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Optimizing MPPT Extraction in Hybrid Energy Systems Using an Adaptive PSO Topology

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ABSTRACT- In both solar and wind energy systems, Maximum Power Point Tracking (MPPT) plays a crucial role in maximizing energy extraction and optimizing overall system efficiency. The concept of MPPT revolves around continuously adjusting the operating conditions of the renewable energy source to ensure that it operates at its MPP under varying environmental conditions. In solar photovoltaic (PV) systems, MPPT is essential due to the non-linear relationship between the voltage and current output of solar panels. This non-linearity arises from factors such as temperature variations, shading, and changes in solar irradiance levels throughout the day. Without proper MPPT control, solar panels may operate below their MPP, leading to significant energy losses. MPPT algorithms play a pivotal role in optimizing the efficiency of photovoltaic (PV) systems by continuously tracking and extracting maximum power from the solar panels. Among various MPPT techniques, Particle Swarm Optimization (PSO) has emerged as a promising approach due to its simplicity and effectiveness in dealing with the nonlinear and dynamic nature of PV systems. Similarly, in wind energy systems, MPPT is critical for maximizing power generation from wind turbines. Wind speed variations, turbulence, and changes in wind direction can cause fluctuations in the output power of wind turbines. Particle Swarm Optimization (PSO) topology adjusts the rotor speed or blade pitch angle to ensure that the turbine operates at its optimal rotational speed, thereby extracting the maximum available wind energy.

Keywords: MPP, PID, PSO, Solar Energy, wind energy.

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1. INTRODUCTION

Renewable energy encompasses a variety of natural resources that can regenerate much faster than conventional fossil fuels, often within the span of a human lifetime or less. These resources provide a viable and sustainable option compared to traditional methods of energy production, playing a vital role in addressing climate change, lowering greenhouse gas emissions, and enhancing energy self-sufficiency. Offering an eco-friendly solution to the reliance on fossil fuels, renewable energy contributes to diminishing carbon footprints, fighting global warming, and fostering both energy security and economic growth. The path to a widespread adoption of renewable energy globally hinges on continuous technological innovation, supportive policies, and increased financial investments[1].

Renewable energy sources are notable for their minimal to non-existent greenhouse gas emissions during the production of electricity, setting them apart from the pollution-intensive fossil fuels. Transitioning from fossil fuel-based energy to renewable sources is a key strategy in combating climate change and diminishing air pollution. This shift not only mitigates environmental damage but also lessens dependence on imported fuels, thereby increasing energy security and insulating economies from the instability and price volatility of international energy markets. Beyond their lower carbon footprint, renewable energy technologies exert significantly less impact on the environment in comparison to their fossil fuel counterparts. They play a vital role in preserving natural resources, safeguarding ecosystems, and curtailing water use, particularly evident in hydroelectric and solar photovoltaic systems. Moreover, renewable energy is pivotal in fulfilling several Sustainable Development Goals (SDGs), encompassing climate action, access to affordable and clean energy, the promotion of sustainable urban and community development, and the encouragement of responsible consumption and production patterns[2].

MPPT algorithms enable renewable energy systems to operate at their maximum power point (MPP) under varying environmental conditions. By continuously adjusting the

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operating parameters, such as the voltage or rotor speed, MPPT ensures that the system extracts the maximum available power from the renewable energy source, maximizing energy output and improving overall system efficiency. MPPT extraction minimizes energy losses by optimizing the energy conversion process. In solar photovoltaic (PV) systems, for example, MPPT ensures that the PV panels operate at their peak efficiency by matching the output voltage and current to the MPP, thus reducing unnecessary energy dissipation and improving overall conversion efficiency[3].

Renewable energy systems are subject to fluctuations in environmental conditions such as sunlight intensity, wind speed, and temperature. MPPT algorithms dynamically adjust system parameters in response to these changes, ensuring optimal performance and maintaining stable operation even under varying environmental conditions. By maximizing energy output and optimizing system operation, MPPT extraction helps enhance the reliability and longevity of renewable energy systems. By operating closer to their MPP, renewable energy components experience less stress and operate more efficiently, reducing the risk of component failure and downtime. MPPT extraction can lead to cost savings by improving the overall efficiency of renewable energy systems and reducing the need for oversized components. By maximizing energy output, MPPT allows for the use of smaller, more cost-effective components while still achieving the desired energy production targets, thereby lowering the overall system costs[4].

1.1. Solar and wind integration

Integrating solar and wind sources for MPPT extraction involves optimizing the harnessing of energy from these renewable sources to achieve maximum efficiency. MPPT techniques are crucial because both solar irradiance and wind speed vary throughout the day and with weather conditions, affecting the power output of photovoltaic (PV) panels and wind turbines[5].

Integrated solar and wind energy systems can significantly improve the efficiency and reliability of renewable energy production, contributing to a more sustainable energy future. Combining solar and wind energy systems can provide more consistent power output, as the availability of sunlight and wind can complement each other. For instance, wind speeds are often higher during periods when there is less sunlight and vice versa[6].

An integrated system requires a coordinated control strategy that considers the input from both solar and wind components. Advanced algorithms can dynamically allocate resources between the two systems to optimize overall energy production. Integrating energy storage solutions, such as batteries, can help manage the intermittent nature of solar and wind energy. MPPT techniques must be applied in a way that also considers the charging and discharging cycles of the storage system to maintain energy availability and prolong battery life[7].

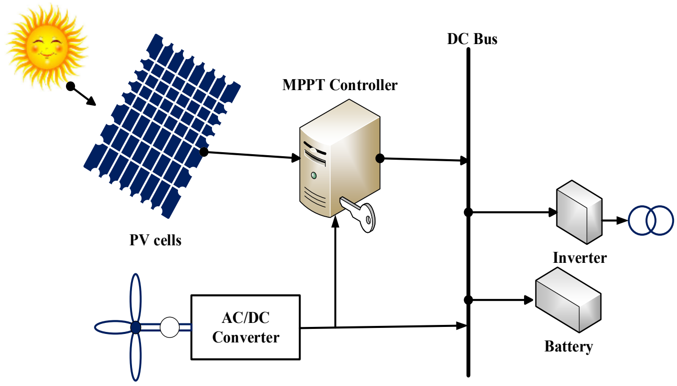

Figure 1. Integration of solar and wind energy systems

Figure 1 illustrates a schematic diagram detailing a hybrid solar and wind power generation system. Below is a breakdown of the components and the operational mechanism of the system[8]:

- **PV Cells**: These are solar panels that convert sunlight directly into direct current (DC) electricity[9].
- **Wind Turbine**: Represented by the windmill icon, it captures wind energy and converts it into DC electricity. In this diagram, it's implied that the wind turbine is connected to an AC/DC converter, though it's not explicitly shown[10].
- **AC/DC Converter**: This device converts the alternating current (AC) electricity generated by the wind turbine into DC electricity so it can be used by the system or stored in the battery. The converter might also condition the power to ensure it's at the right voltage and current for the system[11].
- **MPPT Controller**: This Maximum Power Point Tracking controller is connected to the solar panels. It optimizes the power output from the PV cells, ensuring they operate at their maximum power point to extract the most energy possible under varying light conditions[12].
- **DC Bus:** This is a common electrical bus that collects DC power from both the PV cells and the wind turbine (via the AC/DC converter). It serves as the central point for distributing power to the inverter and battery[13].
- **Inverter**: This device converts DC power from the DC bus into AC power that can be used by standard electrical devices or fed into an electrical grid[14].
- **Battery:** The battery stores excess DC power for use when the solar and wind energy sources are not producing power, such as during the night or when there is no wind[15].

This setup allows for the harnessing of both solar and wind energy, which can increase the reliability and consistency of the power supply since solar and wind resources are often complementary. The system can provide power in off-grid situations or act as a supplemental power source to reduce reliance on the grid. The inclusion of a battery allows the system to provide power even when neither renewable resource is available[16].

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2. PROPOSED METHODOLOGY

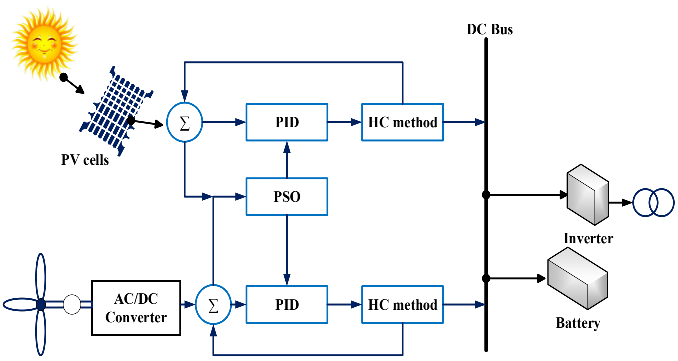

Figure 2. Block diagram of proposed topology

Figure 2 shows a more advanced control system for a hybrid solar and wind power generation system with an emphasis on control and optimization strategies. This diagram introduces additional layers of control algorithms to maximize the efficiency of the energy conversion process. The diagram illustrates a sophisticated system that uses advanced control and optimization techniques (PID controllers and PSO) to adjust the operation of the solar and wind energy components. These adjustments ensure that the system operates efficiently, reliably, and with minimal human intervention. The use of the HC method likely indicates that the system is continuously seeking to improve its operation by finding better settings for the PID controllers, possibly in real-time. This type of system is designed to maximize energy harvest from the available renewable resources[17].

The PID controller serves as a prevalent feedback mechanism in industrial control systems, aiming to maintain the desired set point by adjusting system control inputs. Within this framework, PID controllers regulate the power output from both solar and wind sources. PSO is an optimization algorithm that uses the social behaviour of fish schools and bird flocks to automatically adjust the PID controllers' parameters. Its goal is to find the optimal setting that maximizes power output or achieves other system performance objectives. The HC Method, likely referring to the Hill Climbing Method, is a mathematical optimization technique used to find the maximum or minimum of an objective function by iteratively moving towards increasing or decreasing values. In this context, it would be employed to further optimize the performance of the PID controllers[18].

2.1. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a strategy for problem-solving that seeks to enhance a potential solution iteratively, with the goal of meeting a specific quality standard. This technique involves a collection of possible solutions, termed particles, which traverse a defined search-space governed by straightforward mathematical rules that dictate their movement and speed. The direction in which each particle moves is determined by the best position it has discovered on its own, as well as by the most advantageous positions identified within the search-space by its peers. As these optimal positions are dynamically updated when other particles find improved solutions, the entire group of particles, or swarm, is steered towards the optimal solutions. In the context of MPPT (Maximum Power Point Tracking) for solar and wind energy systems, PSO can be used to dynamically adjust the operating points of the system to ensure that it always generates the maximum power output, despite changing environmental conditions[19].

2.2. How PSO is applied in MPPT[20]

- ***Step 1* Initialization**: A swarm of particles is initialized with random positions and velocities. Each particle represents a possible solution to the MPPT problem, which in this case is a specific operating point of the system[21].
- ***Step 2* Evaluation**: Each particle's fitness is evaluated based on how close its corresponding operating point is to the maximum power point[22].
- ***Step 3* Update Personal Best**: If the current position of a particle is better than its previous best position (in terms of power output), this position is saved as the new personal best[23].
- ***Step 4* Update Global Best**: The best position found by any particle in the swarm is saved as the global best[24].
- ***Step 5* Velocity and Position Update**: Each particle's velocity is adapted according to its individual experience (personal best) and the collective experience of the swarm (global best). Subsequently, the position of each particle is updated according to its revised velocity. This process comprises a blend of deterministic and stochastic elements[25].
- ***Step 6* Iteration**: Steps 2-5 are iterated until a termination criterion is satisfied, such as reaching a maximum number of iterations or attaining a satisfactory power output level.
- ***Step 7:*** satisfy termination

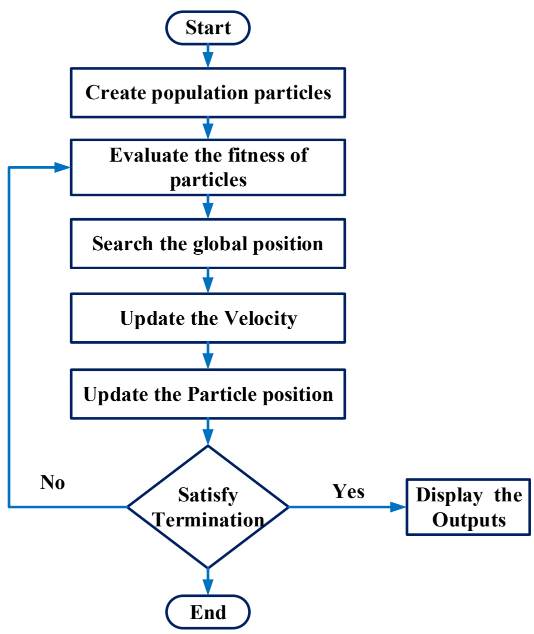

Figure 3. Flow chart representation of MPPT Extraction

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2.3. Mathematical Model of PSO for MPPT

The mathematical expressions governing PSO are:

Velocity Update:

$$V_i(t+1) = w.V_i(t) + C_1.r_1.(pbest_i - x_i(t)) + C_2.r_2.(gbest_i - x_i(t)) \quad (1)$$

Position Update:

$$x_i(t+1) = x_i(t) + V_i(t+1) \quad (2)$$

Fitness Function (Power Output):

$$f(x_i) = Volt(x_i) * curr(x_i) \quad (3)$$

Here, Voltage corresponding to the particle position is $Volt(x_i)$, Current at that voltage is $curr(x_i)$.

2.4. Pseudocode for PSO

Initialize the swarm with random positions and velocities

For each particle:

- Evaluate the fitness based on power output at that point

- Set personal best (pBest) to current position

Identify the global best (gBest) among all particles

For each particle:

- Update velocity using:

*v[i] = w*v[i] + c1*r1*(pBest[i] - x[i]) + c2*r2*(gBest - x[i])*

- Update position using:

x[i] = x[i] + v[i]

- Evaluate fitness at new position

- If current fitness > pBest fitness:

pBest[i] = x[i]

Update gBest if any pBest is better than current gBest

Return gBest as the optimal operating point

Here x[i]: Position of the particle
v[i]: Velocity of the particle
pBest[i]: Best position found by particle *i*
gBest: Best position found by the swarm
w: Inertia weight
c1, c2: Cognitive and social acceleration coefficients
r1, r2: Random numbers between 0 and 1

3. RESULTS AND DISCUSSIONS

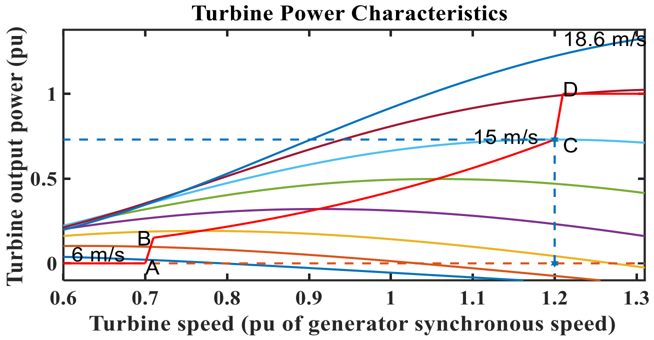

Figure 4. Turbine power characteristics

Figure 4 illustrates the relationship between turbine power and speed. The maximum turbine power is achieved at point C, as indicated.

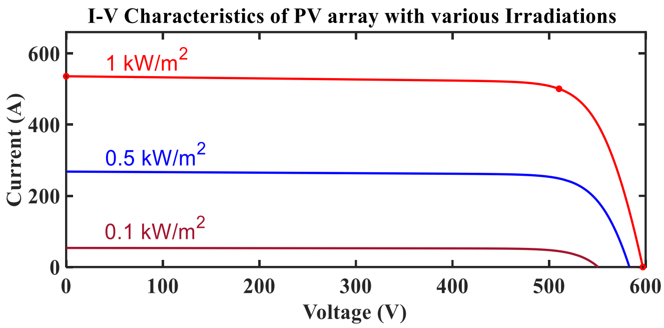

Figure 5. Current Vs Voltage Characteristics of solar system

Figure 5-6 showcases the current-to-voltage and power-to-voltage characteristics at different irradiation levels. The proposed technique involves the utilization of the Sun power-SPR-415E-WHT-D PV array.

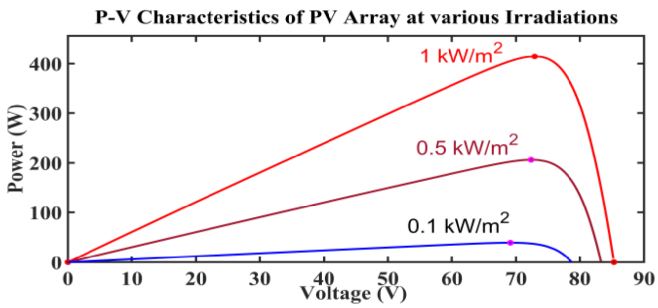

Figure 6. Power Vs Voltage Characteristics of solar system

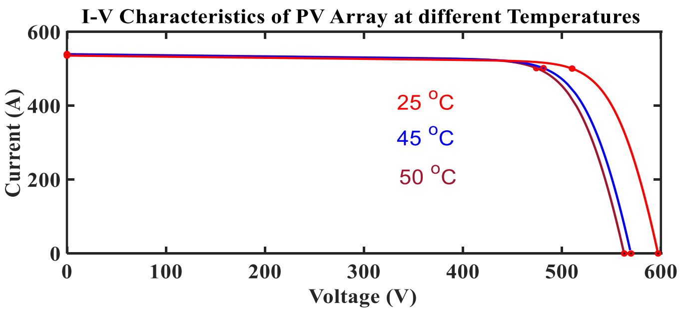

Figure 7. Current Vs Voltage Characteristics of solar system

Figure 7-8 depicts current to voltage, power to voltage characteristics at different temperatures.

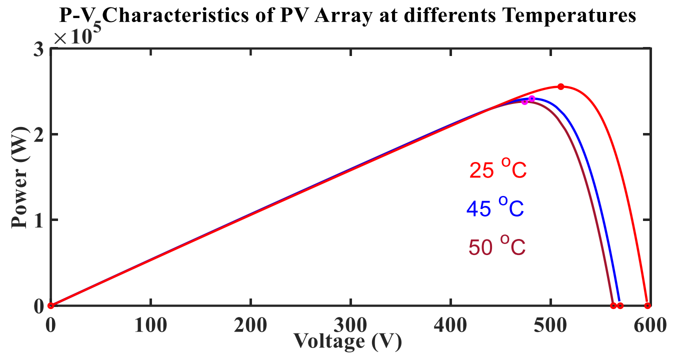

Figure 8. Power *Vs* voltage Characteristics of solar system

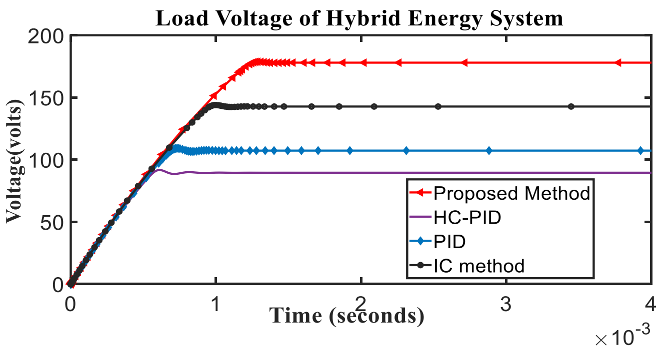

Figure 9. Load voltage representation of various methods

Figure 9 illustrates the load voltage characteristics of a hybrid energy system with four different topologies. Among these, PSO-PID demonstrates superior performance in achieving the MPP in the shortest time compared to the other topologies. The proposed topology shows the potential for reaching the MPP as early as 6ms.

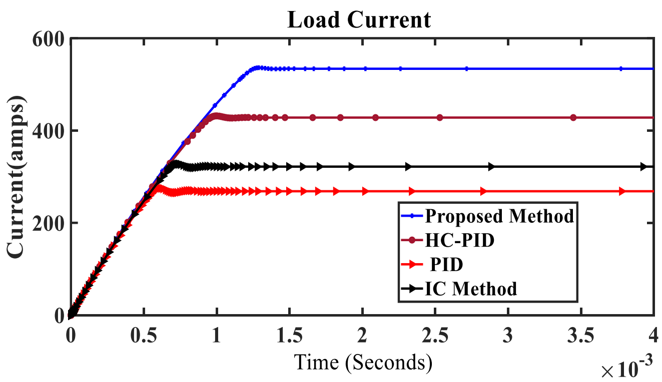

Figure 10. Load current representation of various methods

Figure 10 displays the load current characteristics of a hybrid energy system with four distinct topologies. Among them, PSO-PID exhibits quicker attainment of the MPP compared to the other topologies, achieving it in the shortest duration. The proposed topology indicates the potential for MPP attainment as early as 6ms.

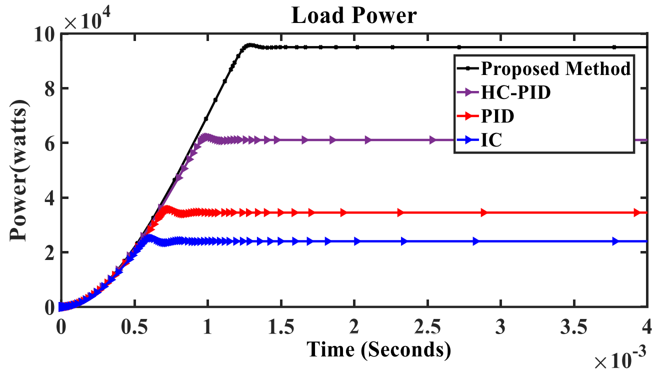

Figure 11. Load power representation of various methods

Figure 11 illustrates the load power characteristics of a hybrid energy system featuring four different topologies. Notably, PSO-PID demonstrates the quickest achievement of the MPP compared to the other topologies, indicating superior performance. The proposed topology suggests the likelihood of reaching the MPP as early as 6ms.

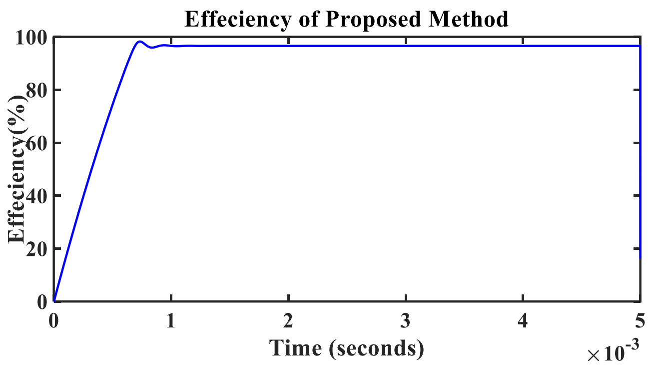

Figure 12. Representation of efficiency of proposed method

Figure 12 represents the efficiency of the proposed method. Notably, the Tracking efficiency reaches 98.02 when compared with the three methods mentioned earlier, indicating an excellent level of efficiency achieved.

Table1 Represents comprehensive analysis of various parameters with different techniques at 1000w/m^2 irradiation and 15m/s wind speed.

Table I. Comprehensive Analysis of Various Topologies

Method	Voltage (volts)	Current(amps)	Power(watts)
HC-PID	160.3	481	7.712*10^4
PID	142.7	428	6107*10^4
IC	125	374	4.686*10^4
PSO-PID	177.87	533.76	9.52*10^4

Table II. Parameters required in Hybrid System

S. No.	Parameter
1	Sun Power SPR-415E-WHT-D Solar Panel
2	7-Module string
3	88 Parallel Strings
4	45°C Temperature

5	1000 Irradiance
6	38m blade radius
7	15m/s wind speed
8	3 blades
9	4 m/s cut-in speed
10	3 rad/s rated speed

4. CONCLUSION

Maximum Power Point Tracking (MPPT) extraction with Particle Swarm Optimization (PSO) in solar and wind energy systems highlights several key outcomes. By integrating PSO algorithms with MPPT techniques, renewable energy systems, particularly those based on solar and wind energy, can achieve significantly improved efficiency and performance. The integration of PSO with MPPT techniques offers a promising avenue for enhancing the performance and efficiency of solar and wind energy systems. By leveraging the adaptability and optimization capabilities of PSO, these renewable energy systems can achieve higher energy production, reduced costs, and improved reliability, making them more competitive and sustainable energy sources.

5. FUTURE RESEARCH SCOPE

The integration of PSO with MPP in hybrid energy systems opens up several avenues for future research. These research endeavors not only seek to improve the efficiency and reliability of renewable energy systems but also tackle the challenges presented by the variability of renewable resources. Here are several promising avenues for future investigation in this domain:

- ***Hardware Implementation:*** Exploring cost-effective and efficient hardware implementations for PSO-based MPPT systems. This involves designing and testing new electronic circuits and control systems that can quickly respond to the PSO algorithm's requirements, minimizing energy losses and improving system responsiveness.
- ***Energy Storage Integration:*** Investigating how PSO-based MPPT techniques can be optimized for systems with integrated energy storage. This research would focus on maximizing energy capture during peak production times and efficiently utilizing stored energy, considering battery life and efficiency.
- ***Hybrid Renewable Energy Systems:*** Examining the application of PSO-based MPPT in hybrid systems that combine solar, wind, and other renewable energy sources. This includes developing algorithms that can dynamically allocate resources and optimize energy production based on the availability and efficiency of each energy source.

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