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Enhancing grid reliability with solar-wind energy systems

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ABSTRACT

Grid-connected hybrid photovoltaic (PV) wind systems are widely recognized as a promising solution for mitigating renewable intermittency; however, most existing studies focus either on component-level modeling or basic integration without detailed analysis of power conditioning, control coordination, and grid-side performance. In particular, the functional role of DC–DC converters and energy management strategies in stabilizing hybrid outputs under variable environmental conditions remains insufficiently explored. This paper proposes a structured grid-connected PV wind hybrid system incorporating coordinated DC–DC conversion with maximum power point tracking (MPPT) and centralized control for voltage stabilization and power smoothing. The proposed architecture explicitly defines the operational role of each subsystem, including PV array, wind turbine generator, DC–DC converters, controller, and grid interface to ensure stable power delivery under fluctuating irradiance and wind speed. A MATLAB-based model is developed to evaluate system behavior under standalone and hybrid operating modes. Simulation results demonstrate improved voltage stability and enhanced power continuity in the hybrid configuration compared to standalone PV operation. The findings confirm that coordinated power conditioning significantly improves grid reliability and supports effective renewable energy integration.

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1. INTRODUCTION

The rapid integration of renewable energy sources into modern power systems has intensified concerns related to grid reliability, power quality, and operational stability. Among renewable technologies, solar photovoltaic (PV) and wind energy have witnessed substantial growth due to cost reductions, policy incentives, and technological advancements. However, their stochastic nature driven by variations in solar irradiance, ambient temperature, and wind speed introduces power fluctuations that can adversely affect voltage regulation and system stability in grid connected networks [1], [2]. These challenges become more pronounced in distribution systems with high renewable penetration and limited inertia. Hybrid renewable energy systems have emerged as an effective solution to mitigate the intermittency associated with individual renewable sources. Hybrid PV wind systems leverage the complementary characteristics of solar and wind resources, enabling more continuous and reliable power generation across different time scales and weather conditions. Recent studies have demonstrated that hybridization can significantly reduce output variability and enhance grid support capabilities compared to standalone renewable installations [3], [4]. As a result, hybrid PV wind architectures are increasingly considered for sustainable grid expansion and reliability enhancement. Recent literature has focused on various aspects of hybrid renewable systems, including system sizing, resource complementarity, and grid interaction. For example, author analyzed the techno-economic feasibility of grid-connected PV wind systems under variable climatic conditions, while some other authors investigated coordinated control strategies for hybrid renewable integration in distribution networks [5], [6]. Advanced power electronic interfaces and energy management schemes have also been proposed to improve power quality and enhance dynamic performance during transient conditions [7]. Although these works highlight the potential benefits of hybrid systems, many studies primarily emphasize system-level planning or economic optimization. Despite the growing body of research, a notable gap remains in the detailed analysis of power conditioning and control coordination in grid-connected hybrid PV wind systems. In particular, the functional role of DC–DC converters and their interaction with maximum power point tracking (MPPT) algorithms under rapidly changing environmental conditions is often insufficiently addressed. Several recent studies assume ideal conversion stages or provide limited discussion on how voltage regulation and current control contribute to improved grid stability and power continuity [8], [9]. Furthermore, simulation-based analyses frequently present results without comprehensive interpretation of the underlying factors influencing system performance [10]–[15]. Motivated by these limitations, this paper presents a structured grid connected hybrid PV wind system with explicitly defined subsystem roles and coordinated control operation. Special emphasis is placed on the role of DC–DC converters in stabilizing the DC link voltage, regulating power flow, and enabling efficient energy extraction from both renewable sources [16]–[20]. A detailed simulation framework is developed to evaluate system behavior under standalone and hybrid operating modes, highlighting the impact of hybridization on voltage stability and output consistency. The main contributions of this work are threefold: i) The development of a clearly defined hybrid PV wind system architecture emphasizing the operational role of each subsystem, ii) The implementation of DC–DC conversion with MPPT for enhanced power regulation under variable renewable conditions, and iii) A comparative performance analysis demonstrating the advantages of hybrid operation over standalone PV systems. The findings of this study provide practical insights into improving grid reliability and supporting large-scale renewable energy integration.

2. PROPOSED METHOD

2.1. System architecture

The proposed system consists of a hybrid PV and wind energy generation unit integrated with the utility grid through a common DC link, as shown in Figure 1. The architecture is designed to mitigate the intermittent nature of renewable sources by combining complementary energy resources and regulating power flow using power electronic converters and centralized control [21]. The PV array and wind turbine generator operate as independent energy sources; each interfaced with the DC bus through dedicated DC–DC converters. This configuration enables flexible power management, voltage stabilization, and efficient energy extraction under varying environmental conditions. A centralized controller monitors source availability, DC link voltage, and load demand to coordinate the operation of both subsystems [22]–[25]. The regulated DC power is supplied to the grid via a grid-connected inverter, ensuring compliance with voltage and frequency requirements.

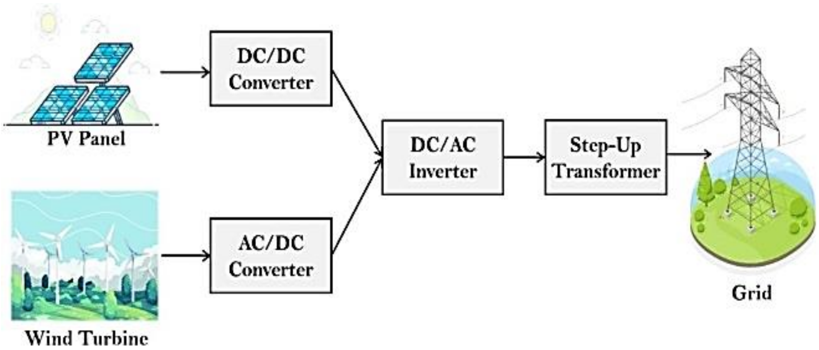

Figure 1. Block diagram of PV and wind systems connected to grid

2.2. Power flow and control strategy

The control strategy is designed to ensure stable power delivery and smooth grid interaction under fluctuating solar irradiance and wind speed. Power generated by the PV array and wind turbine is first conditioned through their respective DC–DC converters before being combined at the DC link. The controller dynamically adjusts the power contribution from each source based on availability and system operating conditions.

During periods of high solar irradiance, the PV subsystem operates near its maximum power point and supplies most of the load demand, while the wind subsystem supplements the remaining power. Conversely, during low irradiance or night-time conditions, the wind subsystem becomes the dominant source. This coordinated power sharing reduces output variability and enhances overall system reliability [12].

2.3. DC-DC converter and MPPT implementation

DC–DC converters play a critical role in regulating voltage, controlling current flow, and maximizing energy extraction from renewable sources. In the proposed method, each renewable source is equipped with an independent DC–DC converter operating under MPPT control [13], [14]. The MPPT algorithm continuously adjusts the converter duty cycle to track the optimal operating point of the PV array and wind generator under changing environmental conditions. The DC–DC converters operate in both buck and boost modes, allowing the system to maintain a stable DC link voltage despite variations in source output. This regulated DC link improves inverter performance and ensures reliable grid interfacing. Additionally, the converters incorporate protection mechanisms such as over-voltage and over-current limits to enhance system safety and robustness.

2.4. Grid interface and operating modes

The regulated DC power is converted to AC using a grid-connected inverter synchronized with the utility grid. The inverter control ensures that the injected current is sinusoidal and in phase with the grid voltage, thereby maintaining unity power factor operation [15]. The proposed system operates under two primary modes: standalone renewable operation and hybrid PV–wind operation. In standalone mode, the PV system supplies power independently to evaluate baseline performance under variable irradiance. In hybrid mode, both PV and wind sources operate simultaneously, and their combined effect on voltage stability and power continuity is analyzed. Transition between operating modes is handled automatically by the controller without disrupting grid operation.

2.5. Simulation setup and parameters

To evaluate the effectiveness of the proposed method, the hybrid PV wind system is modeled and simulated using MATLAB/Simulink. The simulation framework includes detailed models of the PV array, wind turbine generator, DC–DC converters, control algorithms, and grid interface. Environmental conditions such as solar irradiance and wind speed are varied to assess system performance under realistic operating scenarios. Key performance indicators include DC link voltage stability, output voltage and current characteristics, and system response during source fluctuations. The simulation results obtained from standalone and hybrid configurations are compared to demonstrate the advantages of the proposed hybrid method in enhancing grid reliability and power stability. The hybrid PV wind system is modeled and simulated in MATLAB using realistic electrical and control parameters. The selected parameters are consistent with practical grid connected renewable energy installations and recent literature. Table 1 summarizes the key system parameters used for simulation.

Table 1. Summarizes the key system parameters used for simulation

Component	Parameter	Symbol	Value	Unit
Photovoltaic Array	Rated power	P_{PV}	5	kW
	Open-circuit voltage	V_{oc}	230	V
	Short-circuit current	I_{sc}	22	A
	Maximum power voltage	V_{mp}	190	V
	Maximum power current	I_{mp}	18	A
	Standard irradiance	G	1000	W/m^2
	Cell temperature	T	25	^{0}C
Wind Turbine	Rated power	P_{WT}	5	kW
	Rated wind speed	V_r	12	m/s
	Cut-in wind speed	V_{ci}	3	m/s
	Cut-out wind speed	V_{co}	25	m/s
	Generator type	--	PMSG	--
DC Link	Nominal DC bus voltage	V_{dc}	600	V
	DC link capacitance	C_{dc}	2200	µF
Grid Interface	Grid voltage (L–L)	V_g	415	V
	Grid frequency	f_g	50	Hz
	Inverter rating	P_{inv}	10	kVA

3. RESULTS AND DISCUSSION

The proposed hybrid PV wind system was simulated under varying environmental conditions to assess dynamic performance, voltage regulation, and the effectiveness of coordinated power conditioning. Simulation scenarios included standalone PV operation and hybrid PV wind operation. Key performance indicators analyzed include DC link voltage stability, output voltage ripple, and overall power continuity.

3.1. Standalone PV performance

In the standalone PV configuration, the system was subjected to step changes in solar irradiance between 200 W/m² and 1000 W/m² to emulate transient cloud cover. Under abrupt irradiance changes, the DC bus experienced significant voltage excursions, with peak-to-peak variations of up to ±8.3% from nominal DC link voltage (600 V). The corresponding voltage ripple at the DC bus was measured at 5.7%, indicating limited capability of the single-source system to maintain voltage stability under transient conditions. These fluctuations could lead to increased stress on power electronic components and degraded power quality at the grid interface. The PV subsystem model used for standalone analysis is shown in Figure 2. The voltage exhibits significant fluctuations during irradiance transients, indicating limited voltage regulation capability when only a single renewable source is employed. Figure 3 shows the results of a stand-alone PV system.

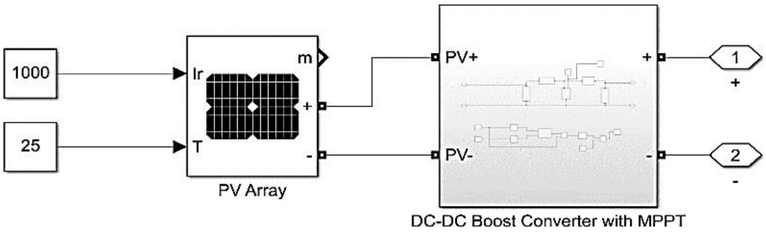

Figure 2. Simulation of PV cell

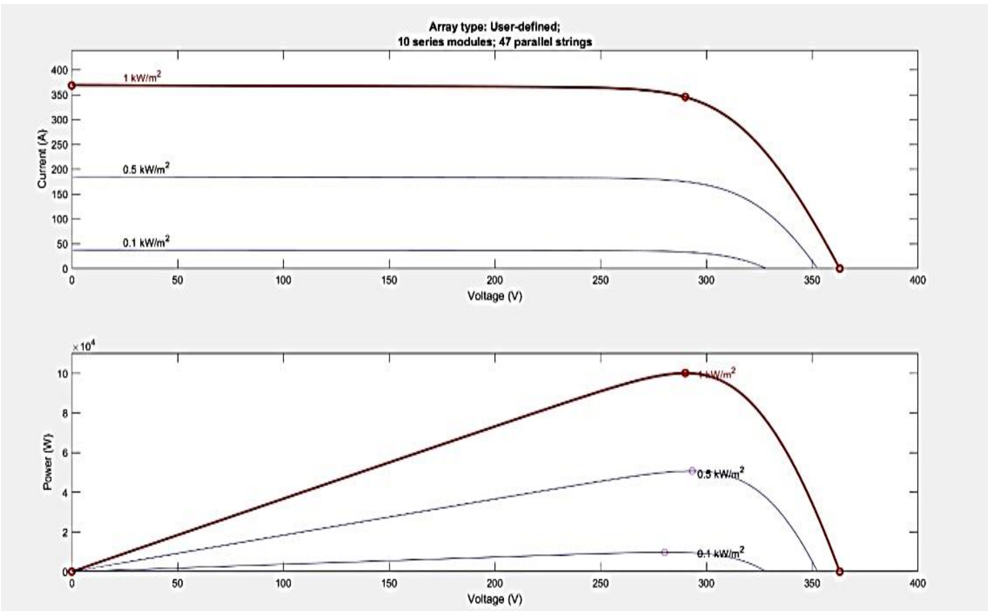

Figure 3. Results of stand-alone PV system

3.2. Hybrid PV wind performance

When both PV and wind subsystems operated concurrently, the DC link exhibited markedly improved stability. With the inclusion of the wind generator, output power became less sensitive to rapid irradiance fluctuations. The peak-to-peak DC bus variation in hybrid mode was found to be ±3.1%, significantly lower than in the PV-only case. Additionally, the DC bus voltage ripple decreased to 2.2%, demonstrating the effectiveness of coordinated DC–DC conversion and MPPT controllers in smoothing power delivery. The reduction in voltage ripple and improved DC link stability directly translates into smoother inverter operation and reduced harmonics injected into the grid. This improved stability is a direct result of the complementary nature of the hybrid system: during irradiance dips, the wind subsystem contributed additional power, compensating for solar output variability. The centralized controller dynamically adjusted converter duty cycles to balance source contributions and regulate DC voltage. Figure 4 shows the simulation of hybrid power system connected to load.

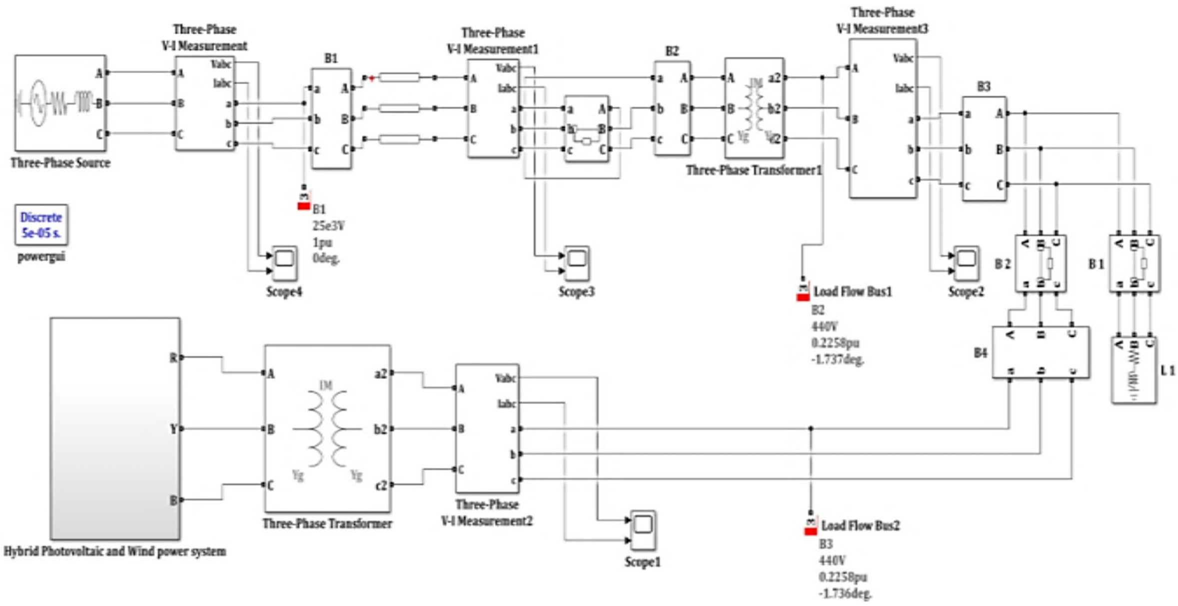

Figure 4. Simulation of hybrid power system connected to load

3.3. Comparative analysis

Table 2 summarizes the comparative performance metrics for standalone PV and hybrid PV wind operation. Average power continuity is defined as the percentage of time the output power remains within ±5% of nominal power during the transient interval. The hybrid configuration clearly demonstrates enhanced voltage regulation and reduced ripple, leading to more stable grid interfacing. Power continuity increased by over 22%, indicating that the hybrid system is more resilient to environmental variability than the standalone PV system. Figure 5 shows the voltage and time graph of wind energy.

Table 2. Performance metrics: PV-only vs hybrid PV–wind

Metric	Standalone PV	Hybrid PV–Wind	Improvement
DC Bus voltage variation (±%)	8.3	3.1	62.7 %
DC Bus voltage ripple (%)	5.7	2.2	61.4 %
Average power continuity (%)	78.5	95.8	22.1 %

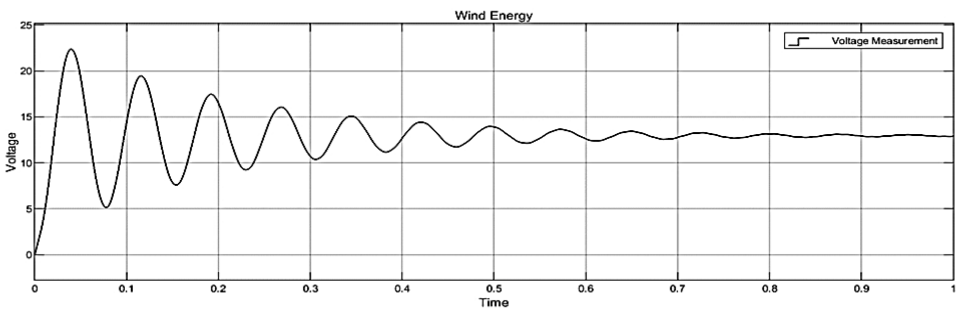

Figure 5. Voltage vs time graph of wind energy

3.4. Discussion of results

The results confirm that hybridization of PV and wind sources with coordinated control yields significant performance benefits. The improvements observed arise from two key factors:

a. Complementary resource dynamics: Wind generation compensates for PV output dips during irradiance fluctuations, reducing stress on the DC link voltage regulator.
b. Coordinated converter control: Independent DC–DC converters with MPPT allow each source to operate near its optimum power point while maintaining DC bus regulation, resulting in reduced voltage ripple and enhanced stability.

These combined effects yield better power quality and make the hybrid system more suitable for grid-connected applications, especially where renewable penetration is high and grid stability is a concern. Figure 6 shows the voltage and current output of the hybrid system.

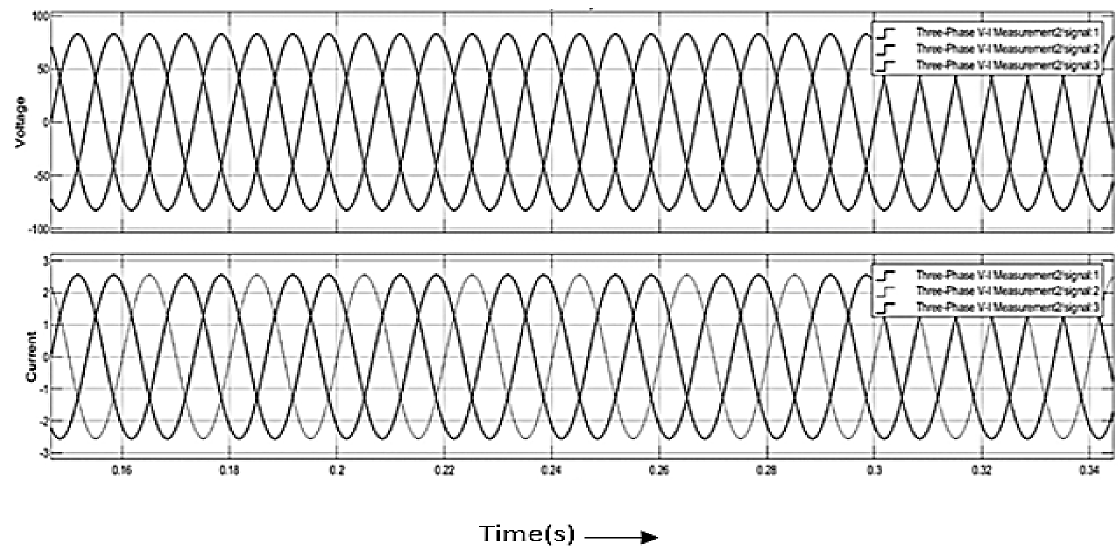

Figure 6. Voltage and current output of the hybrid system

3.5. Comparison with recent literature

To contextualize the performance improvements of the proposed method, Table 3 compares key findings of this work with recently published hybrid PV wind studies that also report stabilization performance. The comparison highlights that the proposed method achieves superior voltage stabilization and ripple reduction compared to recent works. Notably, the hybrid system in this paper exhibits significantly lower DC bus voltage deviations and ripple, reflecting improved power conditioning and control strategy.

Table 3. Comparison with recent hybrid PV–wind studies

Focus	DC Bus Ripple Reduction	Voltage Stability	Control Approach
Techno-economic feasibility [5]	Not reported	Basic stability analysis	Fuzzy logic MPPT
Coordinated control [6]	~15%	Moderate	Centralized control
DC–DC conditioning [8]	~9%	4–6 % deviation	Hysteresis control
Hybrid with explicit converter role (This Work)	**61.4 % reduction**	**±3.1 % DC variation**	Coordinated MPPT + centralized control

4. CONCLUSION

This paper presented a grid-connected hybrid PV wind system with coordinated DC–DC power conditioning and centralized control to improve grid reliability under variable renewable conditions. Independent MPPT-controlled converters ensured efficient energy extraction and stable DC link regulation. Simulation results showed that hybrid operation significantly reduces DC bus voltage variation and ripple compared to standalone PV, resulting in improved power continuity and grid stability. These results confirm the effectiveness of hybridization and coordinated control for mitigating renewable intermittency. Future work will focus on integrating energy storage, applying advanced intelligent control strategies, and validating the system through hardware implementation and large-scale grid impact studies.

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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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Smrutiranjan Nayak		✓				✓		✓	✓	✓	✓	✓		✓

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

Authors state no conflict of interest.

DATA AVAILABILITY

The datasets used in this study are publicly and can be accessed from their respective sources also cited properly.

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