantaneous PV power and compare it with the power measured during the previous sampling interval.

Step 3: Determine the change in PV power and the direction of the perturbation.

Step 4: If the perturbation results in an increase in power, continue perturbing the operating point in the same direction.

Step 5: If the perturbation results in a decrease in power, reverse the direction of the perturbation.

Step 6: Repeat the measurement and control process continuously to track the MPP.

The major advantages of the P&O technique are its simple implementation, low computational burden, and limited requirement for system parameters. However, the method generally produces steady-state oscillations around the MPP because of continuous perturbation. Its tracking performance may also deteriorate under rapidly changing irradiance or temperature conditions because the controller may interpret environmental changes as the effect of its own perturbation.

**B. Incremental Conductance (I&C)**

The Incremental Conductance (I&C) method is another widely used MPPT technique for solar PV systems. It is based on the relationship between the instantaneous conductance and incremental conductance of the PV array. The method determines the location of the operating point relative to the MPP by analyzing the slope of the PV power-voltage characteristic.

Since the output power of a PV array is given by:.

In voltage source region $\frac{\partial I_{pv}}{\partial V_{pv}}$ >-$\frac{I_{pv}}{V_{pv}}$→D=D+ΔD (increment D)

In the current source region, $\frac{\partial I_{pv}}{\partial V_{PV}} < -\frac{\partial pv}{vpv}$,→D=D+ΔD (Decrement D)

At MPP, $\frac{\partial I_{pv}}{\partial V_{pv}} = -$ - $\frac{I_{pv}}{V_{pv}} \rightarrow D = D$ (reatain D)

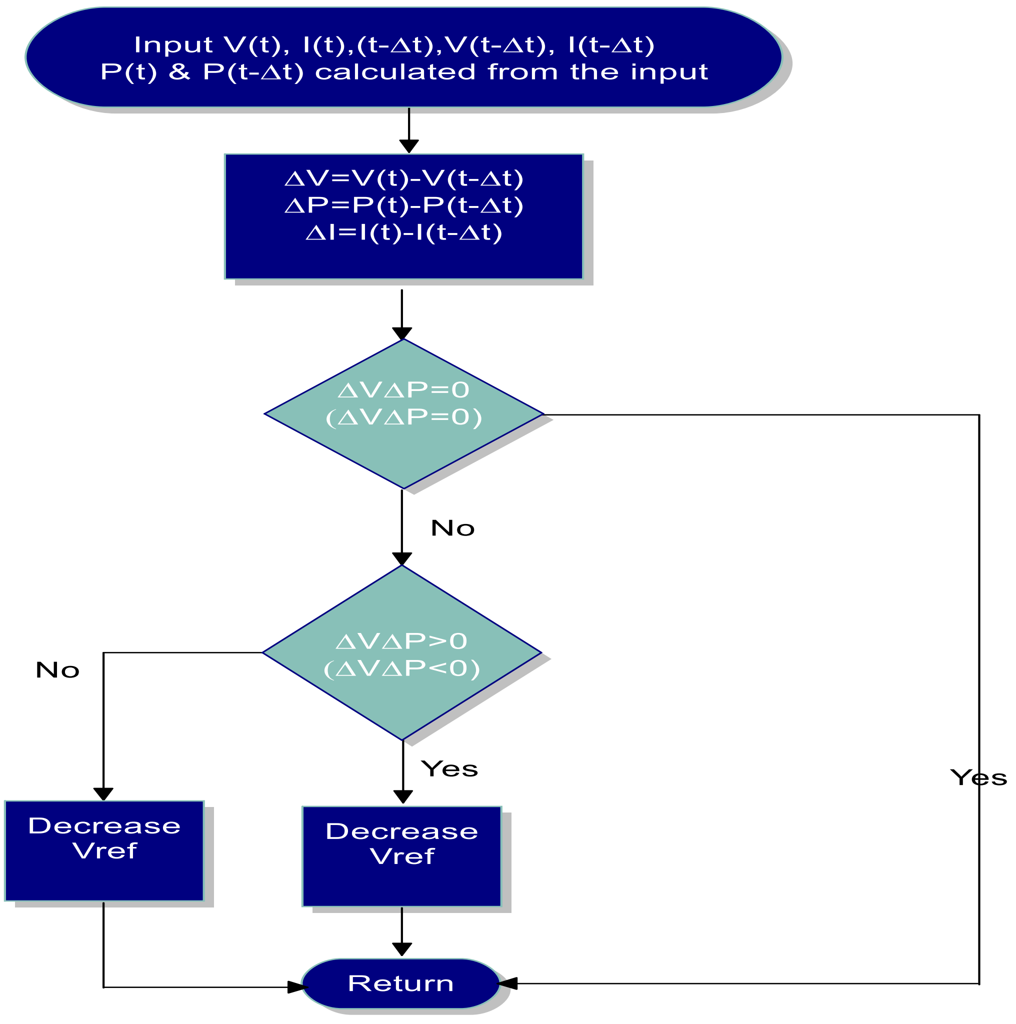


**Figure 4: Incremental Conductance Algorithm**

The I&C algorithm continuously measures the PV voltage and current and calculates the incremental and instantaneous conductance. Based on their relationship, the controller adjusts the converter duty cycle to move the operating point toward the MPP.

**Algorithmic Steps**

Step 1: Measure the present PV voltage and current.

Step 2: Determine the changes in voltage and current between consecutive sampling intervals.

Step 3: Calculate the incremental conductance and compare it with the instantaneous conductance.

Step 4: If the operating point is to the left of the MPP, increase the operating voltage.

ISSN 2277 – 8322

Step 5: If the operating point is to the right of the MPP, decrease the operating voltage.

Step 6: If the MPP condition is satisfied, maintain the present operating point.

Step 7: Repeat the process continuously to track changes in the MPP.

Compared with P&O, the I&C method can provide improved performance under rapidly changing environmental conditions because it determines the direction of movement toward the MPP using the conductance relationship. However, its implementation is comparatively more complex and requires accurate measurements of voltage and current.

### C. Fuzzy Logic Control

Fuzzy Logic Control (FLC) is an intelligent MPPT technique that has received considerable attention because it can operate effectively without requiring an accurate mathematical model of the PV system. It is particularly useful for nonlinear systems in which the operating conditions vary significantly. Fuzzy logic controllers can process uncertain or imprecise input information and provide suitable control actions based on predefined linguistic rules.

A typical fuzzy logic-based MPPT controller consists of three main stages: fuzzification, rule-based inference, and defuzzification. During fuzzification, numerical input variables are converted into linguistic variables according to predefined membership functions. The inference system then evaluates these variables using a set of IF–THEN rules. Finally, the defuzzification process converts the resulting linguistic output into a numerical control signal for the power converter.

For MPPT applications, commonly used input variables include the change in power with respect to voltage and the change in this quantity between successive sampling intervals. The output of the fuzzy controller is generally used to modify the converter duty cycle.

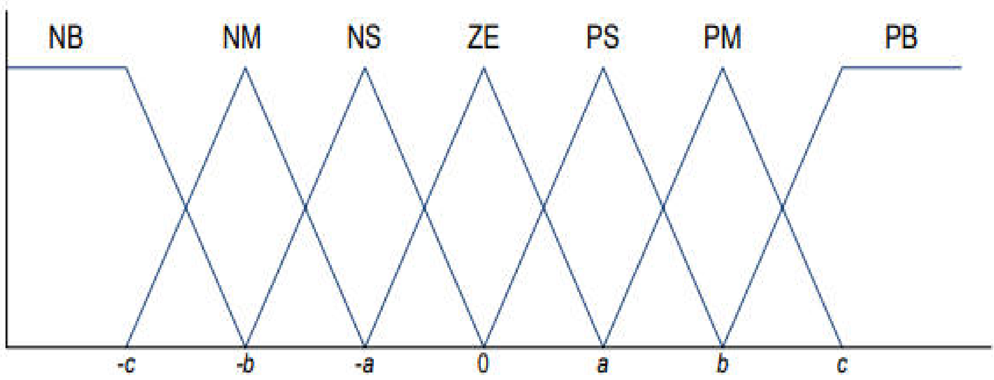


**Figure 5: Membership Functions. (reconsider)**

A fuzzy controller may employ five or seven linguistic membership levels. A commonly used seven-level configuration consists of:

- NB: Negative Big
- NM: Negative Medium
- NS: Negative Small
- ZE: Zero
- PS: Positive Small
- PM: Positive Medium
- PB: Positive Big

The shape and number of membership functions influence the controller's tracking accuracy and dynamic response. Triangular and trapezoidal membership functions are frequently used because of their relatively simple implementation.

The major advantages of fuzzy logic MPPT include good adaptability to nonlinear operating conditions, reduced dependence on an exact system model, and potentially fast tracking under changing environmental conditions. However, controller performance depends strongly on the selection of membership functions, scaling factors, and fuzzy rules. The design process can therefore be more complicated than that of conventional MPPT techniques.

### D. Artificial Neural Network

Artificial Neural Network (ANN)-based MPPT is an advanced intelligent control technique that uses the learning and nonlinear approximation capabilities of neural networks to determine the optimum operating point of renewable energy conversion systems. ANN-based controllers are particularly attractive for systems with highly nonlinear characteristics and rapidly changing operating conditions.

A basic neural network generally consists of an input layer, one or more hidden layers, and an output layer, as illustrated in Figure 6. The input layer receives measured parameters such as PV voltage, PV current, solar irradiance, and temperature. These inputs are processed through the hidden layers using weighted connections and activation functions. The output layer generates the required reference voltage, current, or converter duty-cycle command for MPPT control.

The performance of an ANN-based MPPT controller depends on the structure of the network and the quality of the training data. The number of input variables, hidden layers, neurons, activation functions, and training method can be selected according to the requirements of the renewable energy system.

ANN based MPPT techniques can provide fast tracking and good performance under nonlinear and rapidly changing operating conditions. They can also be extended to hybrid solar PV wind systems by incorporating parameters associated with both energy sources, such as solar irradiance, PV temperature, wind speed, generator speed, and electrical power. However, ANN methods generally require an appropriate training process and sufficient representative data. Their computational requirements and dependence on training quality can also increase implementation complexity compared with conventional MPPT methods.

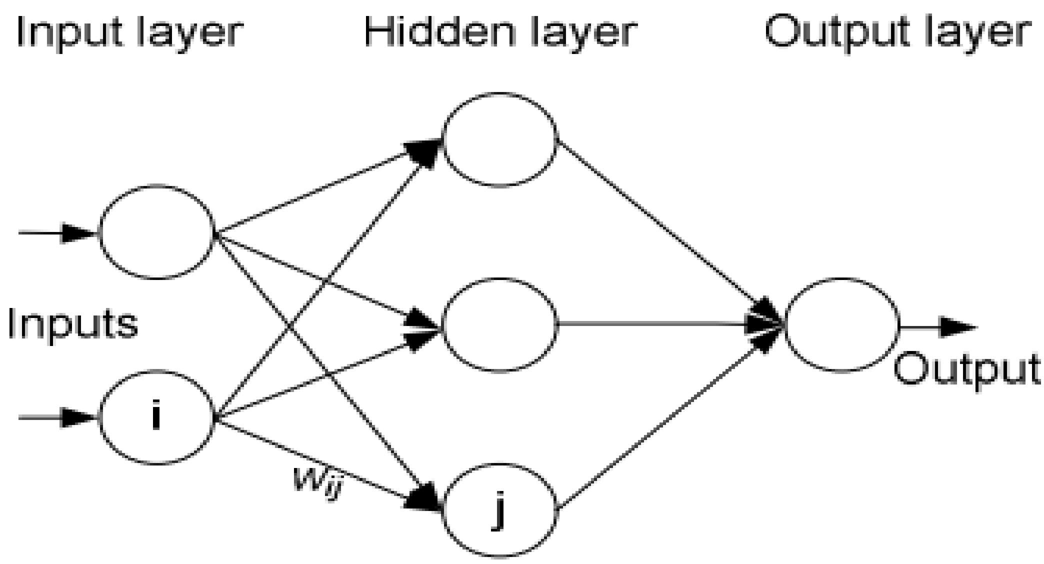


**Figure 6: Basic Architecture of an Artificial Neural Network**

For grid-integrated hybrid solar PV–wind systems, ANN-based MPPT can therefore be combined with power electronic converters and supervisory energy-management strategies to improve maximum power extraction

ISSN 2277 – 8322

under continuously varying solar and wind conditions.

## V. CONCLUSION

The The integration of solar PV and wind energy is important for meeting growing electricity demand and reducing dependence on fossil fuels. However, the variable nature of renewable resources makes efficient power extraction challenging. MPPT techniques such as P&O, Incremental Conductance, Fuzzy Logic, and ANN help maximize energy extraction under changing conditions. P&O is simple and economical but may cause oscillations, while Incremental Conductance provides better tracking with higher computational requirements. Intelligent methods such as FLC and ANN offer improved adaptability but depend on proper design, training, and computational resources. For hybrid solar PV–wind systems, MPPT must work together with power converters, control systems, and energy management. Future research should focus on fast, accurate, robust, and computationally efficient MPPT techniques capable of handling rapidly changing environmental and grid conditions.

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