Optimization of hybrid PV-wind systems with MPPT and fuzzy logic-based control

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ABSTRACT

The growing demand for sustainable and reliable energy solutions has driven the development of hybrid renewable energy systems (HRES) that combine multiple energy sources. This research explores the integration of solar energy and wind energy systems, utilizing permanent magnet synchronous generators (PMSG) for wind energy conversion. PMSGs are gaining popularity due to their high efficiency and ability to operate effectively in variable-speed wind conditions, making them ideal for hybrid systems. The study focuses on optimizing the energy extraction from both PV and wind systems using maximum power point tracking (MPPT) boost converters. The control for the MPPT boost converters is based on fuzzy logic (FL), a method that offers flexibility and adaptability in managing the non-linear and dynamic characteristics of renewable energy sources. A hybrid system consisting of PV, wind energy, and a battery storage system connected to a DC bus is simulated using MATLAB Simulink. The model demonstrates the effectiveness of integrating PV and wind energy with MPPT-controlled boost converters and fuzzy logic control, ensuring optimal energy utilization, stable system performance, and efficient energy storage. This research underscores the potential of hybrid renewable energy systems, showcasing how advanced control strategies can significantly improve the efficiency and reliability of energy generation and storage solutions.

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1. INTRODUCTION

Renewable energy plays a crucial role in the global transition toward sustainable and environmentally friendly power generation. Among the various renewable sources, photovoltaic (PV) and wind energy systems are widely recognized for their abundance, low environmental impact, and continuous technological advancements. These energy sources are increasingly being adopted to reduce dependence on fossil fuels and mitigate climate change. However, both PV and wind energy are inherently intermittent-solar power generation depends on sunlight availability, which varies due to weather conditions and the day-night cycle, while wind power is influenced by wind speed fluctuations and seasonal changes. This unpredictability poses significant challenges for standalone operation, particularly in off-grid applications that require a consistent and stable power supply. To overcome these limitations, hybrid energy systems, combining PV and wind energy, offer a robust solution by capitalizing on the complementary nature of these resources [1], [2].

PV systems harness solar energy through photovoltaic cells, which are typically arranged into modules and arrays. These cells convert sunlight into electrical energy using the photovoltaic effect. The design and connection of PV modules-whether in series for higher voltage or parallel for increased current-are critical to ensuring efficient energy generation and distribution. However, PV systems depend on sunlight availability, making them less effective during cloudy conditions or at night [3]-[5].

Wind energy systems convert the kinetic energy of moving air into electrical power through wind turbines, making them one of the most widely used renewable energy sources. The efficiency and performance of wind energy systems depend on several factors, including wind speed, turbine design, power conversion systems, and control strategies. To enhance energy capture, modern variable-speed wind energy conversion systems (WECS) have been developed, which dynamically adjust their operating speed based on changing wind conditions. At the core of variable-speed wind energy systems, permanent magnet synchronous generators (PMSGs) have become a preferred choice due to their high efficiency, reliability, and low maintenance requirements. Furthermore, PMSG-based WECS offer superior performance across a broad range of wind conditions, particularly in low and medium wind speed regions, where energy generation needs to be optimized. Given these advantages, PMSG technology is widely adopted in hybrid renewable energy systems, where it is combined with PV systems and battery storage to create a more stable and efficient power generation system [6].

To achieve maximum efficiency from both PV and wind systems, maximum power point tracking (MPPT) boost converters are employed. MPPT algorithms adjust the operating point of each energy source in real-time, ensuring optimal energy extraction under varying environmental conditions [7].

The effectiveness of MPPT boost converters is largely determined by the control strategy used to optimize power extraction from renewable energy sources. Due to the highly nonlinear and time-varying nature of PV and wind energy systems, conventional MPPT algorithms, such as perturb and observe (P&O) and incremental conductance (INC), often struggle to maintain accurate tracking of the optimal operating point, especially under rapidly fluctuating environmental conditions. These traditional methods rely on fixed-step perturbation techniques that can lead to power oscillations, slow convergence speed, and reduced efficiency, particularly in hybrid energy systems where multiple sources interact dynamically. To overcome these challenges, fuzzy logic control (FLC) has emerged as an intelligent and adaptive approach for MPPT in hybrid renewable energy systems. Unlike traditional MPPT methods, which depend on explicit mathematical models and predefined parameters, FLC is based on linguistic rule sets, expert knowledge, and heuristic decision-making. This allows it to dynamically adjust the converter's duty cycle in real time, ensuring maximum power extraction while maintaining system stability and reducing energy losses [8], [9].

The scientific aim of the work is to develop and optimize a hybrid renewable energy system integrating PV panels, wind energy, and battery storage to maximize energy output and minimize power fluctuations for standalone applications. The research focuses on implementing a fuzzy logic-based MPPT control strategy to enhance power extraction, distribution efficiency, and system reliability under varying environmental conditions. The proposed adaptive control framework ensures optimal power management by dynamically responding to environmental fluctuations, making it suitable for off-grid applications and microgrids. A comprehensive MATLAB Simulink model is used to validate the system's performance under different operating scenarios. This study advances existing research by introducing a robust MPPT strategy that improves power tracking accuracy and system stability.

Section 2 of the article details the configuration of the proposed hybrid energy system, covering system modeling and the control strategy implemented for efficient energy management. In section 3 focuses on the simulation and discussion of results, evaluating system performance under various conditions. The final section summarizes the research findings and presents conclusions and future directions for improving hybrid renewable energy systems.

2. SYSTEM CONFIGURATION

A hybrid renewable energy system integrates multiple energy sources to ensure reliable and efficient energy generation, storage, and distribution. Figure 1 illustrates the proposed configuration, which consists of PV panels, a wind energy conversion system, and a battery storage system with three separate control units. The PV and WECS function as primary energy sources, while the battery storage system serves as a backup energy source. All energy systems are connected in parallel to a common DC bus through three individual DC-DC converters, ensuring a continuous power supply to the load, even if one source becomes unavailable or diminished. Two DC-DC boost converters are employed to implement MPPT for the PV and WECS, while an additional bidirectional DC-DC converter regulates the battery's charging and discharging cycles, ensuring stable power flow to the load and DC bus voltage regulation. Notably, this hybrid power system is modular and easily expandable, allowing for the addition of new PV panels, WECS, or battery storage systems without increasing circuit and control complexity.

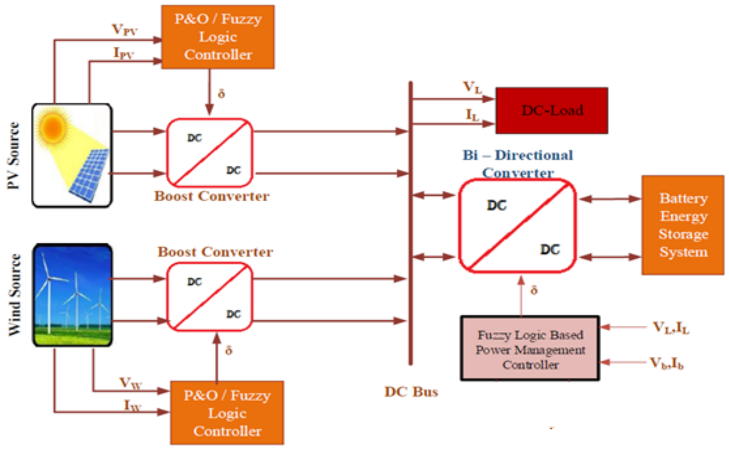


Figure 1. Proposed system configuration

2.1. PV system modeling

A PV module is an interconnected assembly of photovoltaic cells arranged in series and parallel configurations to meet specific power requirements. The series connection increases the module's voltage, while the parallel connection enhances the current output. Each cell in the module operates on the photovoltaic effect, where sunlight excites electrons in the semiconductor material, creating a flow of direct current DC [10]. The equivalent circuit model of a PV module is an extension of a single-cell model and includes multiple ideal PV cells in series and parallel with series resistance (R_s) and shunt resistance (R_{sh}) to account for practical losses, as shown in Figure 2.

The output current (I_{PV}) of a PV module is represented as:

$$I_{PV} = N_p \left(I_{Ph} - I_s \left(e^{\frac{q(V_{PV}+R_S.I_{PV})}{N_S.nkT}} - 1 \right) - \frac{V_{PV}+I_{PV}.R_S}{R_{sh}} \right) \tag{1}$$

Where I_{Ph} is the photocurrent proportional to solar irradiance; I_s is the saturation current of the diode; q is the electron charge; V is the voltage across the module; k is the Boltzmann constant (1.38e-23 J/K); n is the ideality factor; T is the temperature (K); N_s and N_p are respectively the number of cells connected in series and parallel the PV module.

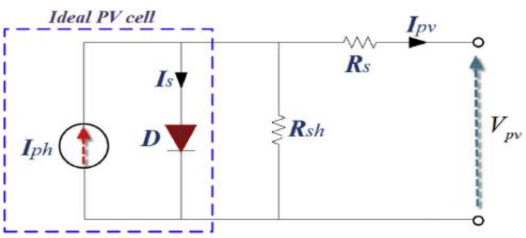
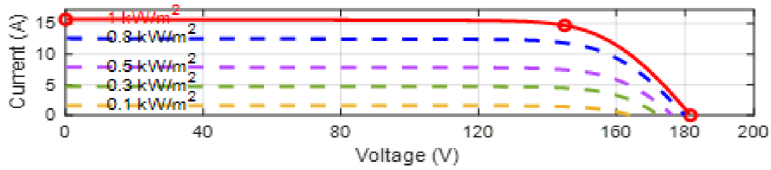


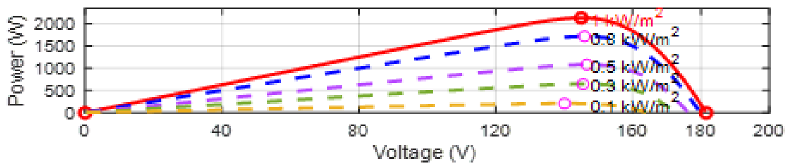
Figure 2. Model of PV cell equivalent circuit

The modeling of a PV module involves simulating the I-V and P-V characteristics, which are non-linear and are influenced by solar irradiance and temperature as shown in Figure 3. Each curve P-V and I-V has a maximum power point, representing the condition where the PV array achieves its highest operational efficiency [11].

$$P_{PV} = V_{PV}.I_{PV} \tag{2}$$



(a)



(b)

Figure 3. Characteristics of the PV array proposed (a) I-V characteristic and (b) P-V characteristic

The topological circuit of Figure 4 is the context in which the investigation of the PV system is examined. A standard PV system comprises a PV array integrated with a DC-DC boost converter and an MPPT controller. The PV panel supplies power to the boost converter, which steps up the voltage to match the DC bus link requirements. The MPPT controller dynamically adjusts the switching of the boost converter to regulate the PV array voltage, ensuring the system consistently operates at the MPP [12]. This maximizes the power output, regardless of changes in solar irradiation or other environmental factors. During the simulation, the PV array's operating voltage is varied to analyze the power flow under specific irradiance conditions. The MPPT controller's primary objective is to quickly and accurately guide the boost converter to track the MPP, enabling optimal energy extraction from the PV array even in fluctuating conditions. The results demonstrate the effectiveness of the system in adapting to environmental variations and achieving efficient power delivery to the DC bus [13].

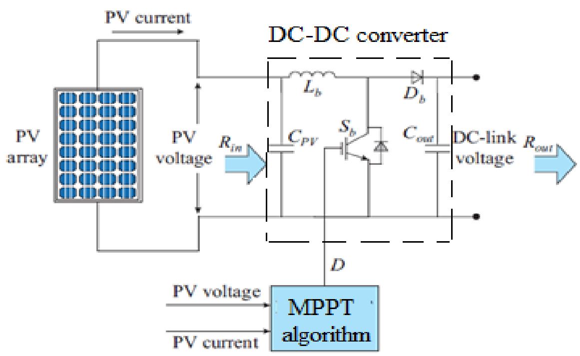


Figure 4. PV array connected to DC-BUS line through DC-DC converter

2.2. Wind energy conversion system modeling

The proposed wind energy conversion system comprises a variable-speed wind turbine and a permanent magnet synchronous generator. wind energy modeling focuses on converting kinetic energy from the wind into electrical energy through the WECS. The process begins with the wind turbine, which extracts kinetic energy based on the turbine's rotor area and wind speed [14]. The power extracted (P_m) from the wind turbine is given by (3).

$$P_m = \frac{1}{2} C_P(\lambda, \beta) \rho \pi R^2 v^3 \quad (3)$$

Where $C_P(\lambda, \beta)$ is the power coefficient, dependent on λ and β; ρ is the air density; R is the radius of wind turbine blade; v is the wind speed; β is the blade pitch angle and λ is the tip speed ratio.

$$C_P(\lambda, \beta) = 0.22 \left(\frac{116}{\gamma} - 0.4\beta - 5\right) exp\left(-\frac{12.5}{\gamma}\right) \quad (4)$$

With,

$$\frac{1}{\gamma} = \frac{1}{\lambda+0.089} - \frac{0.035}{\beta^3+1} \quad (5)$$

The relationship between the wind speed and the rotor speed is defined as tip speed ration λ:

$$\lambda = \frac{\omega R}{v} \quad (6)$$

Where ω is the wind turbine rotational speed. From the value of the rotational motion performance, it is possible to determine the value of the torque T_m acting on the shaft as (7).

$$T_m = \frac{P_m}{\omega} \quad (7)$$

Figure 5 illustrates the relationship between the output mechanical power and rotational speed (P-w) for different wind speeds. The dotted line represents the maximum power points corresponding to various turbine rotational speeds (ω) and wind speeds (v) [15]. Each P−ω curve has a unique rotational speed at the maximum power point for a given wind speed, satisfying the condition $\Delta P/\Delta w = 0$. The primary objective of an MPPT controller is to ensure the turbine operates along this optimal power curve to maximize efficiency.

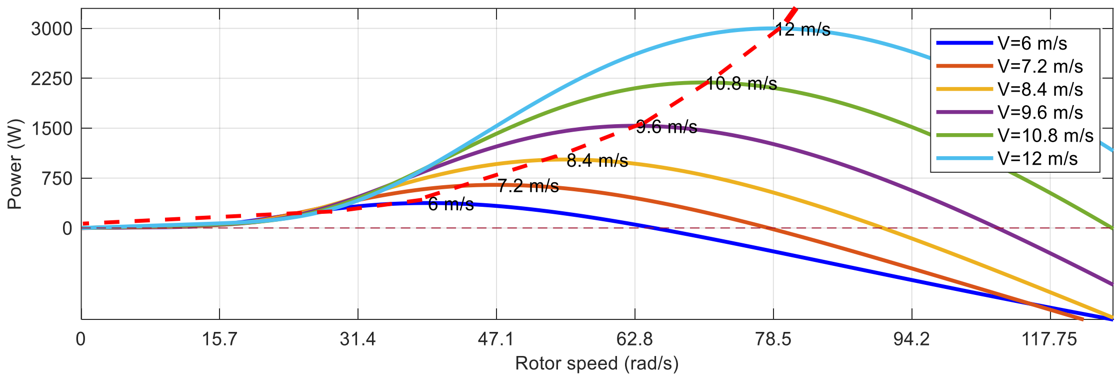


Figure 4. P-W characteristic of the WIND system proposed

The process concludes with the generator, specifically a PMSG, which converts the kinetic energy from the turbine into electrical energy. To assist modeling, the generator model is implemented entirely in dq-coordinates, the stator voltage and electromagnetic torque dynamics are described in the synchronous (dq) reference frame as [6].

$$V_d = -R_s i_d - L_d \frac{di_d}{dt} + \omega_s L_q i_q \quad (8)$$

$$V_q = -R_s i_q - L_q \frac{di_q}{dt} - \omega_s L_d i_d + \omega_s \psi_p \quad (9)$$

$$T_e = \frac{3}{2} p\left[\left(L_d - L_q\right) i_q i_d - \psi_p i_q\right] \quad (10)$$

Where V_d, V_q, i_d, and i_q are the d-axe and q-axe voltages and currents respective; $\omega_s = p\omega$ is the basic electrical angular frequency of the generator; R_s is the resistance of stator; L_d and L_q are the inductance of generator; $\psi_p$is permanent flux; and p is the number of pole pairs.

2.3. Storage power system

Energy storage systems (ESS) are essential in renewable energy applications, addressing the inherent variability and intermittency of sources such as solar and wind. These systems store surplus energy generated during periods of high production and release it during low generation or high demand, ensuring a stable and reliable energy supply. ESS enhances grid stability, supports peak load management, and facilitates the integration of renewable energies into power systems [16]. ESS operation involves bidirectional power converters, energy management systems, and sophisticated control strategies to optimize performance. The choice of storage technology depends on factors such as energy capacity, discharge duration, efficiency, and cost. Among various technologies, batteries are widely used due to their scalability, flexibility, and fast response times. They store energy in chemical form and release it as electricity during discharge. Key parameters include state of charge (SOC), capacity, and efficiency, which directly affect battery performance and lifespan [17]. SOC reflects the available energy as a percentage of the total capacity, dynamically changing during charging and discharging cycles, which can be presented as follows:

$$SOC = SOC_{initial} - \frac{\int I_{bat}\, dt}{Q} \tag{11}$$

where I_{bat} is the battery current and Q is the nominal capacity.

2.4. FLC MPPT for PV system

Fuzzy logic control is a robust and adaptive method used in PV systems to implement maximum power point tracking, ensuring optimal energy harvesting under variable environmental conditions. Unlike conventional MPPT algorithms, such as perturb and observe or incremental conductance, fuzzy logic does not require an exact mathematical model of the PV system. Instead, it utilizes linguistic rules and membership functions to make real-time adjustments based on the relationship between power and voltage, as shown in Table 1 and Figures 6-7. The controller processes two key inputs; the error (E), representing the rate of change of power concerning voltage as shown in (12), and the change in error (ΔE), indicating the dynamic variation of this rate [18], [19]. These inputs are fuzzified into linguistic variables (e.g., negative big, zero, positive small) and processed through a rule base to determine the necessary adjustments to the duty cycle of a DC-DC boost converter. After defuzzification, the crisp output is applied to align the PV system's operating point with its maximum power point. FLC's ability to handle non-linearity and rapid environmental changes makes it highly effective for real-time MPPT in PV systems, enhancing their efficiency and reliability [20], [21].

$$E = \frac{\Delta P}{\Delta V} \tag{12}$$

$$\Delta E = E(k) - E(k-1) \tag{13}$$

Table 1. Rule base for FLC implementation of PV

ΔE \ E	NB	NM	NS	Z	PS	PM	PB
NB	PB	PM	PS	Z	NS	NS	NS
NM	PM	PM	PS	Z	NS	NS	NS
NS	PS	PS	PS	Z	Z	Z	Z
Z	Z	Z	Z	Z	Z	Z	Z
PS	Z	Z	Z	Z	NS	NS	NS
PM	PS	PS	PS	Z	NS	NM	NM
PB	PS	PS	PS	Z	NS	NM	NB

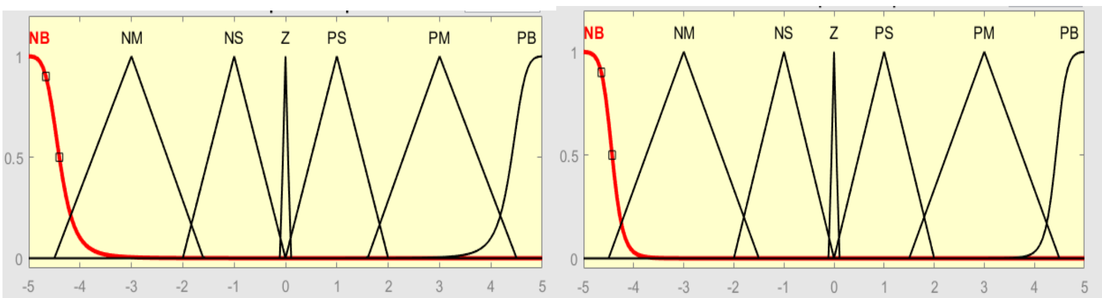


Figure 6. Input membership function of error signal (E) and change in error (ΔE)

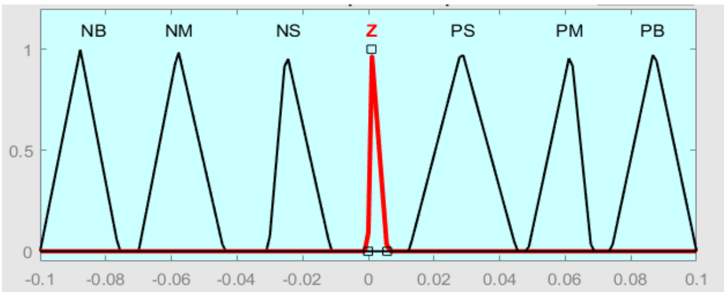


Figure 7. Output membership function

2.5. FLC MPPT for WECS

The output of a wind turbine with a PMSG produces unstable AC power due to fluctuating wind speeds. To stabilize this power, it is first rectified through an AC-DC converter, converting the variable AC into DC voltage. However, the rectified DC may still experience instability and requires further regulation. This is achieved through a DC-DC converter controlled by a FLC [22].

This study introduces a method for MPPT in wind energy systems based on the intrinsic relationship between wind power and rotor speed at the optimal point (ΔP/Δw=0). By leveraging the chain rule, this condition is transformed into a practical form for analysis and implementation.

$$\frac{\Delta P}{\Delta w} = 0 \;\Leftrightarrow\; \frac{\Delta P}{\Delta V}\frac{\Delta V}{\Delta w} = 0 \tag{14}$$

In a PMSG, the rotor speed is directly proportional to the generator voltage ($\Delta V/\Delta w > 0$). Consequently, the MPPT condition simplifies to (15).

$$\frac{\Delta P}{\Delta w} = 0 \;\Leftrightarrow\; \frac{\Delta P}{\Delta V} = 0 \tag{15}$$

This formulation supports the design of a FLC to enhance MPPT performance, applying the same strategy previously utilized in the PV system. The FLC uses two key inputs; the error (E), defined as the rate of change of power concerning voltage ($\Delta P/\Delta V$), and the change in error (ΔE), representing the dynamic variation in this rate as shown in Figure 8. These inputs enable the FLC to precisely adjust the control signals for the DC-DC BOOST converter, ensuring that the system operates at the optimal power point [23]. By dynamically responding to fluctuations in wind speed and system conditions, this approach improves power extraction efficiency, stability, and adaptability in PMSG-based wind energy systems [8], [18], [22].

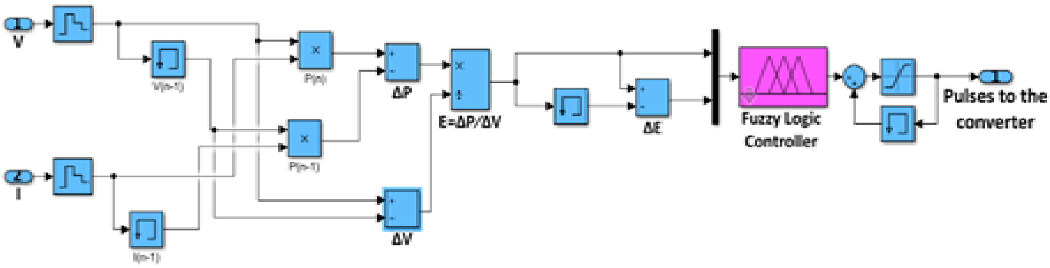


Figure 8. Block diagram of FLC MPPT for wind power

2.6. PID control for battery

The control scheme illustrated in Figure 9 demonstrates a cascaded approach for managing a bidirectional buck-boost converter using proportional-integral (PI) controllers. The system regulates the DC bus voltage (V_{bus}) and ensures safe and efficient battery charging and discharging. The control process begins with sensing V_{bus} and comparing it to a reference voltage ($V_{bus,ref}$), generating a voltage error. This error is minimized by the outer-loop PI controller, which outputs a current reference (I_{ref}). To prevent overcharging or over-discharging, I_{ref} is constrained within battery-specific current limits [$I_{b,max}$, $I_{b,min}$]

using a battery current regulation function. These limits are determined by the battery's capacity and operational safety thresholds. The constrained I_{ref} is then compared to the actual battery current (I_b), generating a current error that the inner-loop PI controller further processes. This controller fine-tunes the error to generate complimentary control pulse-width modulation (PWM) signals to drive the switches (S_1 and S_2) in the converter [24]. This cascaded control scheme ensures stable regulation of the DC bus voltage in the range of $V_{bus,ref}$, accurate current management, and adherence to battery protection requirements. The integration of outer voltage control and inner current control enhances system responsiveness and reliability, making it ideal for bidirectional power flow in energy storage applications and renewable energy systems.

The PID controller is widely utilized in control systems to enhance system accuracy by minimizing the error between process output and the given reference input. The PID controller achieves this by continuously calculating the error and applying corrections based on three distinct parameters proportional K_p, K_i, and K_d. The proportional gain (K_p) ensures immediate correction based on the current error. The integral term (K_i) eliminates residual steady-state errors by summing up all past errors. The derivative gain (K_d) anticipates future errors by responding to the error's rate of change, improving system response speed and stability [25]. The transfer function of the PID controller can be expressed in two equivalent forms:

$$G_e(s) = K_p + \frac{K_i}{s} + K_d s \quad (16)$$

or equivalently

$$G_e(s) = K_p \left[1 + \frac{1}{T_i s} + T_d s\right] \quad (17)$$

where K_p is the proportional gain, K_i is the integral gain, K_d is the derivative gain, T_i is the reset time, T_d is the derivative time.

The PI controller is a simplified form of the PID controller that combines proportional and integral actions to regulate a system's output. It is widely used in applications where eliminating steady-state errors is critical, and derivative action is not required or may amplify noise.

One method for tuning the PI controller parameters is the Ziegler-Nichols method. This approach utilizes the system's step response curve, as illustrated in Figure 10, to determine the required values [26]. The step response is characterized by two key parameters is the delay time (L), and the time constant (T). The PI controller values can be determined using the guidelines provided in Table 2.

The values of outer-loop PI is $K_p = 0{,}85$ $K_i = 0{,}005$ $K_d = 0$

The values of inner-loop PI is $K_p = 0{,}01$ $K_i = 0{,}0005$ $K_d = 0$

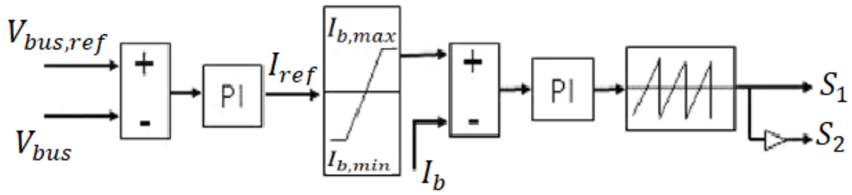


Figure 9. Cascaded PI controller for bidirectional converter

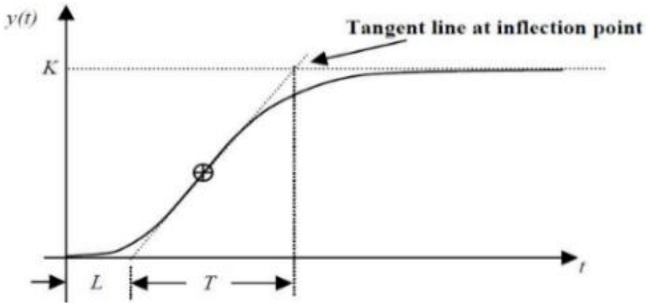


Figure 10. Response curve for Ziegler Nichols

Table 2. Ziegler Nichols tuning rules

Controller type	K_p	T_i	T_d
P	$\frac{T}{L}$	∞	0
PI	$0.9\frac{T}{L}$	$3.3L$	0
PID	$1.2\frac{T}{L}$	$2L$	$0.5L$

3. SIMULATION RESULTS AND DISCUSSION

The proposed hybrid PV-Wind energy system was simulated under varying solar irradiation and wind speed conditions using MATLAB Simulink. The specifications and size of the system components are estimated as shown in Table 3. The system is designed to continuously power a typical 3 kW/300V DC telecommunication load throughout the year, making it suitable for remote locations or isolated islands.

Figure 11 presents the Simulink model of the proposed hybrid energy system. The PV system is connected through a DC-DC boost converter with MPPT control, while the wind turbine's variable AC output is first rectified using an AC-DC converter and then regulated via a DC-DC boost converter with MPPT control before integration into the system. A bidirectional DC-DC converter manages the battery's charging and discharging cycles, ensuring stable power flow and DC bus voltage regulation.

Table 3. Parameter specification

Parameter	Symbol	Value	Parameter	Symbol	Value
PV			Rated load	P	3 kW
Rated power	P_{PV}	2.1 kW	DC bus link voltage	V_{bus}	300 V
No. of series modules	N_s	5	DC bus link capacitor	C	3300 µF
No. of parallel modules	N_p	2	Boost inductor for PV	L	5 mH
Short circuit current	I_{sc}	7.84 A	Boost inductor for WECS	L_1	35 mH
Open circuit voltage	V_{oc}	36.3 V	Bidirectional inductor	L_2	0.5 mH
Maximum power/module	P_{max}	213.15 W	PI outer-loop	K_p - K_i	0.85 - 0.005
WECS			PI inner-loop	K_p - K_i	0.01 - 0.0005
Rated power	P_W	3.0 kW	Battery		
Resistance	R_s	0.42 Ω	Rated capacity	Q_B	65 Ah
inductance	$L_d = L_q$	5.35 mH	Internal resistance	$R_{B,i}$	0.11 Ω
Pole pair	P	4	Nominal voltage	$V_{B,i}$	72 V
Inertia	J	$2.7e^{-3}$ kg.m^2			

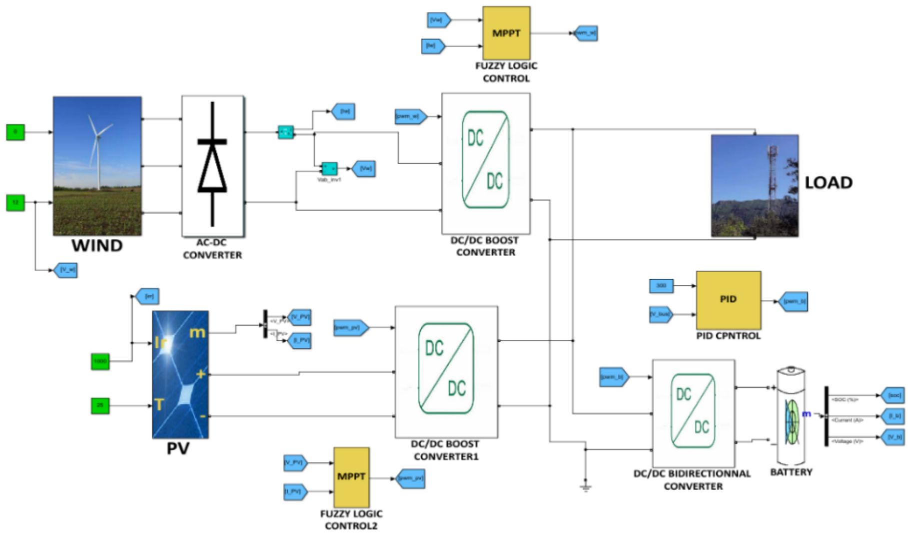


Figure 11. Simulink model of the studied system

To evaluate the dynamic performance of the proposed hybrid system and its response to variations in solar irradiation and wind speed, the results presented in this section are based on simulations conducted at a temperature of 25 °C, with solar irradiation intensity ranging from 300 to 1,000 W/m² and wind speed varying between 8.5 and 12 m/s, as shown in Figures 12(b) and 13(b), respectively.

Figure 12 illustrates the response of the PV system under varying irradiance conditions, while Figure 13 presents the performance of the WECS system under fluctuating wind speed conditions. Figure 12(a) shows that the PV system power output starts at 0.6 kW, increasing in three stages to reach a peak of 2.1 kW, before decreasing in two stages to 1 kW due to sudden variations in irradiance levels. Figure 13(a) indicates that the wind system power output initially generates 3 kW, then drops to 0.5 kW following a wind speed reduction from 12 m/s to 8.5 m/s, before recovering to 3 kW as the wind speed increases again. Both Figures 12(a) and 13(a) confirm that the maximum available power curves from the solar PV and wind power systems align closely with the generated output power. This demonstrates that the FLC-based MPPT controller effectively tracks and extracts maximum power in real-time, ensuring efficient power delivery to the DC bus. Additionally, the smooth transitions in power output validate the robustness of the fuzzy logic control strategy, minimizing power fluctuations and improving system stability.

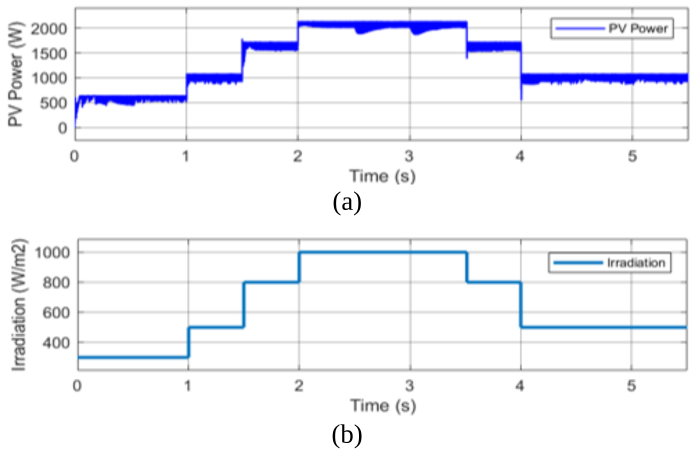


Figure 12. Power of PV under varying irradiation levels (a) PV power and (b) solar irradiation levels

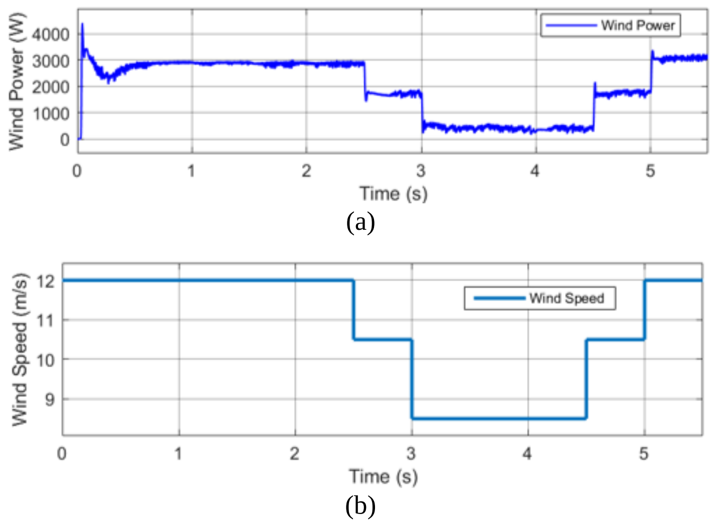


Figure 13. Wind power output under varying wind speed conditions (a) power of wind and (b) wind speed levels

Figure 14 illustrates the electrical performance of the load, where Figures 14(a)-14(c) depict the power, voltage, and current supplied to the load. The results show that the load receives a stable voltage and current, despite fluctuations in power generation. This stability is achieved through the hybrid system's centralized DC bus, which efficiently integrates PV, wind, and battery power sources, ensuring uninterrupted and reliable power delivery. These findings confirm the system's capability to balance energy supply and demand effectively, making it suitable for sustainable energy applications.

Figure 15 illustrates the battery's output performance, demonstrating its role in compensating for the power difference between load demand and the power generated by the wind and photovoltaic systems. Figure 15(a) presents the battery current, showing its dynamic response to charging and discharging cycles, while Figure 15(b) depicts the state of charge (SOC), confirming that the battery operates within safe limits. The bidirectional DC-DC converter, controlled by a PID regulator, effectively manages battery operation, ensuring stable DC bus voltage regulation around 300 V and maintaining accurate current control. The SOC profile further highlights the battery's role in storing excess energy during high-generation periods and discharging energy when renewable generation is insufficient, thereby maintaining system stability and reliability. These results validate the effectiveness of the hybrid energy management strategy, demonstrating the battery's ability to smooth power fluctuations and ensure continuous energy supply in hybrid PV-wind systems.

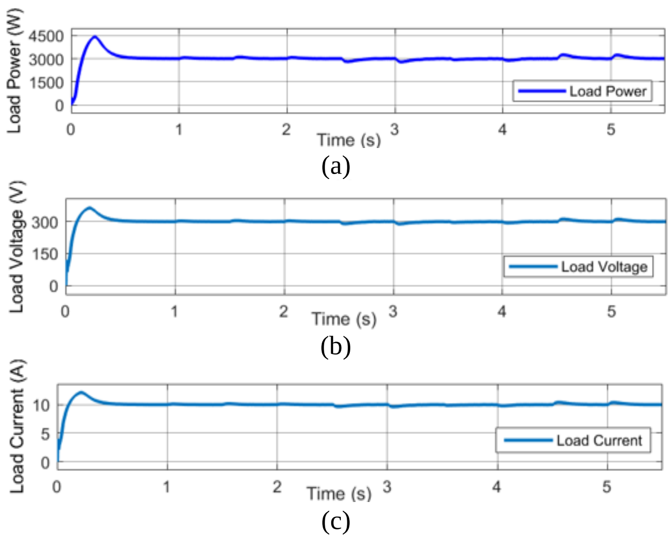


Figure 14. Electrical performance of the load (a) load power, (b) load voltage, and (c) load current

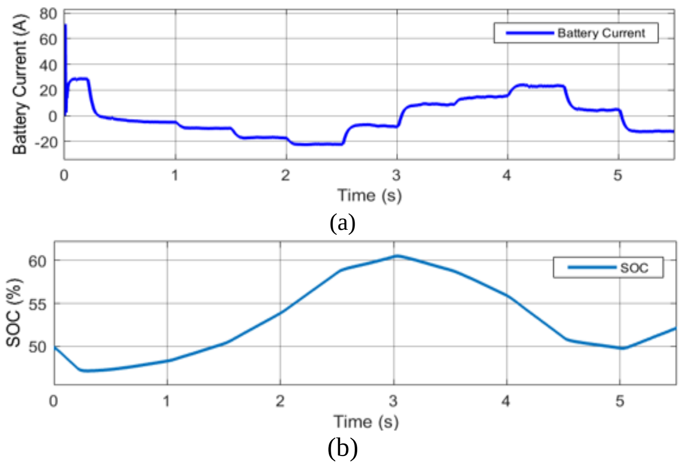


Figure 15. Electrical performance of battery (a) battery current and (b) SOC of the battery

The results in Figure 16 illustrate the output power of the proposed system under varying irradiance and wind speed conditions, demonstrating that total power generation remains stable despite the dynamic nature of the inputs. Initially, the wind energy system alone was sufficient to meet load demand, while excess energy from the PV system was stored in the battery. However, between 2.5 and 3 seconds, a drop in wind power output required the PV system to compensate, with any surplus energy continuing to charge the battery. After 3 seconds, both photovoltaic and wind power generation became insufficient, requiring the battery to discharge stored energy during peak periods to maintain a continuous power supply.The hybrid system effectively utilizes the complementary nature of PV and wind energy, with the battery serving as an essential backup source. The fuzzy logic-based intelligent control strategy ensures that both sources operate at maximum efficiency, reducing power fluctuations, mitigating potential outages, and maintaining a stable 3 kW power supply to meet load demand under all climatic conditions.

This study demonstrated satisfactory efficiency and integration of hybrid renewable energy systems, highlighting the robustness of the FLC-based MPPT and its adaptability to fluctuating environmental conditions such as solar radiation and wind speed variations. However, further research is needed to address challenges related to real-time implementation, scalability, and optimization under extreme conditions. The results confirm that the proposed system maximizes power extraction, balances supply and demand, and ensures stable power delivery. Future work will focus on enhancing hybrid energy systems by integrating additional renewable sources and storage technologies, while implementing advanced optimization techniques to further improve the adaptability and efficiency of MPPT controllers.

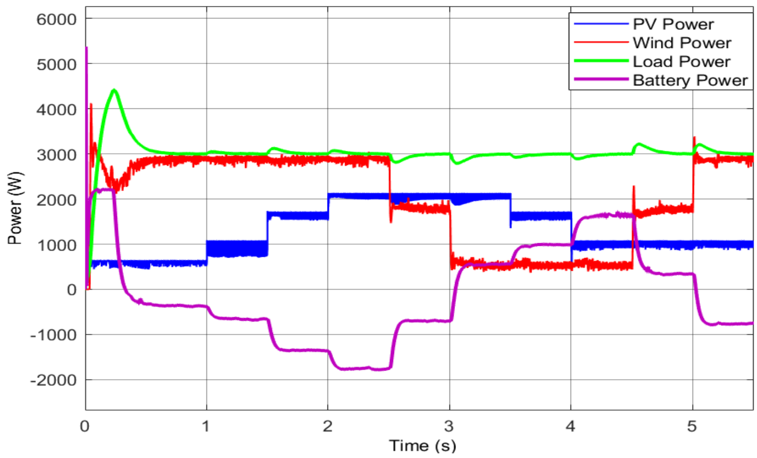


Figure 16. Power generation of the hybrid system under varying irradiation and wind speed

4. CONCLUSION

This paper presents a hybrid renewable energy system integrating PV, a PMSG-based wind energy system, and battery storage with FLC-based MPPT and DC bus voltage regulation. The proposed hybrid system ensures continuous and reliable power delivery, overcoming the limitations of single renewable power sources. The control strategy optimizes energy generation, storage, and distribution, effectively addressing the intermittent nature of renewable energy. A simplified MPPT method eliminates the need for wind speed and irradiance measurements, making it suitable for small-scale renewable applications. This study underscores the potential of hybrid systems for microgrids and off-grid applications, offering a scalable and efficient approach to renewable energy management. The integration of FLC-based MPPT enhances system efficiency while offering a scalable and adaptable approach to renewable energy management. Future work will focus on hardware implementation and system optimization for real-world deployment.

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AUTHOR CONTRIBUTIONS STATEMENT

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

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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