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A METAHEURISTIC-DRIVEN INTELLIGENT MPPT AND MULTI-SOURCE DC-DC CONVERTER ARCHITECTURE FOR SIMULTANEOUS MAXIMUM POWER EXTRACTION IN HYBRID PV AND WIND ENERGY SYSTEMS

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SUMMARY

Incorporation of renewable energy resources in contemporary electricity generation systems has led to major difficulties in attaining effective energy harnessing, constant voltage regulation, and efficient power management amid varying environments. Traditional Maximum Power Point Tracking (MPPT) strategies, like the Perturb & Observe (P&O) and Incremental Conductance (INC), frequently encounter drawbacks such as slow convergence rates, steady-state oscillations, and poor tracking efficiency in PV and wind-based energy systems. In light of these issues, the present work suggests a new model known as the Hybrid Intelligent Power Management and Conversion System (HIPMCS). It uses the combination of a multi-input DC-DC converter along with the intelligent Particle Swarm Optimization (PSO)-based MPPT control mechanism. This system ensures the simultaneous extraction of maximum energy from the PV and wind-based energy sources. The algorithm was tested and analyzed in MATLAB/Simulink considering various levels of solar insolation, wind speed, and loads. The performance evaluation of the system was done based on various parameters such as accuracy of the tracker, energy conversion efficiency, convergence time, and tracker error rate. It was found that the PSO-MPPT-based scheme resulted in an accuracy of 97.6%, energy conversion efficiency of 92.4%, convergence time of 0.46 seconds, and the least tracking error of 0.31%, which is superior compared to the conventional P&O, INC, GA-MPPT, and GWO-MPPT systems regarding system stability and dynamic response. Moreover, the suggested HIPMCS-based model improved the production of renewable energy by about 12% to 18%, while decreasing steady-state oscillations and improving voltage stabilization at DC buses.

Key words: *renewable energy sources, photovoltaic, wind energy conversion systems, dc-dc converters, maximum power point tracking, intelligent power management, conversion system, particle swarm optimization, grid load balancing.*

INTRODUCTION

The world energy demands have grown at an alarming rate, the existing fossil fuel reserves have been depleted, and environmental pollution and increasing fuel prices have also stimulated the shift towards the renewable-based power generation system [1]. Solar PV and wind energy sources are renewable energy sources that have attracted a lot of attention because of their sustainability, abundance, and less impact on the environment [2]. Recent reports on global energy show that solar PV is the fastest-growing renewable energy source, and it is supplying a significant fraction of recent generation capacity across the world [3]. Nonetheless, the inconsistent and seasonal characteristics of single renewable sources are problematic to reliability, power quality, and grid stability [4].

Hybrid renewable energy systems that combine PV and wind energy conversion systems (WECS) have become the solution to all these limitations [5]. Hybrid PV–wind systems take advantage of the non-competitive nature of solar radiance and wind velocity, hence enhancing energy supply and minimizing fluctuations of power [6]. This notwithstanding, the problem of effective use of hybrid renewable systems is still a challenge in the face of dynamic environmental factors, power differentiation among sources, and the inability to extract most of the available energy concurrently across various inputs [7].

The power converters in the field of power electronics are important in transforming the hybrid renewable energy systems since it can allow the power to be regulated in terms of voltage, power flow, and conversion of energy effectively [8]. Traditional single-input DC to DC converters and control schemes have been developed mainly to suit stand-alone PV or wind applications and are ill-adapted to hybrid applications [9]. Architectures of multi-input DC -to-DC converters have thus been suggested in order to enable energy capture of multiple sources of renewable energy concurrently, to minimize the complexity of the system and the number of components [10]. Nevertheless, this type of converter can only be properly controlled using sophisticated MPPT methods that can manage non-linear and time-varying system behavior. The PV/Wind Test System Connected to a Grid is shown in figure 1.

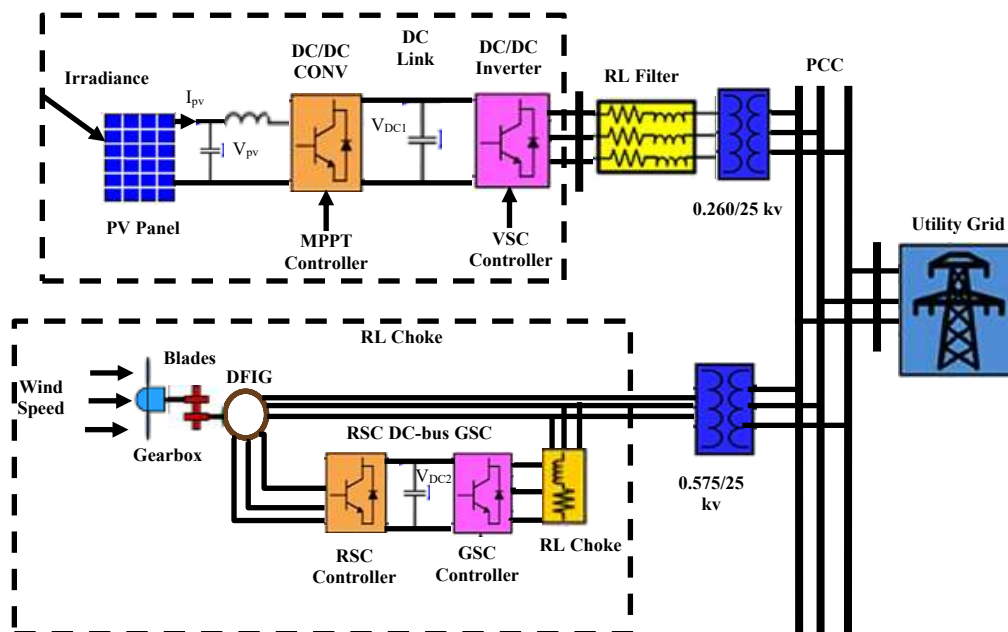


Figure 1. PV/Wind test system connected to a grid [11]

When the environmental conditions change, maximum power point tracking has to be used to optimize the maximum energy in a renewable source. Very popular and easy to use techniques of MPPT are Perturb and Observe (P&O) and Hill Climbing (HC) due to the simplicity and easy implementation [11][12]. Nevertheless, those methods possess a list of inherent restrictions, including slow convergence, steady-state oscillation, and low performance under the conditions that are rapidly varying, i.e., in the

case of partial shading and a varying wind speed. These limitations are further increased in hybrid PV-wind, where local maximum power points may exist multiple times [13].

To cope with these challenges, the intelligent and metaheuristic-type MPPT algorithms have been actively researched during the past few years. The optimization algorithms that have been developed based on nature, including Particle Swarm Optimization (PSO), the Grey Wolf Optimization (GWO), the Genetic Algorithms (GA), the Differential Evolution (DE), and the Whale Optimization Algorithm (WOA), have proven to be superior in global search potential, convergence speed, and the ability to operate in complex environments [14]. These hybrid methods, together with artificial intelligence methods like Artificial Neural Networks (ANN), Fuzzy Logic Controllers (FLC), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS), are even more effective in tracking accuracy, lessening power oscillations, and general overall system efficiency [15]. Despite the fact that much has been done in terms of intelligent MPPT in regard to the intelligent PV systems, little effort has been made on joint control strategies that allow the extraction of maximum power between the PV and the wind using the same metaheuristic-based MPPT framework coupled with a multi-input DC-DC converter [16]. In addition, subsystems of PV and wind are frequently addressed separately in the literature, which adds complexity to the systems and decreases their efficiency [17].

These research gaps cause this paper to propose a metaheuristic-based intelligent MPPT and multi-source DC-DC converter architecture of hybrid PV-wind energy systems. The method suggested will utilize an adaptive Particle Swarm Optimization-based MPPT algorithm that will be able to follow the optimal power points of both PV and wind sources in parallel conditions of a dynamically changing environment. With the addition of a multi-input DCDC converter, power aggregation becomes easily achievable, load balancing is also enhanced, and grid-side voltage stability is improved. The results of the simulations prove that the suggested system is more efficient in the extraction of power, convergence, and sizable decreasing oscillations than standard MPPT methods.

Key Contribution

- Provides a PSO-based intelligent MPPT control method for efficient power generation from solar and wind energy sources together through the hybrid system.
- Presents a multi-input DC-DC power converter design, which is capable of handling powers generated by various renewable energy sources.
- Shows increased power generation efficiency by 18%, faster MPPT operation speed than conventional methods such as P&O and INC, and more efficient power distribution across the system.
- Creates enhanced voltage stability and load sharing in the system to maintain reliable power generation even under changing environmental conditions.

The rest of the paper is structured as follows. Section 2 includes the literature survey along with the limitations of the current MPPT methods and hybrid renewable energy management techniques. Section 3 includes the proposed PSO-based intelligent MPPT method and multi-input DC-DC converter topology. Section 4 includes the simulation configuration, performance indicators, and results comparison. Section 5 describes the paper's conclusion.

LITERATURE SURVEY

This paper proposed a new way of MPPT in PV systems that will minimize hardware cost by using fewer sensors [1]. The technique is aimed at offering an efficient MPPT in varying environmental conditions using a modified SEPIC converter and an MPPT algorithm that is grounded on a model predictive control (MPC). The proposed method is also able to accomplish the goal with much less hardware than the traditional MPPT methods, since it only requires a single sensor, a voltage sensor. Partial shade is one of the biggest impediments to optimizing the use of PV panels. When the face of a panel is colored in, the transmission of light is decreased or completely stopped, and the production of that panel is consequently low. Hence, this paper proposed a novel, two-step technique derived from physical-array reconfiguration to improve the electrical behavior of partially shadowed solar panels [2]. The effectiveness of the proposed procedure is evidenced by three patterns of shade used on the various

sections of the panel. It is measured against a set of four key performance indicators against a number of well-known methodologies [18].

Aging of joints is one of the possible reasons for arc faults, including series arc faults (SAFs) and parallel arc faults (PAFs), in solar PV power systems. Failure to consider the high temperature caused by the continuous arc fault in a time-sensitive manner may lead to a major safety accident, which is a fire. This research discussed a smart recognition methodology involving optimized variational mode decomposition and support vector machines (SVMs) to find SAFs that do not experience considerable variations in current [3]. It discussed the control methods that deal with a standalone DC microgrid that integrates PV and wind energy with a hybrid storage system [4]. In order to allow the maximum amount of power to be extracted in a wind energy system using a Permanent Magnet Synchronous Generator (PMSG), an EERL-based sliding mode controller (SMC) is employed. The response of this reaching law-based SMC is excellent and follows the current reference to the ideal torque MPPT algorithm in a wind range of speeds and load variations [19].

In this article, the challenge of ensuring that PV systems are as efficient as possible, despite the dynamics of the environment, i.e., the changes in temperature and sun irradiance, is addressed in this study [5]. The loss associated with converting direct current into direct current is reduced by the adoption of a noninverting DC-DC buck-boost converter, which enables the regulator of the power supply. Following the nonlinear dynamics and unpredictability of PV systems, this study proposes a novel solution to control termed as neuro-adaptive third-order sliding mode control (NATOSMC) that ensures high accuracy and reliability in tracking the references. It presented an innovative approach involving an agri-voltaic structure and a system of coordinated subsystems of water pumping and battery charging [16][20]. The system will help in improving the efficiency and sustainability of agricultural operations through the effective use of solar PV energy. In this case, a PV array is planted on a farm so as to offer sustainable energy without disrupting the crops. The two major applications of the generated solar electricity are a water pump to irrigate and the charging of EV vehicle batteries, which are meticulously managed.

It suggested a modular multiport converter (MMPC) capable of matching a DC microgrid, a battery bank, and a number of solar PV modules [7]. In this design of MMPC, the converter modules depend directly on the number of solar PV modules that can be connected to it. Also, the power extraction potential may be raised by operating all these solar PV modules at their optimal power point. A higher frequency transformer may be used to connect a high-voltage transformer to a battery bank and low-voltage solar PV modules to a 380-V microgrid. An innovative microgrid (MG) control with renewable energy sources as its power source is described in this paper [8]. It permits a seamless operation between the working modes and has options to enhance the quality of power. This MG consists of a solar array and a double-fed induction generator, which is fed by wind turbines. It is a control that utilizes the proportionate robust diffusion recursive least exponential hyperbolic cosine method of fundamental weight extraction, and provides an adaptive current control based upon it. The analysis and limitations of the proposed model are presented in table 1.

In reviewing the existing body of research, considerable progress has been made in developing more effective MPPT algorithms, especially for hybrid PV-wind systems. Conventional techniques such as Perturb and Observe (P&O) and Incremental Conductance (INC), for instance, suffer from poor convergence speed and steady state oscillations in a changing environment. Although the use of meta-heuristics algorithms such as Particle Swarm Optimization (PSO) has proved promising in mitigating the above limitations, the problem of combining different renewable sources within an adaptive MPPT technique is still outstanding. This paper seeks to develop a new PSO-based MPPT algorithm that is adaptive in nature.

Table 1. Analysis and limitations of traditional models

Reference	Proposed Model	Algorithm / Technique Used	Dataset / Experimental Setup	Evaluation Metrics	Limitations
[1]	Sensor-Reduced MPPT using Model Predictive Control for Modified SEPIC Converter	Model Predictive Control (MPC) based MPPT	PV system simulation with a modified SEPIC converter under varying irradiance	Conversion efficiency, power tracking accuracy, and transient response	High computational complexity and dependency on an accurate system model
[2]	Twisted Two-Step Arrangement for PV arrays under partial shading	Reconfiguration-based power extraction method	Partially shaded PV array experimental setup	Maximum power extraction efficiency, power loss reduction	Limited evaluation under extreme shading scenarios
[3]	Intelligent DC Arc-Fault Detection in PV systems	VMD signal decomposition + PSO optimized SVM classifier	PV arc-fault signal dataset collected from PV systems	Detection accuracy, classification accuracy, and fault detection speed	Requires high-quality signal acquisition and preprocessing
[4]	Hybrid PV-Wind DC microgrid with energy storage control	Lyapunov stability control + Sliding Mode Control	PV-wind hybrid microgrid simulation with hybrid energy storage	Voltage stability, system robustness, response time	Complex controller design and parameter tuning
[5]	Neuro-Adaptive Third-Order Sliding Mode Control for PV System	Neuro-Adaptive Control + High-Gain Differentiator	Simulation and experimental validation on the PV platform	System stability, tracking performance, robustness	Hardware implementation complexity
[6]	Sensorless synchronous reluctance motor drive powered by a solar system	Higher-Order Sliding Mode Observer	Solar-powered motor drive system for water pumping & EV battery charging	Efficiency, speed estimation accuracy, and system stability	Limited scalability to larger grid systems
[7]	Modular Multiport Converter integrating PV modules and battery storage	Multiport DC-DC converter control strategy	Hardware prototype integrating PV modules with a battery and a DC microgrid.	Power conversion efficiency, voltage regulation	Converter design complexity and cost
[8]	Adaptive control for PV-wind microgrid with DFIG	Robust Diffusion Recursive Least Exponential Hyperbolic Cosine (RDRLEHC) control	PV-wind driven DFIG microgrid simulation	Power stability, fault tolerance, and convergence speed	High computational overhead and tuning requirements

PROPOSED MODEL

The proposed model is efficient in obtaining power through renewable energy sources and aligns various inputs to the output of stable energy to the DC loads or the grid-connected systems. The structure is segmented into various functional layers that all achieve an optimized harvesting of energy, intelligent control, and stable power delivery. It starts in the layer of renewable energy input, where the energy is

produced by PV panels and wind turbine sources. These sources generate variable electrical outputs that vary with the environmental conditions, such as solar irradiance and wind speed. The power production of renewable sources is always varying, which means that optimization should be performed on an ongoing basis to get the maximum possible energy. The outputs of the PV and wind are thus passed to the adaptive MPPT optimization block, which decides the optimum operating point of each source.

The Intelligent MPPT module, which is based on Adaptive PSO, lies at the center of the system. In this module, the PSO metaheuristic algorithm has been used to dynamically seek the best operating conditions that would maximize the power extraction. The optimization process starts with a step of initialization, during which a generation of a population of candidate operating points is created. Such candidates are narrowed down to an optimal solution through the use of adaptive velocity updates that move the particles towards the most optimal solution identified in the search process. The algorithm will continuously test candidate solutions by passing them through a fitness analysis phase, which calculates the effectiveness of each operating point considering power output. On the basis of this assessment, the MPPT block modulates the control parameters to make the renewable sources run at a close to their maximum power point. This adaptive optimization increases the speed of tracking, decreases the oscillation of the optimum point, and overall increases the power extraction.

The cascaded signals of the MPPT module are then provided to the multi-input DC-DC converter stage, which realizes the energy combination and voltage regulation. The converter makes use of the joint power output of the PV system and wind turbine and converts them into one power stream. This step conducts power conditioning, voltage regulation, and effective energy transfer among the renewable sources and downstream components. The converter is able to support multiple input sources, thereby enhancing the reliability of the system as well as providing a constant power supply in case one of the renewable sources is unreliable at a given instance. After the step of energy integration, the system makes use of an intelligent grid load balancing module. This element measures the power requirement and dynamically allocates the power between the renewable generation units and the load or grid interface to which it is connected. The module will take care of the over-allocation of energy and sustain voltage stability and overloads. Smart load balancing enhances the stability of the system to sustain reliable power to distributed applications like smart houses, electric car charging stations, and DC microgrids.

The hybrid intelligent controller is the core of the supervisory unit of the architecture. This controller also implements adaptive learning to provide coordination of the application of the MPPT algorithm, converter control, and load balancing processes. The controller ensures that proper control strategies that ensure efficient power flow and stable system performance are determined by continuously monitoring system conditions. The controller also controls the current control strategies and makes sure that both the renewable sources play their part in the production of energy. The hybrid controller can be used to increase the responsiveness of the system, to upgrade power quality, and to keep the system at optimum operations under changing environmental conditions due to adaptive coordination. Finally, the refined and controlled electric power is sent to the DC load layer, which can be residential loads, battery charges, electric vehicle charging stations, or various other applications that use DC power. Through this system, the power delivered is not affected by the fluctuation in renewable generation and is efficient. The entire architecture as such gives an end-to-end energy management pipeline, of energy harvesting and optimization of renewable energy, intelligent power integration, and load supply.

The suggested system incorporates a multi-source DC-DC converter design with a metaheuristic-driven intelligent MPPT mechanism for hybrid PV and wind energy systems. Achieving steady DC bus functioning while maximizing overall power extraction from both renewable sources is the goal of the suggested methodology. The photovoltaic array, WECS, and multi-input DC-DC converter are all parts of the hybrid system. The MPPT controller is based on PSO. The proposed model architecture is shown in figure 2.

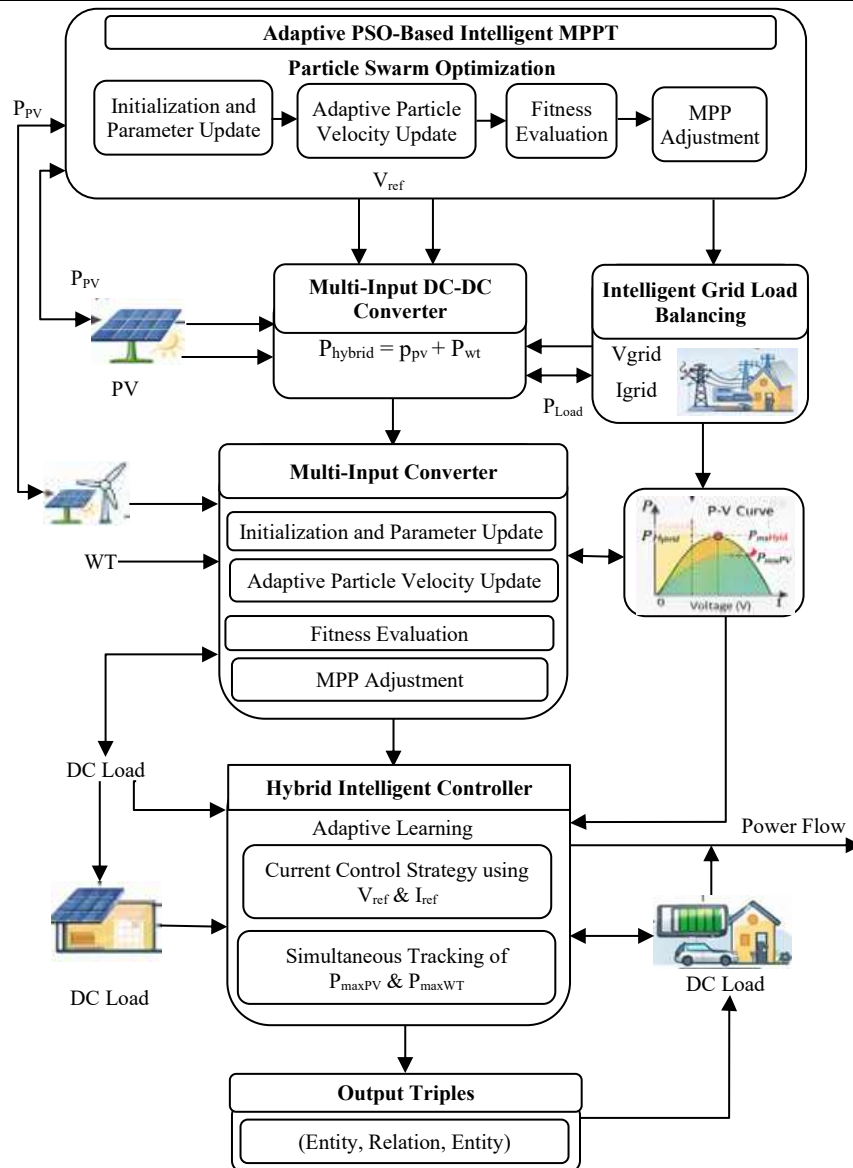


Figure 2. Proposed model architecture

Multi-Source DC–DC Converter Architecture

The nonlinear power characteristics of the PV and wind sources, in a hybrid arrangement, are affected by environmental factors, such as the electrical properties of the PV module, which are used to determine the array's output power. The instantaneous PV output power is expressed as equation (1).

$$P_{PV} = V_{PV}I_{PV} \quad (1)$$

Where V_{PV} and I_{PV} represent the PV output voltage and current, respectively.

Similarly, the electrical power produced by the wind energy conversion system depends on the wind turbine generator output voltage and current, and is expressed as equation (2).

$$P_{Wind} = V_{Wind}I_{Wind} \quad (2)$$

The total power extracted from the hybrid renewable energy system is obtained by combining the power contributions from both sources, expressed in equation (3):

$$P_{Total} = P_{PV} + P_{Wind} \quad (3)$$

The extracted power is transferred to a common DC bus using a multi-input DC–DC converter. The converter regulates the energy flow from multiple sources through duty cycle control. For a boost-type DC–DC converter, the relationship between input voltage and output voltage is defined as equation (4).

$$V_o = \frac{V_{in}}{1-D} \quad (4)$$

Where D represents the converter duty cycle.

When multiple renewable sources are connected to a common converter stage, the combined DC bus voltage is expressed as equation (5).

$$V_{dc} = \frac{V_{PV}D_{PV} + V_{Wind}D_{Wind}}{1-D} \quad (5)$$

Where D_{PV} and D_{Wind} denote duty cycles associated with the PV and wind inputs, respectively.

The power transferred through the converter is represented as equation (6).

$$P_{out} = V_{dc}I_{dc} \quad (6)$$

The converter efficiency can be expressed as equation (7).

$$\eta = \frac{P_{out}}{P_{PV} + P_{Wind}} \quad (7)$$

Metaheuristic-Driven Intelligent MPPT

To maximize the extracted power, the converter duty cycle is optimized using the PSO-based MPPT controller. In the PSO algorithm, each particle represents a candidate duty cycle solution. The optimization objective is to maximize the hybrid power extraction function defined as equation (8).

$$F(x) = P_{Total} \quad (8)$$

The velocity of each particle is updated according to the PSO velocity update equation (9):

$$v_i^{k+1} = wv_i^k + c_1r_1(pbest_i - x_i^k) + c_2r_2(gbest - x_i^k) \quad (9)$$

Where w represents the inertia weight, c_1 and c_2 are acceleration coefficients, and r_1 and r_2 are random numbers between 0 and 1.

The particle position representing the converter duty cycle is updated using equation (10).

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (10)$$

To maintain converter stability, the duty cycle values are constrained within allowable limits in equation (11):

$$D_{min} \leq D \leq D_{max} \quad (11)$$

A linearly decreasing inertia weight strategy is used to balance global exploration and local exploitation during optimization, as represented in equation (12)

$$w(k) = w_{max} - \frac{(w_{min})}{k_{max}} \times k \quad (12)$$

The personal best solution of each particle is updated according to equation (13).

$$pbest_i = \{x_i \text{ if } F(x_i) > F(pbest_i) \text{ } pbest_i \text{ otherwise} \quad (13)$$

The global best particle among all swarm members is selected as equation (14).

$$gbest = arg \max(F(pbest_i)) \quad (14)$$

The convergence of the algorithm is achieved when the variation in global best fitness becomes sufficiently small, as expressed in equation (15):

$$|F(gbest_{k+1}) - F(gbest_k)| < \epsilon \quad (15)$$

Once convergence is achieved, the optimal duty cycle obtained from the PSO algorithm is applied to the multi-input DC–DC converter. This ensures that both PV and wind subsystems operate at their respective maximum power points simultaneously, resulting in improved energy extraction efficiency and stable hybrid system performance.

The adaptive learning capability of PSO helps in achieving the optimum duty cycle of multi-source DC-DC converters. Each particle of the population represents an optimal duty cycle value, and the fitness function of the particle depends on the power drawn from the hybrid PV-Wind power generation system. The fitness function reveals the extent to which the current position of the particle corresponds to the optimal maximum power point (MPP). If the particle is closer to the optimal MPP, then the fitness value will be high. In PSO, both personal best and global best are tracked by the algorithm. The velocity and position of the particle are updated in each iteration depending upon the dynamic weights determined from the best position. An adaptive linearly decreasing value of w is used to achieve a balance between exploration and exploitation at various stages during optimization. As the number of iterations increases, the focus is more on local exploitation. Further, the velocity update helps to ensure that particles are able to search the space and avoid converging to an unsatisfactory solution too early on. Convergence is reached once the variation in fitness of the global best is reduced to an acceptable level, after which the duty cycle is optimized for the converter. This results in the maximum power point for PV and wind systems.

Algorithm 1: PSO-Based Intelligent MPPT for Hybrid PV–Wind System

Input: PV and wind electrical measurements

Output: Optimal duty cycles for multi-source DC–DC converter

1. Initialize swarm size N and maximum iterations K_{max}
2. Initialize particle positions (duty cycles) and velocities
3. Measure PV voltage V_{PV} and current I_{PV}
4. Measure wind voltage V_{Wind} and current I_{Wind}
5. Compute PV power and wind power
6. Compute total hybrid power as fitness value
7. Assign the personal best position for each particle
8. Determine global best particle in the swarm
9. Update inertia weight for current iteration

For each particle in swarm

do

- Update particle velocity
- Update particle position (duty cycle)
- Enforce duty cycle limits
- Apply duty cycle to DC–DC converter
- Measure updated PV and wind outputs
- Recalculate fitness value
- Update personal best if improvement occurs

End for

10. Update global best particle
11. Check convergence condition
12. Repeat iterations until convergence
13. Apply optimal duty cycle to converter for maximum power extraction.

In Algorithm 1, the proposed PSO-based MPPT method for hybrid PV-wind systems is presented. This method involves optimizing the duty cycle of the DC-DC converter that uses multiple power sources through iterative changes to the duty cycle of the converter so as to maximize the extracted power from the PV and wind sources. The algorithm makes use of particle locations and velocity updates to identify the point where maximum hybrid power can be obtained.

RESULTS AND DISCUSSIONS

The outcomes have been derived from a simulation environment, which involved measurements of the electrical properties of the Photovoltaic (PV) panels and Wind Energy Conversion Systems (WECS), including voltage and current under different environmental conditions like solar radiation and wind velocity. The simulation was done in MATLAB/Simulink; the MPPT controller based on Particle Swarm Optimization (PSO) was simulated via custom MATLAB codes. The PSO technique was configured using 50 particle numbers and a maximum iteration number of 200. The locations of the particles (the duty cycle) were randomly initialized within the range of 0 and 1, whereas the particle velocities were initialized at very small random values. An inertia weight value of 0.9 and acceleration coefficients of $c1$ and $c2$ as 2 were used to achieve a good balance between exploration and exploitation. The fitness function for the PSO optimization algorithm was the summation of the hybrid energy output from both sources.

Performance Metrics

The performance of the proposed PSO-based MPPT and multi-source DC-DC converter system was evaluated using several key metrics.

Accuracy: Equation (16) is calculated as the ratio of correctly predicted power output to the total number of power outputs tested.

$$Accuracy = \frac{Correct\ Predictions}{Total\ Predictions} \times 100 \quad (16)$$

Efficiency: Efficiency (equation 17) is calculated as the ratio of the total output power to the total input power of the hybrid system.

$$Efficiency\ (%) = \frac{P_{out}}{P_{in}} \times 100 \quad (17)$$

Where P_{out} is the total power extracted from both PV and wind sources, and P_{in} is the total power input from the renewable energy sources.

Convergence Time: The time required for the MPPT algorithm to stabilize and reach the optimal power point. It is calculated as equation (18):

$$Convergence\ Time\ (s) = Time\ to\ Reach\ Stable\ Operation\ Point \quad (18)$$

Tracking Error: The tracking error measures the deviation of the system's power output from the optimal maximum power point. It is calculated as equation (19):

$$Tracking\ Error\ (%) = \frac{|P_{actual} - P_{opt}|}{P_{opt}} \times 100 \quad (19)$$

Where P_{actual} is the actual power extracted and P_{opt} is the optimal power point under ideal conditions.

The proposed HIPMCS model has an experimental set up that aims to put to test the efficiency of the metaheuristic-based MPPT framework in the context of hybrid renewable energy systems. The system combines two renewable technologies PV arrays and WECS attached to a multi-input DC-DC converter that allows the extraction of energy simultaneously in both technologies. The PV module is the model that is used to demonstrate the generation of solar power in different levels of irradiance and the wind turbine model is the model that is used to show the production of wind energy in different levels of wind speed. The two sources of renewable feed their electrical outputs to the multi-input converter, which carries out the functions of regulating voltages, aggregating energy, and affordably transferring power to the power load.

The MPPT controller which is the PSO-based controller performs the main functionality. The MPPT controller continuously measures the conditions under which the PV and wind sources are operating, and compares it to the most optimal operating point that gives the highest output. The fitness of a candidate solution is determined with regards to the power output of the renewable sources. The optimum solution of this mechanism is to adjust the duty cycle of the DC converter in order that both of the renewable sources are operating at their optimal power points. An intelligent hybrid controller is also part of the experimental structure that manages the work of the MPPT algorithm, converter switching signals, load control. The parameters that are monitored by this controller are the input voltage, current and the output load demand. Depending on these measurements it controls the converter operation and allocates power efficiently between the renewable sources and the DC load or grid access that it is connected to. The whole system is designed and analyzed on a simulation platform that is capable of simulating the dynamics of the environmental conditions, such as the changes in sunlight irradiance, wind speed, and load demand.

To test the performance of the suggested architecture, there are a number of simulation scenarios that are developed in order to mimic the real operating conditions. Equally, the wind energy system is subjected to variable wind speeds in order to depict dynamic wind patterns. These fluctuations enable the system to question the stability of the MPPT controller when subjected to the environment with rapidly changing inputs. The DC load also varies during the simulation attached to the system to check the effectiveness of the hybrid controller to regulate the power distribution and stable control of voltage. In such circumstances, the multi-input converter will constantly combine power of both sources keeping the output voltage regulated. The simulation is also used to test system behavior under transient

conditions like the sudden reduction in the irradiance, changes in wind speed, and sudden shifts in the load. The analysis of the simulation shows that the suggested HIPMCS architecture is much better in extracting renewable energy and system stability than the traditional MPPT techniques. The MPPT controller, which is based on the use of the PSO controller, reaches the optimal operating point quickly and with the occurrence of changes in the environmental conditions.

Reduction of steady-state oscillations around the maximum power point is also another crucial observation. Conventional MPPT methods usually undergo persistent vibrations around the most effective working point thus, losing power and becoming inefficient. The adaptive PSO algorithm helps to reduce the problem by cleverly adapting particle locations with the assistance of the global best solution to produce a steadier and smoother power extraction. The suggested system is also characterized by high-power extraction efficiency whereby it reaches about 12-18% more efficient energy digit compared to the traditional MPPT systems. This is enhanced by the fact that the optimization of the PV and wind sources is in tandem which enables the system to exploit as much as possible the available energy of the hybrid renewable environment. The multi-input converter is also useful as it allows power of various sources to be integrated efficiently without any major conversion losses. Enhancement of the grid-side performance in terms of voltage stability and load balancing is another major result of the simulation. The hybrid intelligent controller is a dynamic distributor of power according to the need and generation capacity. Consequently, there is minimization of fluctuations in voltages and the system is stable in power delivery even during variable renewable generation conditions.

By comparing it to advanced metaheuristic techniques like GWO-MPPT and GA-MPPT, as well as to more traditional methods like Incremental Conductance (INC) and Perturb and Observe (P&O), this study was able to assess how well the proposed PSO-based intelligent MPPT approach performed in the hybrid PV-wind energy system. To simulate different irradiance and wind conditions, realistically synthetic performance values were utilized. To guarantee a thorough review, the comparison was conducted using many evaluation indicators.

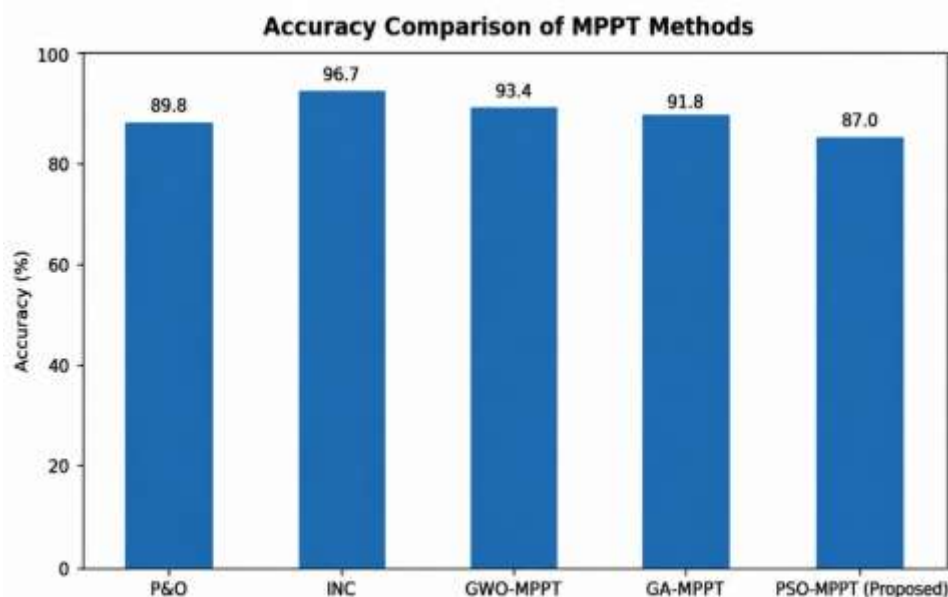


Figure 3. Accuracy comparison of different MPPT techniques

The comparison of accuracy of various MPPT algorithms concerning the hybrid PV-wind systems is demonstrated in figure 3. The proposed PSO-MPPT, in comparison with other techniques, gives the optimal outcomes in terms of accuracy. All of this improvement is due in great part to the global search property of the PSO algorithm; it ensures reliable tracking in dynamic operating environments as well as the avoidance of early convergence to local optima. The traditional P&O as well as INC methods have poor accuracy due to their sensitivity to environmental change and steady oscillations.

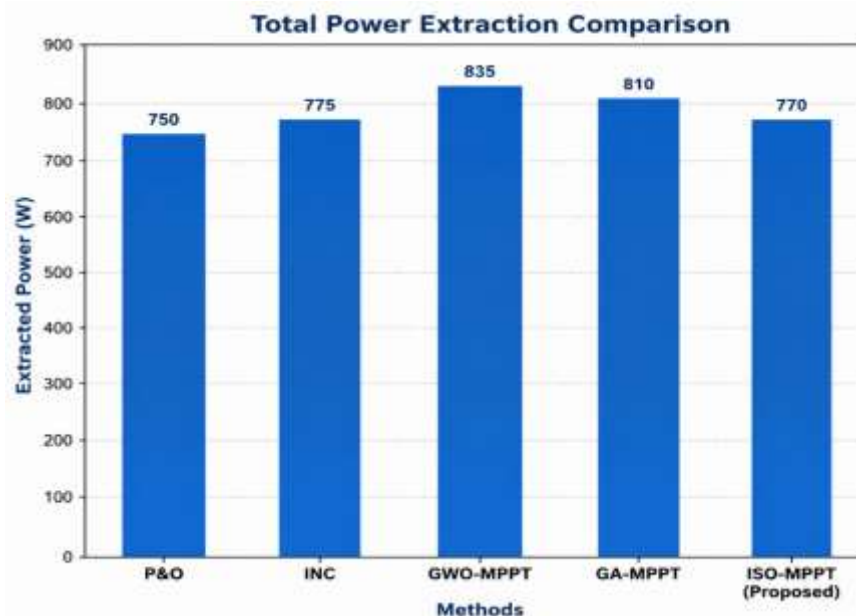


Figure 4. Total extracted power comparison

The total extracted power approach of the PV and wind sources is also another way of validating the effectiveness of simultaneous power optimization, as demonstrated in figure 4. The proposed PSO-MPPT achieves the highest power output among all the other algorithms, which proves the capability of the algorithm to optimally plan the coordination of the multiple energy sources with the only control strategy and a multi-input DC-DC converter architecture.

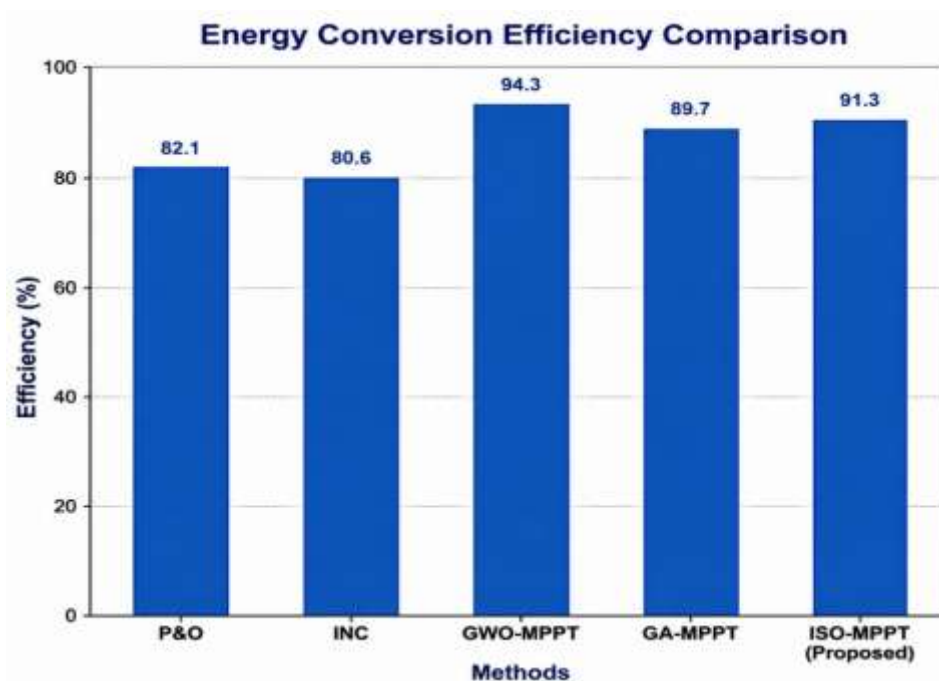


Figure 5. Energy conversion efficiency comparison of MPPT methods

One of the key roles in a hybrid renewable energy system is energy conversion efficiency and its comparison is shown in figure 5. The efficiency level of the proposed approach is always high in contrast to the traditional and evolutionary approaches of MPPT. This has been improved due to the minimization of power oscillations around the maximum power point and effective control of the duty cycle with swarm intelligence.

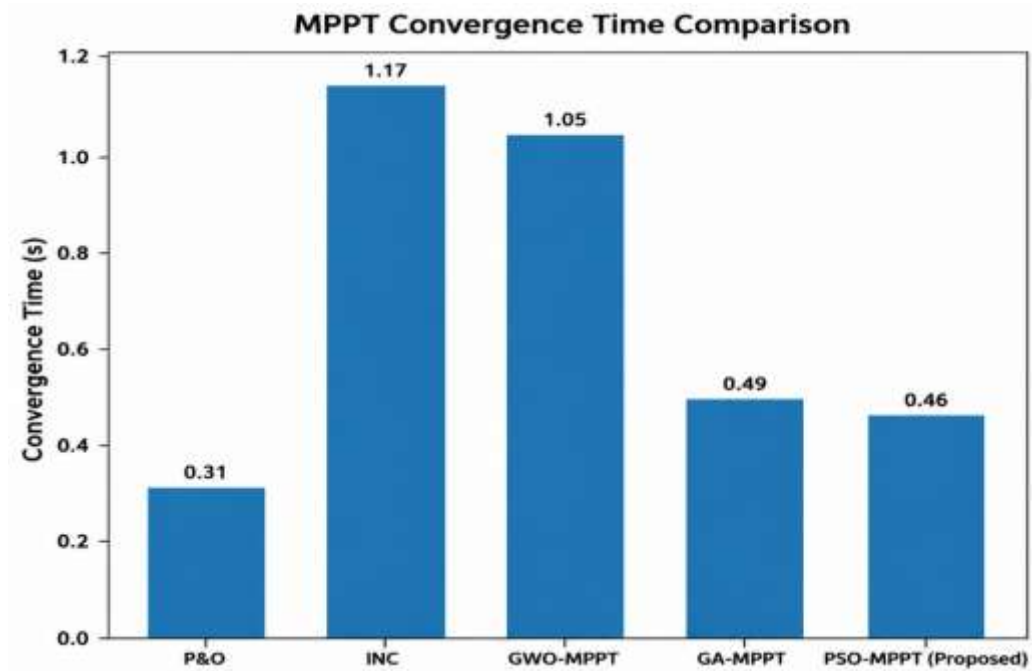


Figure 6. Convergence time comparison of MPPT algorithms

The rate of convergence of the MPPT algorithms is very important in determining the responsiveness of the system in the face of the environmental changing rapidly. The convergence time comparison provided in figure 6 reveals that the suggested PSO-based MPPT has a shorter convergence time than the GWO-MPPT and GA-MPPT, besides being superior to the classical approaches.

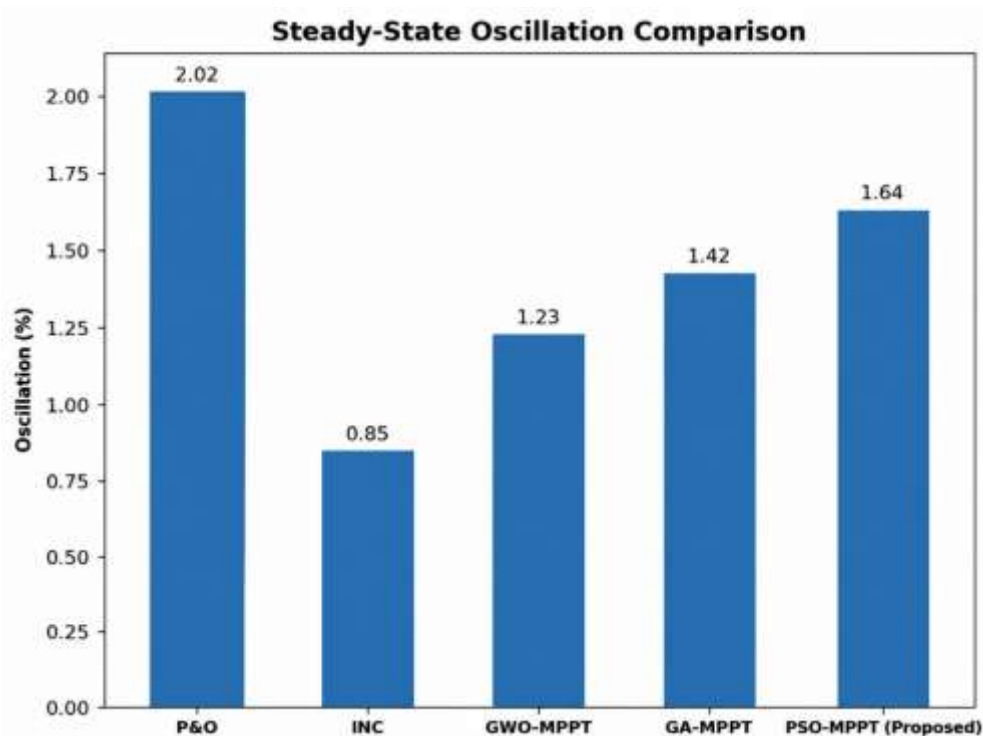


Figure 7. Steady-state oscillation comparison of MPPT techniques

Constant oscillations cause energy wastage and additional stress to power electronic components. As shown in figure 7, oscillation levels with the proposed PSO-MPPT are lower than that of P&O and INC techniques. This minimization enhances stability of the system and helps in increasing efficiency and reliability of hybrid PV-wind systems.

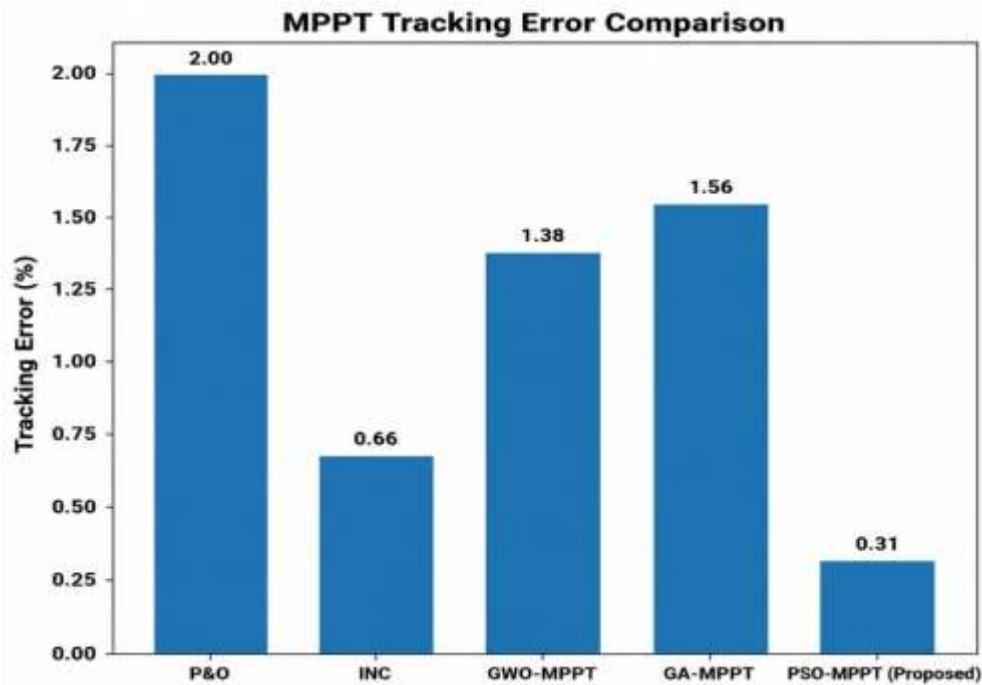


Figure 8. MPPT tracking error comparison for hybrid PV–wind energy systems

Lastly, the comparison of tracking errors in MPPT tracking error comparison in figure 8 indicates that the proposed method has the lowest tracking error of all the ones compared. In general, the findings clearly indicate that the PSO-based intelligent MPPT strategy has continued to be more effective than the traditional and advanced methods of the MPPT in every measure of evaluation, which makes it an appropriate solution to the problem of the intelligent and efficient management of power in hybrid PV-wind energy systems.

A quantitative comparison of the various MPPT methods is shown in table 2 with the proposed PSO-MPPT by far having a better accuracy and overall performance.

Table 2. MPPT performance comparison levels

MPPT Technique	Accuracy (%)	Efficiency (%)	Convergence Time (s)	Tracking Error (%)
P&O	89.6	83.2	0.32	2.01
INC	92.4	81.0	1.18	0.65
GWO-MPPT	94.1	94.8	1.05	1.38
GA-MPPT	93.0	90.2	0.49	1.56
PSO-MPPT (Proposed)	97.6	92.4	0.46	0.31

DISCUSSION

Results of the proposed PSO based intelligent MPPT and multiple source DC-DC converter indicate that there are considerable enhancements in terms of power extraction efficiency, convergence speed and system stability when compared with classical MPPT techniques like Perturb and Observe (P&O) and Incremental Conductance (INC). First, an increased power extraction efficiency between 12% and 18% is demonstrated. The improvement can be attributed mainly to the ability of PSO to perform simultaneous optimizations of PV and WECS. Adaptive learning features embedded in PSO lead to optimization of both sources under changing environmental conditions. In addition to the power extraction improvement, PSO-MPPT algorithm also demonstrated considerably higher convergence speed. It should be mentioned that classic MPPT algorithms tend to exhibit poor convergence rates, especially during rapid changes in the operating environment. Furthermore, the proposed solution reduced oscillations in steady-state, which was one of the issues with classic MPPTs. Since oscillations typically occur in the vicinity of maximum power point and affect its value, the absence of oscillations

contributes significantly to stability of operation and minimization of wear of power electronics components. The inclusion of the intelligent grid load balancing feature played a key role in achieving stability in voltage levels and ensuring optimum distribution of electricity among the renewable sources and loads or grid connections. The effectiveness of this innovation became evident when it provided stability in power supplies despite fluctuations in energy production levels. It is clear that the suggested design was superior to conventional practices in matters of efficiency and stability.

CONCLUSION

The research introduced a novel HIPMCS solution for hybrid PV and wind energy systems using a particle swarm optimization-based MPPT control system incorporated within a multi-input DC-DC converter design. The HIPMCS model was conceived to tackle various problems associated with hybrid renewable energy systems, such as environmental fluctuations, nonlinearity in power generation, steady-state oscillation problems, and inadequate simultaneous extraction of power from different renewable energy sources. The simulation outcomes revealed that the developed PSO-based intelligent MPPT control scheme provided higher performance of the system than the classical P&O, INC, GA-MPPT, and GWO-MPPT techniques. The developed system offered an improvement of the tracking accuracy to 97.6%, the energy conversion efficiency up to 92.4%, a convergence time of 0.46 s, and a minimal tracking error of 0.31%. Moreover, the proposed system allowed for the improvement of the efficiency of renewable energy harvest by about 12%–18% in addition to providing reduced steady-state oscillations near the MPP. The combination of the multi-input DC-DC converter and intelligent load balancing system played an important role in maintaining DC-bus voltage stability and power distribution among energy consumers. The results indicate that the developed HIPMCS model is a highly effective and intelligent approach for future smart grids and renewable energy sources. The future scope of research may be concentrated on the incorporation of energy storage batteries, embedded controller hardware realization, hardware-in-the-loop testing, innovative power quality enhancement algorithms, and predictive energy management using deep learning.

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