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A Study on Performance Improvement of MPPT-Based Grid-Connected Hybrid Renewable Energy Systems

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Abstract

The increasing demand for clean and sustainable energy has led to the widespread integration of hybrid renewable energy systems, particularly solar–wind based grid-connected configurations. These systems combine the complementary characteristics of solar photovoltaic (PV) and wind energy sources to improve reliability and energy availability. This paper presents a comprehensive review on the performance improvement of MPPT-based grid-connected hybrid renewable energy systems. The study begins with an overview of solar–wind hybrid systems, including the operational principles of wind energy conversion systems (WECS) and solar photovoltaic generation. The fundamental components and working of basic PV and wind systems are discussed to provide a clear understanding of power generation dynamics. An extensive review of existing literature is conducted to analyze recent developments, challenges, and research trends related to hybrid renewable integration and MPPT techniques.

Fuzzy Logic Control, and Neural Network–based approaches are critically reviewed and compared in terms of tracking accuracy, dynamic response, complexity, and adaptability to changing atmospheric conditions. Intelligent MPPT techniques are found to offer superior performance compared to conventional methods, particularly under rapidly varying solar irradiance and wind speed conditions. The review highlights that effective MPPT implementation significantly improves system efficiency, grid power quality, and overall energy yield.

The paper concludes by summarizing key findings and identifying research gaps in MPPT optimization, intelligent control integration, and grid compliance. Future research directions emphasize hybrid intelligent MPPT algorithms, real-time implementation, and advanced control strategies to further enhance the performance and reliability of grid-connected hybrid renewable energy systems.

Keywords: MPPT, Hybrid Renewable System, Grid-Connected System, Power Quality, Control Techniques.

Introduction

In our daily lives and industries there are vital services and products generated from electricity. The subsystem of electricity consists of 4 major subsystems (1) power generation; (2) power transmission; (3) power conversion; and (4) power consumption. Transmission systems and distribution systems for supplying small volumes of electrical power to remote sites, especially those that may be difficult or cost ineffective to install, such as agricultural farms, forest areas, islands, etc., are very limited. In addition, prolonged power interruption due to storms and natural disasters has become commonplace. Because of the increasing concern about climate change and the degradation of the environment, transitioning electricity generation systems towards using renewable energy sources will help reduce the dependency on fossil fuels and lower the amount of greenhouse gases released into the atmosphere. Therefore, the development of off-grid renewable energy system(s) is gaining momentum. The hybridization of these systems is one of their main benefits, and by combining various forms of renewable energy with energy storage technologies, they will create reliable and sustainable power sources in areas where conventional electricity distribution networks do not exist. Individual renewable energy systems may have limited benefits due to their natural non-linear and intermittent nature, so hybrid renewable energy systems can be designed to improve overall system reliability and efficiency. A hybrid renewable energy system includes multiple energy sources and a combination of energy storage technologies into one system to maximize the output of electrical energy and improve energy management capabilities.

A hybrid solar-wind power system combines two renewable energy sources—solar and wind—and uses them to produce electricity. In this configuration, solar panels and small wind generators work together to provide energy to users. Understanding a solar-wind hybrid system requires understanding how each of the components works individually; specifically, how solar power systems work and how wind power systems work. Solar power systems produce electricity by collecting energy from the sun through photovoltaic (PV) cells with the help of solar panels. Solar panels generate electricity in a direct current (DC) format that can be stored in batteries or sent to DC electrical loads directly. If needed, DC electricity from solar panels can be converted to alternating current (AC) by means of an inverter. Wind power systems generate electricity by using wind turbines and generators. Wind turbines are made up of two or three blades that spin as wind pushes against them. The axis of the blades is positioned to align with the direction the wind is blowing. A gearbox serves to convert the mechanical energy produced by a turbine into a usable speed for the generator through mechanical transmission. Wind turbines are typically categorized as horizontal- or vertical-axis turbines. Wind energy is available all day long, depending on weather conditions, unlike solar energy. Thus, combining both wind and solar sources creates a more continuous and reliable power supply.

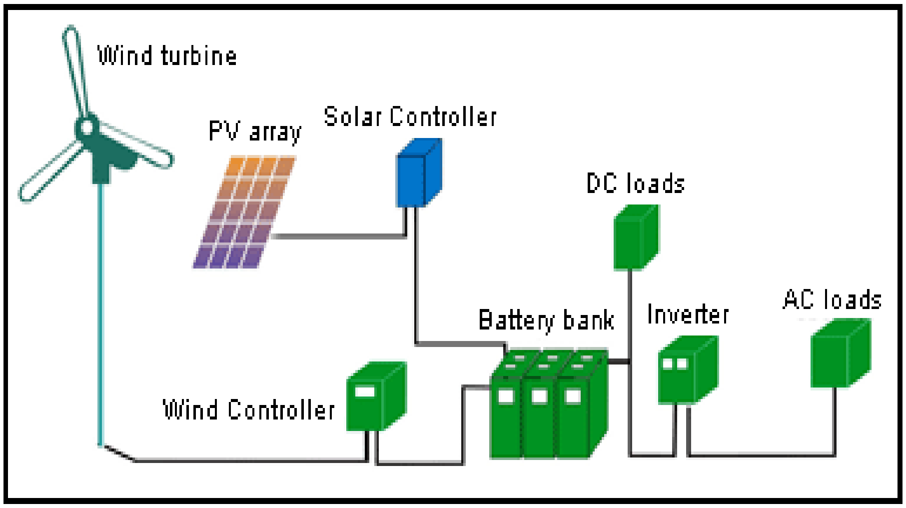

Figure 1. A Small Size Solar-Wind Hybrid Power System[5]

Solar–Wind Hybrid System Architecture

The WECS electrical energy comprises a wind turbine, mechanical connection, generator, and integration with the grid. Blades of a wind turbine are placed in the hub, as shown in Figure 1.5. As the wind blows, the shaft of the turbine starts to rotate. Then gearbox is used to make the rotational speed increase or decrease according to the suitableness of the generator. Now important part integration of the grid with the wind farm is done power electronic devices, which makes the voltage and frequency fixed so that power can be supply direct to load or synchronized with the grid. In the present era, two types of generators are widely used in wind farms: PMSG and DFIG. Both generators generate high-quality electrical power with controlled grid integration. But superconducting generators bring lots of losses due to AC associated with the stator leads to a time-varying magnetic field, so this generator is still under research.

Wind Power-Wind turbines are used to harvest the energy available in airflows. Current day turbines rated power range from 600kW to 5MW.

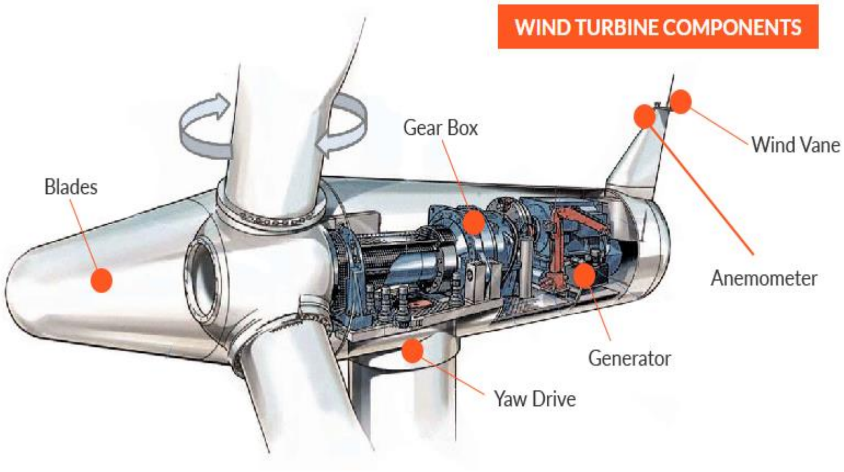

Figure 2: Component of Wind Turbine

The output power of a wind turbine enhances by amplifying the cube of wind speed. Thus turbines are always installed in high altitudes or particularly in places known for high wind speeds.

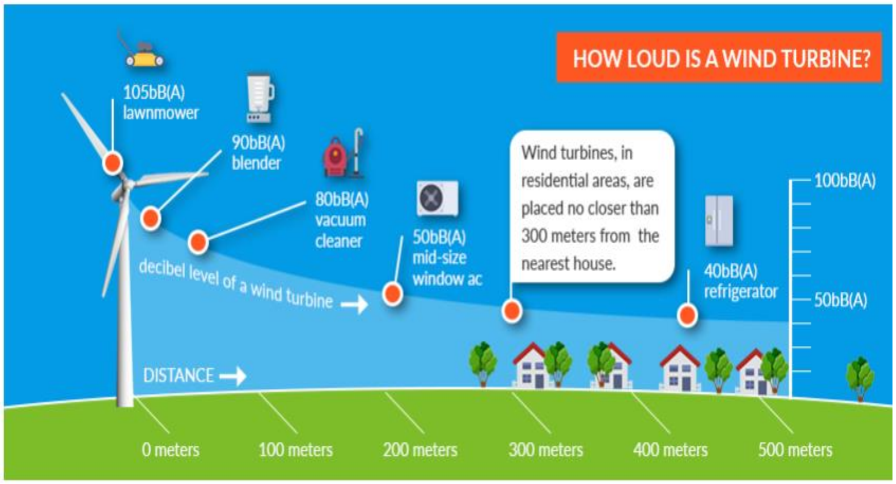

Figure 3: Turbine Execution.

Component	Description	Function / Notes
Wind Turbine Blades	Blades mounted on the hub	Capture wind energy and convert it into rotational motion
Shaft & Rotor	Connects blades to gearbox	Transmits mechanical energy from blades to generator
Gearbox	Mechanical device	Adjusts rotational speed to match generator requirements

Component	Description	Function / Notes
Generator	Converts mechanical energy to electrical energy	Common types: PMSG (Permanent Magnet Synchronous Generator), DFIG (Doubly Fed Induction Generator). Superconducting generators are still under research due to AC losses in the stator
Power Electronics / Grid Integration	Voltage and frequency control devices	Ensure stable output for direct load supply or synchronization with the grid
Wind Power Characteristics	Wind turbines rated from 600 kW to 5 MW	Power output proportional to the cube of wind speed; installed at high altitudes or high-wind locations
Output Enhancement	Turbine placement	High altitudes and wind-rich areas maximize energy harvest

Table 1: Solar–Wind Hybrid System Architecture

MPPT **Techniques: Classification and Comparison**

MPPT is a technique that can help improve your PV or wind energy system's efficiency. Because of changing weather conditions (i.e., solar irradiance, temperature, and wind speed), the operating point of renewable energy sources will also change. With MPPT you will be operating at or near your MPP to extract maximum power from your renewable energy source and to provide better overall performance to the entire renewable energy system. Many different MPPT methods have been developed over time and generally fall into one of four categories: Conventional, Fractional, Intelligent, and Optimization-based.

The Conventional MPPT methods (e.g., Perturb and Observe (P&O) or Incremental Conductance (INC)) are straightforward to use and have been popularized due to their simplicity of design, implementability, and ease of use. For P&O, you perturb your operating voltage or current, then observe how it affects your output power. This method can provide steady-state oscillations around the MPP but can also lose accuracy when the input sources change too quickly. The method of Incremental Conductance uses voltage and current relationships to help identify where the MPP is located. It is an improved tracking method that provides high trackability and rapid response rates; however, it is more computation-intensive than the conventional methods.

Fractional Maximum Power Point Tracking (MPPT) techniques use the relationship between open-circuit voltage (OCV) and short-circuit current (SCC) to estimate the Maximum Power Point (MPP) based on fixed proportional constants derived from the system's characteristics. While these techniques are simple to implement and cost-effective, they provide lower accuracy because the proportional constants that are assumed to remain constant, can vary with operating conditions. On the other hand, Intelligent Maximum Power Point (IMPP) techniques, such as Fuzzy Logic Control (FLC) and Artificial Neural Networks (ANN), provide better performance for tracking MPP accuracy because of their ability to handle the non-linear characteristics of renewable energy systems. For example, while FLC-based MPPT systems utilize a rule-based approach to rapidly track MPP with a high level of accuracy, ANN-based approaches utilize trained models to accurately predict the MPP of a renewable energy system. Although FLC and ANN-based MPPT techniques are wellsuited for the dynamic, non-linear conditions of renewable energy systems, they require more careful design, training, and computational resources than Fractional MPPT techniques. Optimization-based MPPT techniques, such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), provide effective solutions for renewable energy systems that experience partial shading and multiple local MPPs. Both of these techniques provide excellent tracking accuracy by searching for the Global Maximum Power Point (GMPP), but they are often more complex and take longer to converge than FLC and ANN techniques. Thus, with all of these MPPT techniques, there is a trade-off between accuracy, speed, complexity, and cost.

Grid Integration and Power Quality Issues

The increasing use of distributed generation systems such as solar PV (photovoltaic) and wind energy has made grid integration of renewable energy sources more critical than ever. When these systems are connected to the utility grid, numerous benefits can be realized including increased reliability of electricity service, less transmission losses and maximized use of clean renewable energy sources. The characteristics of renewable energy systems (intermittent and variable) create a unique set of power quality problems that may adversely affect both the stability and performance of the grid. Variations in solar irradiation and wind velocity can cause fluctuations in generated output levels resulting in voltage instability, frequency imbalances and elevated stress on utility infrastructure.

One of the primary power quality concerns related to the use of renewable energy systems interfaced with the utility grid includes the problem of voltage fluctuations, sag and swell due to sudden changes in load or generation. In addition, harmonic distortion (caused by power electronic converters such as inverters that are used to interface with the utility grid) is also a major concern that can degrade power quality, increase losses, and negatively affect sensitive equipment connected to the grid. Other challenges include poor power factor, flicker and unbalanced currents, which may be experienced, especially when using high penetrating renewable energy systems and when servicing weak grid systems.

As mentioned above, to reduce problems in grid-connected hybrid renewable energy systems, advanced control techniques and power conditioning equipment must be implemented in these systems. By using synchronized grid-tied inverters with appropriate control methods (e.g., PWM), voltage and frequency levels can be controlled to stay within their respective boundaries. Techniques like MPPT, active/reactive power control, and integrating battery systems improve the ability to support the grid and reduce power fluctuations. In addition, using filters, FACTS, and complying with applicable grid codes will improve the quality of the electrical power produced by the hybrid renewable system and increase the reliability of the grid. Therefore, effective integration of hybrid renewable energy systems and good management of the quality of the electrical power produced by these hybrid systems are key components to successfully implementing hybrid renewable energy systems in today 's electrical utility systems.

Table 2: Comparative Analysis of MPPT Algorithms

MPPT Algorithm	Operating Principle	Tracking Accuracy	Convergence Speed	Computational Complexity	Performance under Rapid Changes	Partial Shading Capability	Advantages	Limitations
Perturb and Observe (P&O)	Perturbs voltage/current and observes power change	Moderate	Moderate	Low	Poor	No	Simple, low cost, easy implementation	Oscillations around MPP, inaccurate under fast-changing conditions
Incremental Conductance (INC)	Uses dP/dV = 0 condition at MPP	High	Fast	Medium	Good	No	Higher accuracy than P&O, reduced oscillations	Increased complexity and sensing requirements
Fractional Open-Circuit Voltage (FOCV)	MPP voltage is a fraction of open-circuit voltage	Low	Fast	Very Low	Poor	No	Simple, minimal hardware	Requires periodic disconnection, low accuracy
Fractional Short-Circuit Current (FSCC)	MPP current is a fraction of short-circuit current	Low	Fast	Very Low	Poor	No	Easy to implement	Power loss during measurement
Fuzzy Logic Control (FLC)	Rule-based decision using error and change in error	High	Fast	High	Very Good	Limited	Robust, no precise mathematical model needed	Rule design complexity, tuning required
Artificial Neural	Predicts MPP using trained	Very High	Very Fast	Very High	Excellent	Yes	Accurate, adaptive, fast	Requires training data, high

MPPT Algorithm	Operating Principle	Tracking Accuracy	Convergence Speed	Computational Complexity	Performance under Rapid Changes	Partial Shading Capability	Advantages	Limitations
Network (ANN)	data						response	computation
Particle Swarm Optimization (PSO)	Population-based optimization technique	Very High	Moderate	Very High	Excellent	Yes	Global MPP detection, effective under shading	Slower convergence, high processing demand
Genetic Algorithm (GA)	Evolutionary optimization using selection and mutation	Very High	Moderate	Very High	Excellent	Yes	Global optimization capability	Complex implementation, higher computation time

Research Gaps and Challenges

Although many techniques used to track maximum power point (MPPT) in hybrid renewable energy systems connected to a grid have made considerable progress since their introduction in the early 2000's; many research opportunities and obstacles remain to overcome. One area that needs further investigation is the response of traditional MPPT algorithms to quick shifts in environmental conditions, for example, abrupt changes in the sunlight shining on solar panels and wind blowing across wind turbines. As a result, many of the currently available MPPT paradigms provide slow responses to sudden changes in the environment or oscillation around a single fixed point during steady state operation, leading to a loss of electrical power output. Furthermore, because of the complexity of the algorithms, advanced optimization and intelligent MPPT methods are generally resource intensive and therefore may limit the ability of low-cost control systems to produce adequate real-time responses.

Additionally, the research opportunities associated with Partial Shading Effects (PSEs) and Non-Uniform Operating Conditions (NUOCs) for MPPT systems connected to the grid are still in their infancy. In theory, while optimization-based methods can locate the Global Maximum Power Point (GMPP), these optimized algorithms can experience very slow rates of convergence and difficulties maintaining stability when used in conjunction with grid-connected systems.

The enhancement of Hybrid Renewable Energy Systems (HRESs) also creates new coordination issues due to the presence of additional sources of energy, such as battery storage. To receive energy from multiple sources efficiently, and share that electricity in a coordinated manner, an effective Energy Management Strategy (EMS) is required to facilitate this type of seamless sharing of electrical power while ensuring system stability.

Integrating power grids presents major power quality and grid code compliance issues. Fluctuating voltage, harmonic distortion, unintentional frequency changes, and low power factor are all huge problems, especially in weak grids with increased renewable energy content. Current control strategies may not be completely effective under changing conditions and very few studies have concentrated on one unified control strategy that can meet the needs of MPTT performance, generate better-quality power, and stabilise the grid.

Moreover, the absence of a standard means to compare MPPT algorithms makes it hard to know how they performed in a real-world environment. Many researchers choose to conduct simulations based on their assumptions of ideal situations rather than conducting real-life testing or using hardware in their simulations. Future work should focus on developing hybrid and adaptable MPPT methods that minimize computational complexity, maximize resilience, and develop the capability of supporting the grid; thereby, making it practical for use in grid-connected hybrid renewable energy plants.

Research Gap / Challenge	Description	Implications / Notes
MPPT Response to Rapid Environmental Changes	Traditional MPPT algorithms respond slowly to abrupt changes in sunlight or wind	Leads to oscillations or power loss during sudden variations
Algorithm Complexity	Advanced optimization and intelligent MPPT methods are resource-intensive	Limits real-time performance in low-cost control systems
Partial Shading Effects (PSEs) & Non-Uniform Operating Conditions (NUOCs)	MPPT systems struggle under non-uniform solar/wind conditions	Optimization-based methods may find Global Maximum Power Point but converge slowly and may be unstable
Energy Management Strategy (EMS) Coordination	Hybrid systems with multiple energy sources (e.g., batteries) require efficient coordination	Essential to distribute power seamlessly while maintaining system stability
Power Quality & Grid Integration	Fluctuating voltage, harmonic distortion, frequency variations, and low power factor, especially in weak grids	Current control strategies may not fully stabilize the grid under dynamic conditions
Lack of Standardized MPPT Evaluation	No universal method to compare MPPT algorithms; many studies rely on ideal simulations	Real-world performance is uncertain; hardware-in-the-loop testing is needed
Future Research Directions	Develop hybrid/adaptable MPPT methods that are computationally efficient, resilient, and grid-supportive	Practical for real-world, grid-connected hybrid renewable energy systems

Table 3: Research Gaps and Challenges

Review of Literature

An efficient, adaptable, and compatible microgrid configuration based on renewable energy sources has received considerable attention. Hamzeh et al. (2015) presented a research paper that considered a microgrid configuration based on renewable energy sources, including photovoltaic systems, energy storage systems, dc loads, electric machines, and an energy management system. The most considerable objective of this system design was to effectively manage power demand under various operational requirements. The authors explored a microgrid power system with various load points based on MATLAB/Simulink software with a potential to effectively manage power demand by means of an adaptive energy management system.

Kollimalla et al. (2014) pointed out that hybrid energy storage systems coupled with batteries and supercapacitors will result in better energy storage performance. Batteries have high energy density, whereas supercapacitors have high power density. Hence, the integration of batteries and supercapacitors is suitable for DC microgrid applications. Correspondingly, a power management strategy was developed in order to balance the DC bus voltage and system power and reduce battery degradation caused by its frequent charge–discharge cycles. Simulation results validated that the power demand is well met in a suggested control strategy which presented better storage life.

MPPT techniques play a very critical role in optimizing renewable energy extraction. Zhou et al. have proposed the P&O MPPT algorithm for photovoltaic systems. The described approach incrementally changes operating parameters to track the maximum power point without prior system knowledge. This technique is quite simple and easy to implement. However, performance decreases when rapid changes in environmental conditions develop oscillations around the maximum power point.

Another alternative approach of PV system controls, utilizing various PV convertor configurations, has been presented by Wang & Peng (2012), involving a system where two inverters, i.e., small film capacitors, together with a dual active voltage bridge, together with a multi-level inverter, were used, so that even traditional high voltage capacitors were replaced, thus enabling a high-efficiency controlled result, even during dynamic conditions of the PV system, by testing a 5 kW PV convertor unit.

The thermal aspects incorporated into MPPT control were treated by Lee et al. (2013), where a monitoring technique was invented, resulting in a system that considers thermal stress on semiconductor devices. Consequently, this reduced switching losses and resulted in a better system efficiency compared to others with varying climatic conditions.

Advanced intelligent control methods have been used to improve renewable energy sources. In one such contribution, Wei et al. presented an algorithm for maximizing energy extraction for wind energy conversion system using a combination of artificial neural network (ANN) and q-learning methods. The algorithm was used to maximize energy extraction for wind energy conversion systems by optimizing rotor speed for maximum energy extraction. The results validated for a wind energy system of 5 MW capacity were obtained both using simulation and experiment; however, requirement of large quantities of data was listed as a drawback.

Xing et al. (2020) presented hybrid renewable systems combining wind and solar resources. The research provided the technical feasibility of hybrid power generation with wind and solar energy, built mathematical models of the wind turbine, PV system, and battery, and focused on MPPT control strategies for both sources. Simulation in MATLAB/Simulink proved that the control approaches proposed in this work can assure maximum combined renewable power.

In wind energy applications, Jagwani et al. presented an SRG-based wind energy conversion system interfaced with an interactive grid inverter. Maximum wind power was extracted using an MPPT algorithm based on optimal tip-speed ratio control. This provided for designing the system to operate in both grid-connected and standalone modes while ensuring that power flow was regulated according to the state of charge of the battery. The proposed control strategy has proven to deliver reliable power to the critical loads when operating under widely variable conditions.

More recently, Trusova et al. (2021) proposed a modular and distributed control architecture for solar power plants to overcome the limitations of traditional lumped-element designs. The system, by integrating MPPT control, inversion, and filtering into a multilevel modular topology, reduces cost and complexity for higher power ratings. Using a proportional-resonant controller eliminates the need for phase-locked loops, enhancing flexibility in the system and simplifying control. A 10 kW solar power plant model operating at the standard 220 V supply validated the feasibility of the proposed approach.

Maximum Power Point Tracking Algorithms

Hill-Climbing Techniques

Numerous different types of MPPT algorithms have been devised to boost the efficiency of photovoltaic system efficiency. Some of the MPPT algorithms used for efficiency maximization include hill climbing MPPT, incremental conductance MPPT, constant voltage control, modified hill climbing MPPT, system oscillation MPPT, ripple correlation MPPT, etc. These various types differ from one another in terms of efficiency, tracking speed, etc. Amongst all these techniques, the hill climbing technique is one of the most widely used approaches for MPPT. This is because this technique is very simple to implement. This technique adds a periodic perturbation to the duty cycle of the DC–DC converter; subsequently, the PV voltage & current are measured to obtain the power output. The algorithm measures the change in power over a specific perturbation.

If an increased power level is obtained in reference to the previous level, the operating point is said to be shifting towards the maximum power point (MPP); in this case, the perturbation continues in its original direction. Conversely, in case the power obtained goes below the reference power level, the direction of the perturbation changes its course. The corrective tracking method relies on the positive or negative slope information identified from the PV curve with reference to its power-voltage curve in order to continuously reach the maximum power point.

In voltage source region, $\frac{\partial P_{PV}}{\partial V_{pv}} > 0 \rightarrow D = D + \Delta D$(Increment D)

In the current source region, $\frac{\partial P_{pv}}{\partial V_{pv}} < 0 \rightarrow D = D + \Delta D$ (Decrement D)

At MPP, $\frac{\partial P_{pv}}{\partial v_{pv}} = 0 \rightarrow D = D or \Delta D = 0$ (Retain D)

Where, D is duty cycle and D is change in duty cycle. As per equation 3.1 to 3.3, $P_{new}>P_{old}$, the duty cycle is increased. This means that the slop is positive and the operating point is in the constant current region. Incase $P_{new}<P_{old}$, the duty cycle is reduced. This means that the slope is negative and the operating point is in the constant voltage region (Ting-Trishan & Patrick 2007). The algorithmic steps of hill climbing algorithm are given below.

Algorithmic steps:

Step 1: Measure the value of voltage and current of solar PV.

Step 2: Set the modulation index m.

Step 3: Calculate the initial power Pm.

Step 4: Increase the value of m.

Step 5: Sense the voltage and current of solar PV.

Step 6: Calculate the modified power Pf.

Step 7: If the change in power is positive, increase m, if it is negative decrease the value of m. If no change the value m is maintained.

Step 8: Repeat step 5.

Perturb and Observe

Likewise, the algorithm of Perturb and Observe is also called the hill climbing algorithm. Both of these expressions refer to the very same technique of control. However, the term utilized in the application varies. Under this control strategy, a disturbance in the operating point of a given system is produced by adjusting the duty cycle of a given power converter. As a result, the operating conditions of the direct current connection of the photo voltaic vector and the given power converter change, thus influencing the photo voltaic source. The algorithm observes the change in the output power and utilizes the obtained data to determine the direction of the following perturbation. When the obtained data show an increase in the power level following the occurrence of the disturbance, the following step is taken in the same direction. Otherwise, the direction is inverted. In this case, the algorithm utilizes the data obtained by comparing the previous and current power levels in order to forecast the result of the following step. As depicted in Fig. 5, for the operating point positioned at the left side of the maximum power point (MPP), increasing voltage will result in increasing power. For locations at the right side of the MPP, a drop in voltage will mean an increase in power. Following this logic, the system will finally reach and operate around the maximum power point.

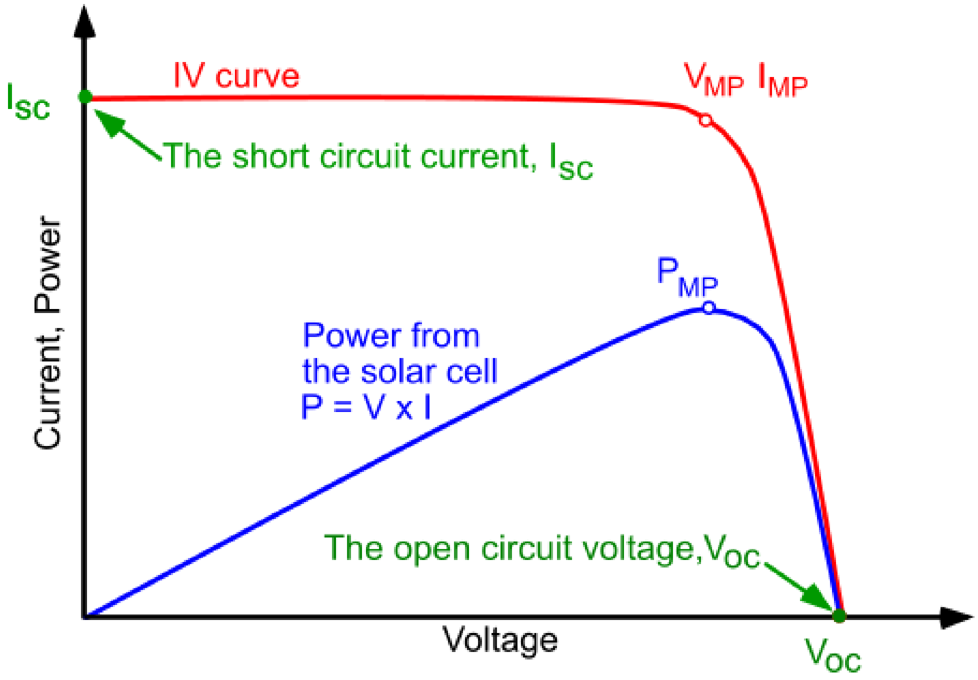

Figure 4: PV Panel Characteristic Curves[11]

Perturb and Observe (P&O), one of the most frequently used MPPT control strategies in Solar and Wind Energy Converters, has a simple structure and is easy to implement. For a Photovoltaic System, it has been found that by measuring different time intervals, it is possible to calculate the output voltage, current, and consequently the measured power derived by a Solar Panel Array. The change in power is compared with the change in voltage by this algorithm. The operating direction of this system is then decided by this. When this observed change shows a tendency to increase power output, the control parameter is varied by moving the operating point towards the maximum power operating point. When the change shows a tendency for reduced power, the variation is done inversely. The system operating at a point with no observed change in power with reference to the variation of voltage is assumed to be operating at the maximum power operating point.

The process is carried out on a continuous basis to ascertain a better tracking result with regards to different states of irradiance and temperatures. The process by which the P&O method functions can be characterized by accounting for the impedance matching condition relating to the source constituted by the photovoltaic array and the load conditions. The duty cycle of the main converter enables this condition by adjusting its load appropriately to attain maximum power during this process. The step-by-step process of this method is discussed below.

Algorithmic steps:

Step 1: Measure the two consecutive values of voltages and currents of solace PV.

Step 2: Calculate the powers P(n) and P(n-1).

Step 3: If the powers are increasing, then decrease the duty cycle.

Step 4: If the powers are decreasing, then increase the duty cycle.

Step 5: Go to step 1.

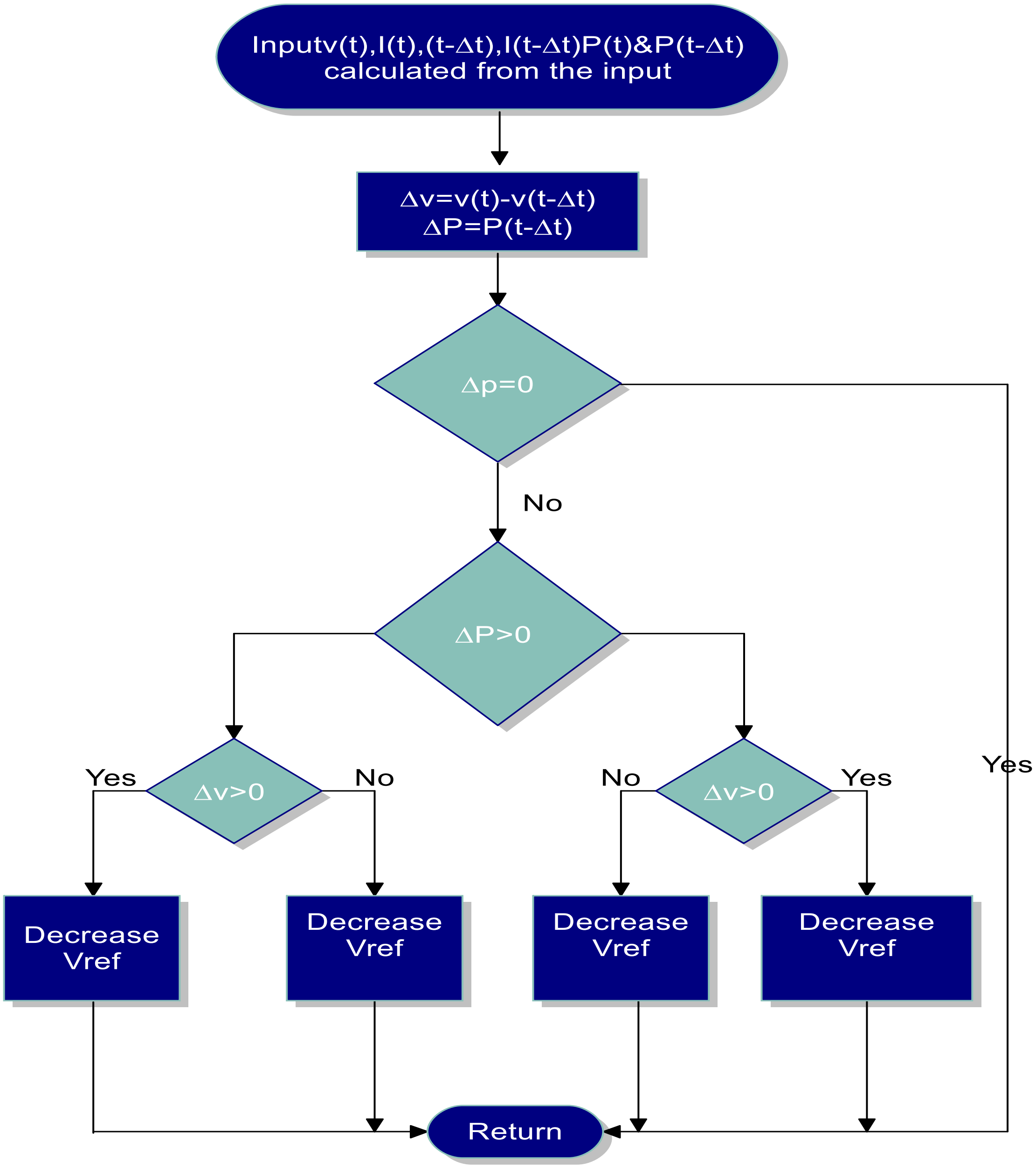

Figure 5: The Flowchart of the P&O Algorithm

Incremental Conductance

The incremental conductance method is to determine the terminal voltage of the PV module by measuring and comparing the incremental conductance with the instantaneous conductance. The maximum power is reached when the incremental conductance is equal to the instantaneous conductance. The terminal voltage of the PV module is continuously perturbed at regular intervals until the incremental conductance is equal to the instantaneous conductance. This is represented in the following equation (Ting-Chung & Yu-Cheng 2012).

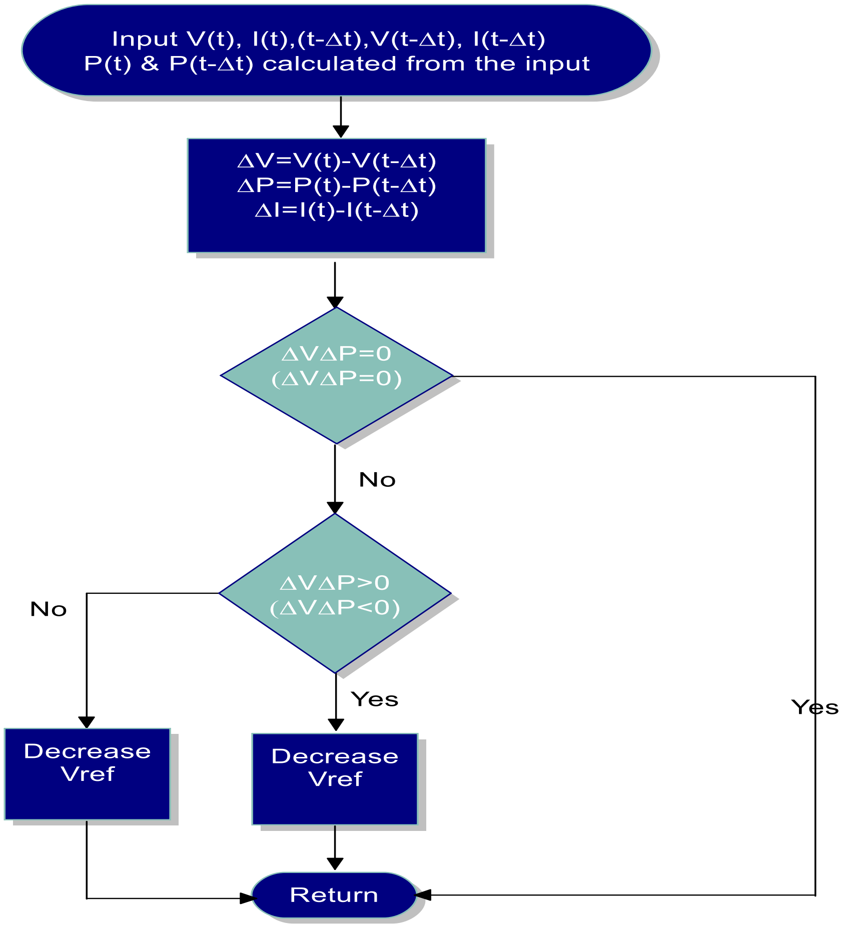

Figure 6: Incremental Conductance Algorithm

In voltage source region $\frac{\partial I_{pv}}{\partial V_{pv}} > -\frac{I_{pv}}{V_{pv}} \rightarrow D = D + \Delta D$ (Increment D)

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

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

The incremental conductance method is explained in detail in chapter 4 for the maximum power point tracking for solar PV energy conversion system. The algorithmic steps are given below:

Algorithmic steps:

Step 1: Sense the two consecutive voltages and current of solar PV

Step 2: Calculate the dI/dV.

Step 3: If dI/dV>0, the operating point is in the left of MPP. Increment the voltage.

Step 4: If dI/dV<0, the operating point is in the right of MPP. Decrement the voltage.

Step 5: Go to step 1.

Another important drawback of the two methods, namely the hill climbing and Perturb and Observe approaches, is related to the sustained steady-state oscillations about the maximum power point (MPP). The aforesaid oscillations occur as a consequence of continuous perturbation applied to the control variable, which is either voltage and/or current, even after reaching the MPP. In this context, the operating point does not remain constant; rather, it starts to fluctuate around the optimal operating spot. The degree of these oscillations depends on the magnitude of the step size used in perturbation. If large step sizes are used, faster tracking to MPP is provided by MPP trackers, but large oscillations will also exist in steady-state operation. Conversely, small step sizes provide less oscillation but result in slow tracking, especially in response to large changes in environmental factors. The disadvantages of existing MPPT devices, which were traditionally used to improve tracking speed, can be summarized by this trade-off.

In order to resolve the aforementioned disadvantages associated with the traditional algorithm, several advanced MPPT techniques have been suggested in recent times with the aim of overcoming variations in irradiance and temperature levels. One method for increasing the accuracy level in an MPPT algorithm is an advanced version of the Perturb and Observe method, denoted by the term "dP-P&O." The proposed method involves an additional power observation in the algorithm while developing an inequality in voltage or current levels. The algorithm makes an accurate observation by employing an analysis at three points in the sampling methodology with the ability to accurately separate power variations resulting from changes in irradiance and temperature levels.

Fuzzy Logic Control

In recent years, fuzzy logic control has attracted global attention owing to its capacity to handle imprecise inputs, function without precise mathematical models, and perform robust control in uncertain or nonlinear situations. Fuzzy logic controllers can efficiently be achieved using just one microprocessor, making them suitable in real-time control applications. The control of fuzzification, inference, or decision-making, and defuzzification are commonly found in the control of fuzzy logic as depicted in Figure 3.4. The membership functions, as shown in Figure 3.5, are defined in terms of various membership functions relating specific inputs or variables to defined sets of linguistic variables, and they usually range between five and seven, depending on control resolution requirements. In Figure 3.4, there are seven linguistic levels, which are utilized in FLC; they are defined as: NB—negative big, NM—negative medium, NS—negative small, ZE—zero, PS—positive small, PM—positive medium, and PB—positive big. The parameters are chosen according to the data distribution, but in certain cases, irregular membership functions are utilized to improve control precision or system performance as depicted in Figure 3.5.

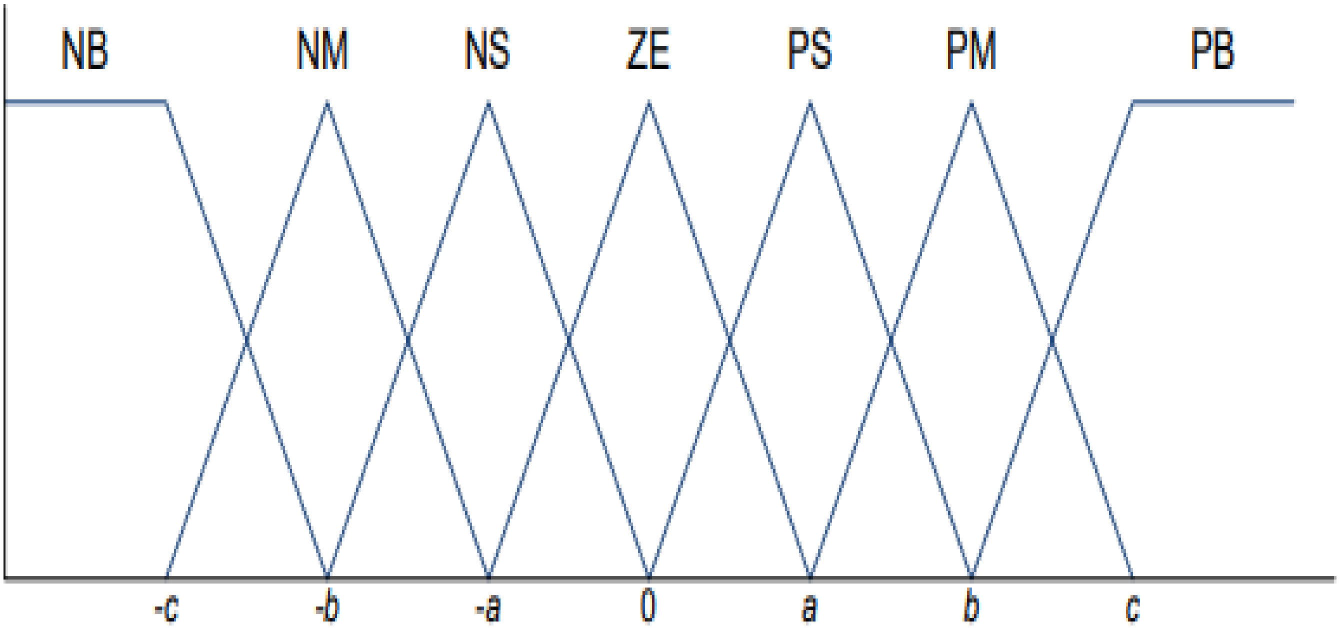

Figure 7: Membership Functions

The fluffy contribution from the regulator is generally an E deficiency, or the flaw transformation is E. The flaw can be chosen by the maker, however by and large chooses it as PV on the grounds that it is zero in MPP. Then, at that point E or E is characterized as follows: In different cases, use PI as the default and think about different data sources, like U and P. The norm, known as fluffy table or fluffy table guideline, relates fluffy yield to fluffy information relying upon the force converter utilized and the information on the client. Table 3.1 shows the standard of a three-stage inverter, whose applications are the I and E characterized in (7) or (8), and whose yield is the variety of the worth of the DC transport V. directly close to MPP, E is NB, E is zero, then, at that point when MPP is reached, the worth should be brought down, so V should be NB (negative) to move the functioning point to MPP.

The final step in mastering fuzzy logic is despair. In this process, the priority is converting the output from a linguistic variable to a digitally defined output. There are many ways to convert language changes to explicit values. Arguably the most popular is the center of gravity process. In addition to incorrect input processing, no need for accurate mathematical models, and inequality processing, these controllers have the advantage of fast speeds and small oscillations around the MPP. In addition, they can make small changes in the measurement channel. However, there is no evidence to suggest that they perform well under the water's edge. Therefore, their performance in testing the effectiveness of MPPT under the conditions described in is unknown[20]. Another disadvantage is that their success depends a lot on the skill of the creator. It is necessary to choose the correct false calculation and present a valid principle.

Table 4: Rule Base

E/dE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS

NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PA	PM	PB	PB	PB	PB

Neural Networks

Another MPPT strategy truly appropriate for microcontrollers is the neural network [8]. They have fluffy rationale and have a place with what is designated "delicate registering." The most straightforward illustration of a neural organization has three layers: an info layer, a secret layer, and a yield layer, as displayed in Figure 3.6. More intricate NN develops add more secret layers. The quantity of layers and hubs in each layer and the activities utilized by each layer will be unique and rely upon the information on the client. The application factors can be various principles, climatic information, or a mix thereof. The yield is generally at least one signs, for example, heading cycles or DC transport input voltage.

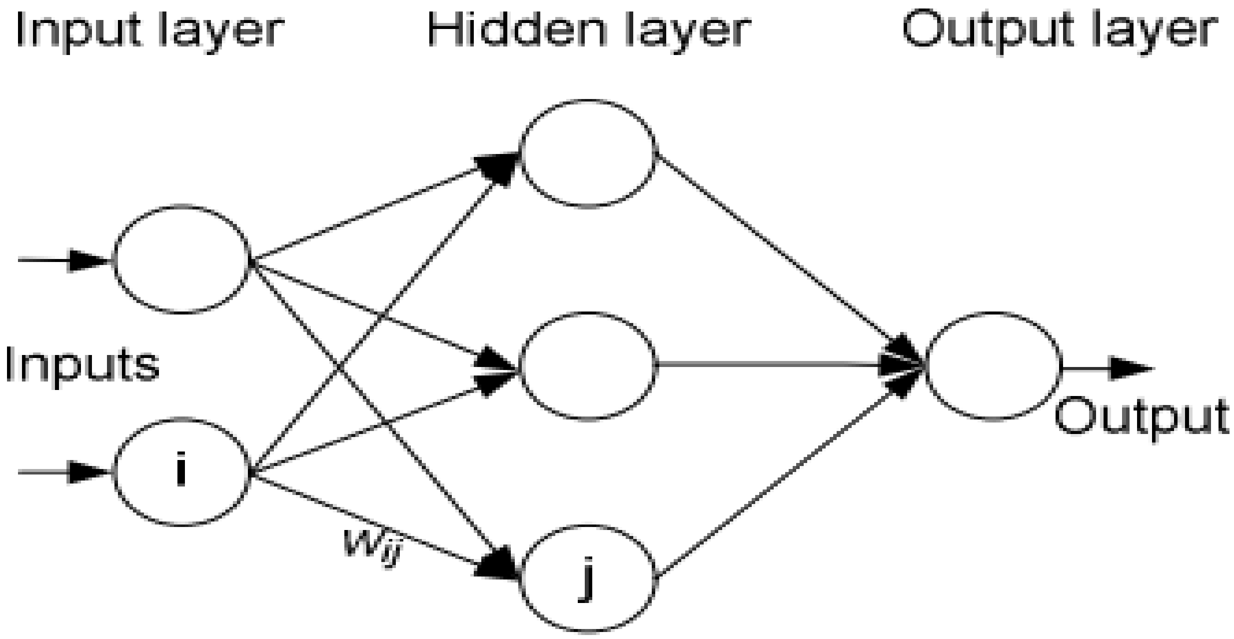

Figure 8: Neural Network

Conclusion and Future Scope

Conclusions

Renewable energy is an alternative source of energy and is becoming more prominent due to its sustainability features. The renewable energy system assumes significance in remote areas due to the infeasibility of conventional power supply in such regions. This thesis proposes a hybrid system of solar and wind energies connected in a Boost converter and controlled by Maximum Power Point Tracking. In order to improve the energy conversion efficacy of the system, MPPT algorithms are utilized to facilitate efficient energy harvesting under changing operating conditions. Perturb and Observe and Incremental Conductance are MPPT algorithms that are utilized to obtain suitable control signals in terms of duty ratio control of the boost converter under changing solar insolation and wind speed fluctuations. Detailed modeling and analysis of solar PV, wind, PMSG, etc., are performed in this article. Based on the simulation results, satisfactory dynamic and steady-state response of the proposed wind/solar energy harvesting system are obtained using the control strategy adopted, i.e., control of the pitch angle, generator-side inverter control, and grid-side inverter control.

In the simulation results obtained for the maximum power, perturb, observation, and incremental conductance-based MPPT algorithm, and THD performance calculated for the both techniques. Perturb and Observe (P&O) and IC MPPT technology is used for the efficient tracking of solar and wind energy and a boost converter is used to remove inverter fluctuations in the conversion of power to AC. A considerable reduction is achieved in THD (82.2% and 80% using P&O and IC technique respectively) as compared to already existing scheme of control with a permanent magnet synchronous generator; the wind power system generates sinusoidal AC power. In order to meet demands, the two energy sources are combined to power the grid.

Future Scope

The future scope of the work is the application of optimization based MPPT techniques for PV, Wind and hybrid power generation systems for extracting and transferring the maximum power from source to load. The project is efficient for continuous electricity generation, but problems of power quality affect the overall systems' performance. The problems related to power quality include voltage sag, voltage swelling, and harmonics, transients, which mainly reduce the quality of solar and wind energy generation.

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