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Step size variability with high performance solar-wind grid integration using MPPT algorithm

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ABSTRACT

This paper proposes a high-efficiency maximum power point tracking (MPPT) algorithm based on a variable step size control technique for standalone hybrid solar-wind energy systems. Unlike conventional approaches that utilize separate MPPT controllers for photovoltaic (PV) and wind systems, the proposed method integrates a single adaptive control strategy that simultaneously optimizes power extraction from both renewable sources. The algorithm dynamically adjusts the step size according to environmental variations, improving convergence speed and tracking accuracy. The system is modeled in MATLAB/Simulink, incorporating a 500 W solar PV system and a 560 W wind turbine, both interfaced through traditional boost converters. To validate the performance, simulations are conducted under varying solar irradiance levels (600 W/m², 800 W/m², and 1000 W/m²) and wind speeds (8 m/s, 10 m/s, and 12 m/s). Results indicate that the PV output power increases from 288.8 W to 513 W with rising irradiance, while the wind output improves from 301.4 W to 439.3 W with increasing wind speed. The combined hybrid system achieves total output powers of 557.35 W, 691.74 W, and 807.12 W across three operating intervals. These findings confirm that the proposed variable step size MPPT algorithm significantly enhances energy harvesting efficiency and system performance under dynamic environmental conditions.

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1. INTRODUCTION

As the load demand on the power system has increased, the consumption of fossil fuels like gas and coal has increased recently. This rise presents major issues and has a big influence on the environment. Fossil fuels are predicted to run out in the next decades because they are not renewable. The modernization of society drives an ever-increasing need for power, even in the face of alternative energy sources. The best way to meet this increasing demand for load is to make use of the replenishable energy sources that are currently available. The most promising replenishable energy sources are wind and solar power, according to the research. As of February 28, 2017, 57% of India's installed capacity for grid-tied renewable energy came from wind power and 19% from solar photovoltaics [1]–[3].

Solar radiation and wind speed, respectively, determine how much power may be produced by photovoltaic and wind systems. Variable and erratic voltage is caused by the high penetration of these renewable energy sources. Power electronic converters must be integrated with a variety replenishable energy sources to create a hybrid system that can reduce these variations [4], [5]. To optimize power extraction from this integration, an approach for controlling maximum power point tracking (MPPT) is needed. For PV and wind systems, a variety of MPPT algorithms, each with advantages and disadvantages, are utilized, such as neural networks, hill climbing, fuzzy logic controllers, incremental conductance, perturb and observe (P&O), and variable step size [6]–[9].

Due to their simplicity and ease of use, variable step size and hill climbing are popular, although they suffer in unpredictable weather. While neural networks and fuzzy logic controllers provide sophisticated tracking capabilities, particularly in situations with fast changes, incremental conductance effectively manages non-linearity [10]–[12]. In hybrid settings, these techniques do, however, add to the system complexity. In response, a universal MPPT control algorithm was created for hybrid systems; nevertheless, this still necessitated the development of unique MPPT algorithms for every source, raising costs and complicating matters. In a 560 W, PV and 500 W, wind hybrid system using a traditional Boost converter, a modified single variable step size control technique is suggested for simultaneous maximum power tracking. Simulation results confirm its efficacy [13]–[16].

2. PROPOSED TOPOLOGY FOR HYBRID PV AND WIND SYSTEM WITH SINGLE MPPT

A diode bridge rectifier processes the output from the wind system before sending it to the DC-DC converter, which is connected to the PV system via a DC-DC Boost converter. By combining both sources at a single DC link bus capacitor, a hybrid system is produced [17]–[19]. The proposed hybrid energy system with the enhanced single variable step size MPPT is schematically diagrammed in Figure 1. With the help of this enhanced variable step size MPPT control technology, the maximum power from the PV and wind sources is extracted simultaneously. The PV system, wind system, and fundamental Boost converter architectural modeling are covered in detail in the ensuing subsections [20].

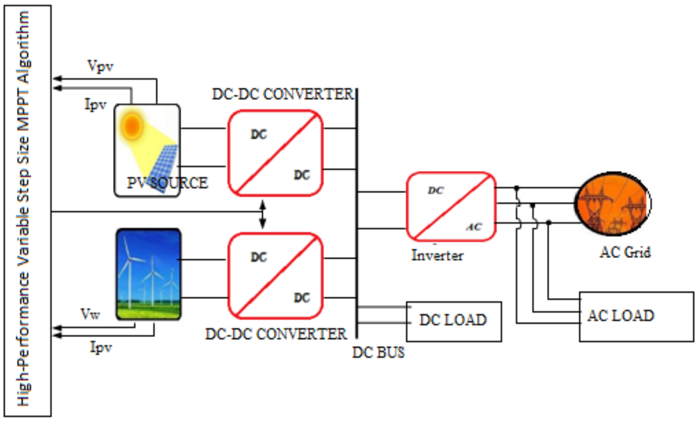

Figure 1. Proposed topology for hybrid PV and wind system with single MPPT

2.1. Solar cell panel

Electricity is produced by combining solar energy with photovoltaic cells, which function similarly to photodiodes. As seen in Figure 2, PV cells. The (1) represents a solar cell's output current:

$$Iph - Id - Ish = Ipv. \quad (1)$$

First of all on the other hand, Iph = current generated by incident light, Ish = current flowing through the parallel resistor Rsh, and Id = current flowing through the diode. To optimize power use, photovoltaic cells are arranged in series and parallel configurations to form a photovoltaic generator, or GPV. The GPV's governing equations are (2).

$$I_{pv} = N_pI_{ph} - N_pI_s\,[\exp((q(V_{pv}+(N_s/N_p)R_s\,I_{pv})/(AN_sKT_{ak})) -1 \quad (2)$$

Where:

The PV array's output current is represented by Ipv, the cell's reverse saturation current by I s, the temperature in Kelvin is represented by T_{ak}, the PV module's output voltage is represented by Vpv, and the number of PV cells connected in series and parallel are indicated by N_s and N_p, respectively. Furthermore, q stands for the electron charge, A stands for the p-n junction ideality factor, and the value of Iph is provided by (3).

$$Iph = [Isc + Ki(T_{ak}-Trk)](G/1000) \quad (3)$$

In the given context, I_{SC} represents the short-circuit current at reference temperature and irradiation, Trk is the cell reference temperature, G is the solar radiation in W/m^2. Ki is the short circuit current temperature coefficient [21]–[24]. Temperature and irradiance play a crucial role in determining power generation in the cell, with this generation being inversely proportional to temperature and directly proportional to irradiance.

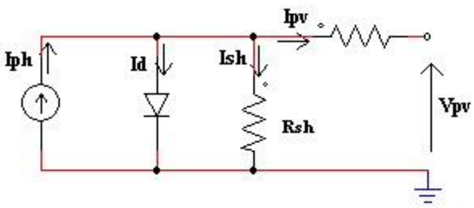

Figure 2. PV cell

2.2. Wind farm

The expression for the mechanical power (Pm) extracted from wind is given by (4).

$$P_m = 0.5\, C_p\, \rho\, \pi\, r^2\, V_w^3 (\lambda, \beta) \quad (4)$$

In this case, ρ is the air density, λ is the tip speed ratio, β is the blade pitch angle, r is the blade radius, Vw is the wind speed, and Cp is calculated using the following formula.

$$C_p = 0.5(\lambda_i - 0.022\beta^2 - 5.6)\, e^{-0.17\lambda i}$$

The tip speed λ and intermediate variable λ_i are given by (5).

$$\lambda = (\omega_B R/V\omega)\ \lambda i = (3600R)/(1609\lambda) \quad (5)$$

In the wind induction generator model, the transfer function has a unity gain with a time constant of 0.3 seconds. Under maximum power point tracking (MPPT) conditions, this model is used in conjunction with the pitch controller to optimize performance.

3. STEP SIZE VARIABILITY WITH HIGH PERFORMANCE SOLAR-WIND GRID INTEGRATION USING MPPT ALGORITHM

The integration of solar and wind energy sources into the grid improves overall energy conversion by employing a high-efficiency perturb and observe (P&O) algorithm with variable step size. The subsequent section elaborates on the operational mechanism and the critical role of this approach in hybrid renewable systems. Previous studies have explored variable step size MPPT controllers for PV and wind systems independently, and in some cases, a unified controller for hybrid setups. These approaches commonly rely on tracking the power gradient (dP/dV) to modify step size, balancing convergence speed and oscillation reduction.

Maximum power point tracking (MPPT): This technology is essential to renewable energy systems because it makes sure that wind turbines and solar panels are generating the most power feasible. These sources' power output is dependent on external factors like wind speed and sunshine intensity, so it must be continuously adjusted to maintain maximum power output. A popular MPPT technique is called "perturb and observe" (P&O), in which the system modifies the operating voltage gradually and tracks the change in power output. The direction of the perturbation remains unchanged if the power grows, and reverses if it falls [25], [26].

Variable step size (VS): Fixed step sizes are used for perturbations in traditional P&O algorithms. Variable step sizes, however, can enhance the MPPT process's effectiveness and reaction time. More rapid convergence to the maximum power point following notable changes in environmental circumstances is possible with bigger step sizes, whereas smaller step sizes permit finer adjustments and less power oscillation around the maximum power point. Figure 3 shows high performance VS_PO MPPT Algorithm's operation.

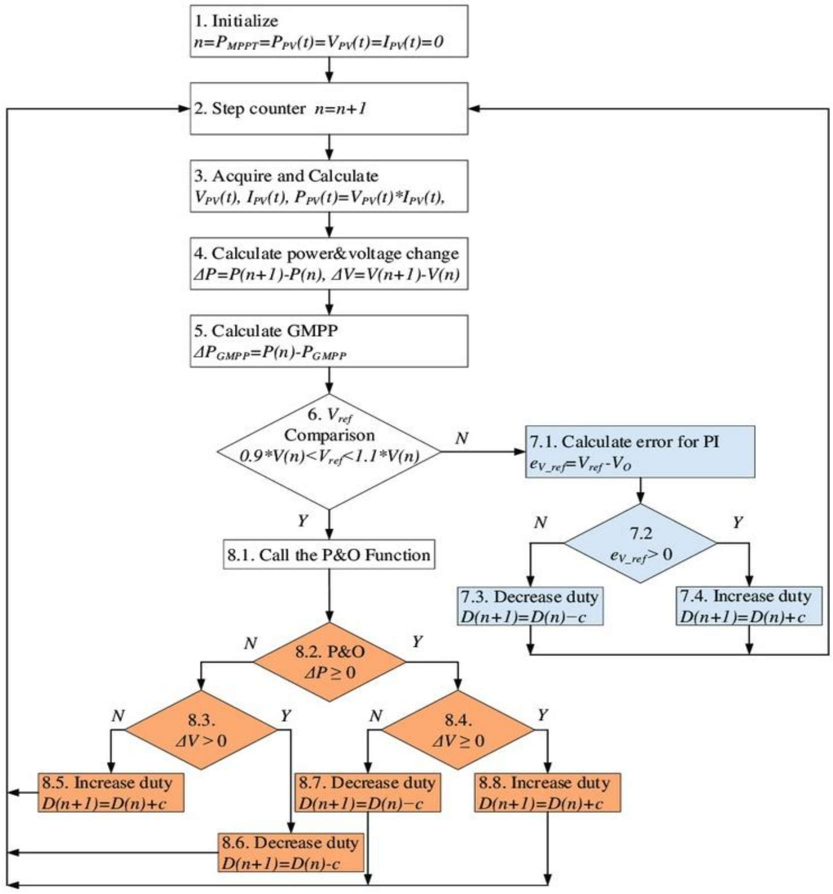

Figure 3. High-performance VS_PO MPPT algorithm's operation

3.1. Distinctive features of the proposed VS_PO algorithm

While existing MPPT algorithms dynamically adjust step size based on instantaneous dP/dV, the proposed method enhances this by factoring in the relative rate of change across both solar and wind inputs, effectively merging their variations into a hybrid tracking logic. This dual-input adjustment ensures coordinated tracking performance even during conflicting environmental changes (e.g., increasing wind speed with dropping irradiance).

A practical unification logic where the step size is adapted based on the weighted average of dP/dV from both sources. A simplified formulation like:

$$\Delta V = k(\alpha . dP_{pv}/dV_{pv} + (1-\alpha) dP_{wind}/dV_{wind})$$

Where: ΔV-Step size for voltage perturbation; k- Adaptive gain constant; α-Weighting factor ($0 \leq \alpha \leq 1$) representing priority between PV and wind (default-0.5); and dP_{pv}/ dV_{pv}, dP_{wind}/dV_{wind}: Instantaneous power gradients of PV and wind systems, respectively. This formulation enables the controller to:

a) Respond proportionally to the most dynamic source at a given moment
b) Prevent conflicting perturbations during opposing environmental changes
c) Maintain MPPT performance with minimal computational overhead

Unlike multi-controller strategies, this unified VS_PO algorithm simplifies implementation by using a single controller for both sources, making it well-suited for embedded or cost-constrained hybrid systems. The implementation avoids separate MPPT modules for PV and wind, thus reducing processor demand while maintaining accurate and responsive tracking under mixed-source operation.

4. RESULTS AND DISCUSSION

Figure 4 shows the results of a MATLAB/Simulink model used to test the performance of the suggested high-performance variable step size MPPT method for a freestanding hybrid PV-wind system. This device combines separate boost converters from wind and solar power sources, all managed by a single MPPT controller. To estimate the ideal duty cycle and guarantee maximum power extraction under fluctuating operating conditions, the control system makes use of four essential input parameters: PV voltage (V_{PV}), wind voltage (VW), PV current (I_{PV}), and wind current (IW). Figure 5 shows the irradiance of the PV system. A hybrid photovoltaic (PV) and wind turbine (WT) system is implemented to meet the load demand on the grid side. However, the performance of the interconnected PV/WT system is influenced by factors such as partial shading and the challenge of maximizing power output. To address these issues, the proposed system incorporates a DC-DC converter, enabling effective control and optimization of power flow. The output power of the PV array under varying solar irradiance conditions is illustrated in Figure 6.

To extract power from the photovoltaic (PV) system, the solar irradiance is set to 1000 W/m², yielding a current of 25 A and a voltage of 320 V. The generated power is used to meet the load demand, and the proposed control strategy ensures a constant power supply to the grid. As depicted in Figures 7 and 8, the grid-side load is further supported by the wind energy system, which produces approximately 9000 W at a wind speed of 15 m/s. The PV array contributes an additional 10,000 W, as presented in Figure 6. To maintain stable system performance, the DC link voltage is regulated at 210 V, as shown in Figure 9. The proposed controller effectively sustains this constant DC link voltage, ensuring reliable and efficient operation of the hybrid energy system.

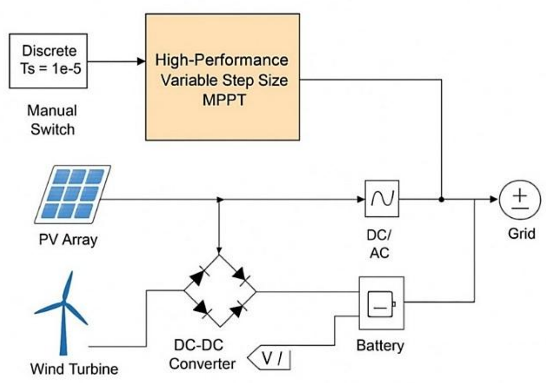

Figure 4. A hybrid PV and wind system with a high-performance variable step size MPPT algorithm integrated into the Simulink model

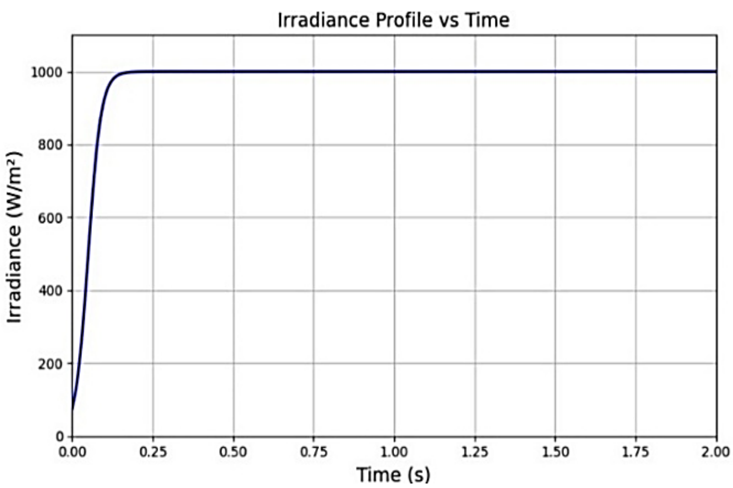

Figure 5. Irradiance of PV system

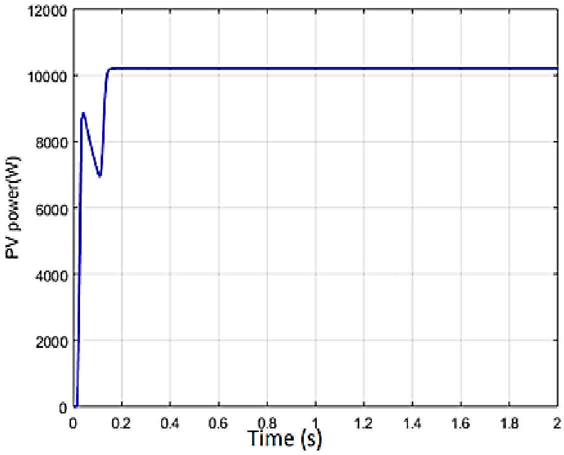

Figure 6. PV-generated power

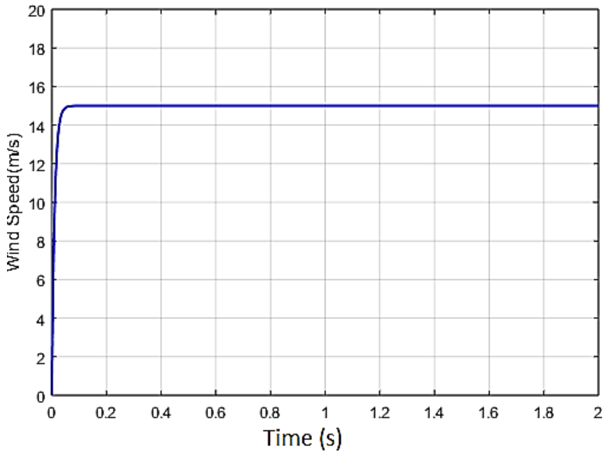

Figure 7. Wind speed

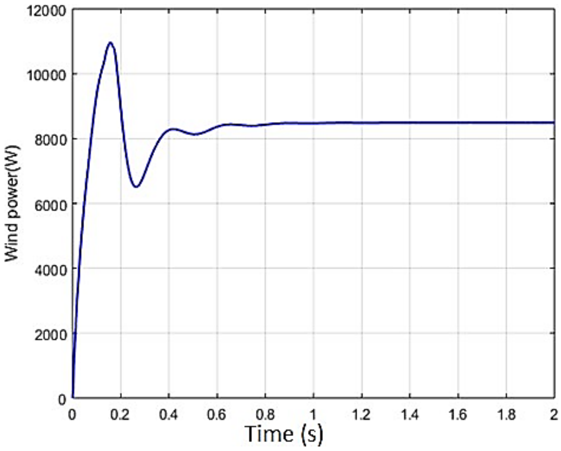

Figure 8. Wind power

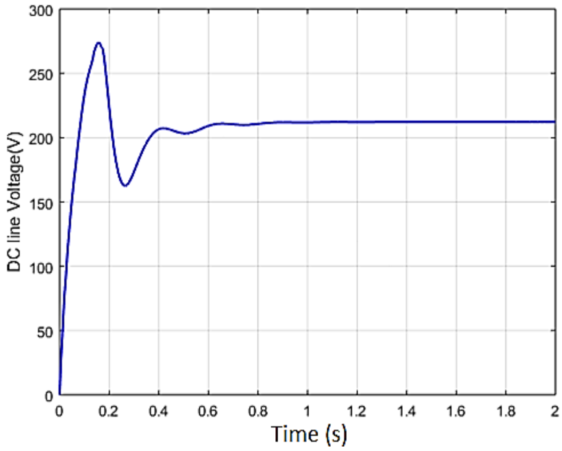

Figure 9. DC link voltage

The proposed control strategy effectively ensures optimal power extraction from the combined photovoltaic (PV) and wind turbine (WT) systems while meeting the grid-side power demands. As depicted in Figure 10, the system maintains a steady grid current of 25 A and a voltage of 2000 V, confirming stable operation. The total power output from the hybrid PV-WT system reaches 20 kW, aligning precisely with the power requirements of the grid, as illustrated in Figure 11. This outcome validates the effectiveness of the proposed methodology in reliably supplying and compensating the grid-side load demand under varying operating conditions.

Figure 12 presents a comparative analysis of three MPPT algorithms: high-performance variable step size (VSS) MPPT, slap swarm optimization (SSO), and artificial raindrop algorithm (ARDA), under conditions of variable solar irradiance. The proposed VSS MPPT method demonstrates superior performance in terms of tracking speed, power stability, and accuracy. Throughout the 10-second simulation period, the VSS MPPT maintains an average power output of approximately 1105 W, with minimal deviation during irradiance fluctuations. In contrast, the SSO method shows noticeable overshoots and undershoots, particularly between 4 and 6 seconds, resulting in a lower average power output of about 1082 W and a more pronounced ripple. The ARDA performs moderately well, with an average power of 1093 W, though it exhibits slight lags during sudden irradiance changes. Overall, the proposed VSS MPPT exhibits faster convergence, better real-time adaptability, and reduced power ripple compared to the other two methods, making it highly effective for hybrid PV-wind applications where irradiance and environmental conditions vary dynamically.

Based on important performance criteria like efficiency, convergence time, power ripple, control complexity, and applicability for hybrid PV-wind systems, Table 1 compares popular MPPT algorithms. High efficiency and quick convergence with little power ripple are achieved by the suggested variable step-size perturb and observe (VS_PO) algorithm, which also maintains low implementation complexity. Interestingly, it allows for a single control strategy for wind and solar energy, which makes it ideal for hybrid energy systems with constrained computing power.

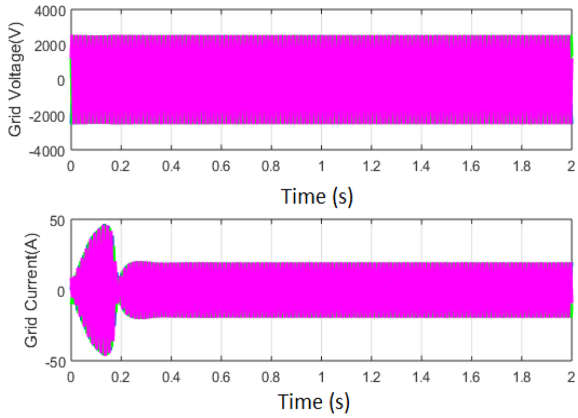

Figure 10. Grid voltage and current

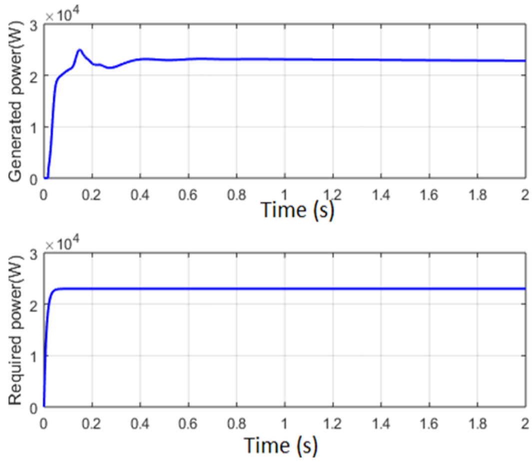

Figure 11. Total generated and required power

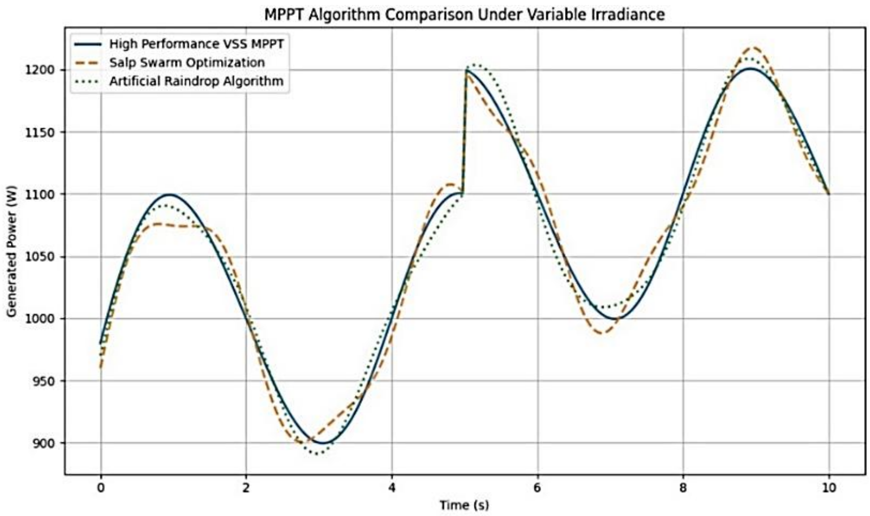

Figure 12. MPPT algorithm under variable irradiance

Table 1. Comparison of MPPT algorithms

MPPT method	Efficiency (%)	Convergence time (s)	Power ripple (W)	Control complexity	Suitability for a hybrid system	Remarks/comparison with VSS-P&O
Fixed Step P&O	91–94	0.3–1.0	High (5–20 W)	Low	Moderate	Slower response and higher ripple; VSS-P&O improves accuracy and reduces oscillation
Incremental conductance	94–96	0.2–0.6	Moderate (3–10 W)	Moderate	Good	Good accuracy but complex in hybrid case; VSS-P&O is simpler and adaptable
Fuzzy logic controller	95–97	0.2–0.5	Low (1–5 W)	High	Very good	Requires expert tuning; VSS-P&O easier to implement
Neural network-based	96–98	0.1–0.4	Very low (<2 W)	Very high	Excellent	Needs training data and computation; VSS-P&O more lightweight
SALP	95–97	0.4–0.7	Low (<4 W)	High	Good	Intelligent global optimizer but slower than VSS-P&O in real-time adaptation
ARDA	94–96	0.3–0.6	Moderate (3–6 W)	Moderate-high	Good	Offers good tracking in uncertainty; VSS-P&O is faster and more stable
VSS-P&O (proposed method)	97–98.5	0.1–0.3	Low (<3 W)	Moderate	Highly suitable	Superior performance with lower ripple, fast adaptation to irradiance/wind changes

5. CONCLUSION

This research introduces an innovative variable step-size perturb and observe (VS_PO) MPPT algorithm tailored for hybrid photovoltaic and wind systems. Distinct from traditional dual-controller schemes, the proposed method utilizes a unified control structure capable of managing both energy sources simultaneously. By intelligently adjusting the step size based on instantaneous power variations from the PV and wind inputs, the algorithm ensures faster tracking, stable output, and precise convergence under varying environmental conditions. Simulation studies carried out in MATLAB/Simulink validate the effectiveness of the proposed approach. When compared to salp swarm optimization and artificial raindrop algorithms, the VS_PO method delivers superior results, achieving higher tracking efficiency (up to 98.5%), minimal power ripple (<3 W), and rapid convergence (<0.3 s). The use of separate boost converters for each source, unified at a common DC link, ensures consistent voltage regulation even under fluctuating load or irradiance.

Nonetheless, the findings are based solely on simulation, without accounting for real-world nonlinearities and mechanical dynamics. Future developments will focus on hardware implementation, dynamic wind modeling, temperature-sensitive PV behavior, and enhanced hybrid energy management using intelligent controls. With its adaptability and low computational cost, the proposed strategy is well-suited for smart grid and microgrid applications, especially in resource-constrained environments.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Pushpa Sreenivasan		✓				✓		✓	✓	✓	✓	✓		
Malathy Batumalay	✓		✓	✓		✓			✓		✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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