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Optimization of a Hybrid PV-Wind Power System for Enhancing Efficiency and Power Quality Using MATLAB/SIMULINK Simulations

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ABSTRACT

The increasing reliance on renewable energy has driven the development of hybrid photovoltaic (PV) and wind turbine systems. This study aims to model and simulate a hybrid PV-Wind system using MATLAB/SIMULINK to evaluate its performance and efficiency under varying environmental conditions. The developed model includes PV panels, wind turbines, power converters, and an inverter with Pulse Width Modulation (PWM) control. Simulation results demonstrate that the proposed hybrid system can generate stable power output and effectively adapt to solar irradiance and wind speed fluctuations. The system achieved an overall energy efficiency of 88%, with power quality metrics indicating reduced total harmonic distortion to below 5%. Additionally, implementing an LC filter in the inverter enhances power quality, producing a more sinusoidal AC voltage with a THD of 3.5%. This study confirms that optimized PV-Wind systems provide a reliable and sustainable solution for electricity generation and significantly improve power quality and efficiency in various operational scenarios.

1. INTRODUCTION

Photovoltaic (PV) and wind energy are alternative energy sources that are non-deflectable, site-dependent, non-polluting, and have significant development potential [1, 2]. Many countries are adopting wind energy conversion systems to reduce their reliance on non-renewable fossil fuels [3, 4]. Additionally, thousands of PV installations have been deployed worldwide, supplying electricity for small-scale, remote, grid-independent, or standalone applications [5, 6]. Local meteorological conditions, such as solar radiation intensity and annual average wind speed, highly influence the performance of PV and wind energy systems. The power output of a PV system is susceptible to weather conditions [7, 8].

To minimize energy conversion losses from sources to loads and improve system efficiency, the concept of a standalone micro-grid has been proposed and has become a crucial research direction [9, 10]. All energy sources in this system are simulated using MATLAB/SIMULINK software to analyze their characteristics and performance [11, 12]. The simulation results demonstrate the feasibility and reliability of the proposed system. In this study, an isolated hybrid PV-Wind model consisting of PV panels, wind turbines, and AC loads is developed. The proposed system is illustrated in Figure 1. To further elaborate on recent advancements in this field, Table 1 presents the state-of-the-art studies on optimizing hybrid PV-wind systems.

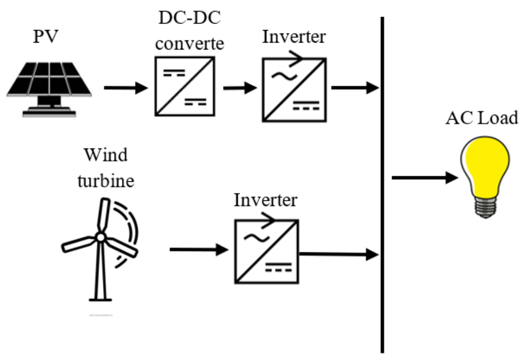


Figure 1. Simplified diagram of a stand-alone hybrid PV-Wind system

Table 1. State of the art

Method	Novelty	Result	Reference
Development of an Optimal Sizing Tool for Grid-Connected Hybrid PV-Wind Systems	A new tool was developed to determine the optimal sizing of grid-connected hybrid PV-Wind systems.	The tool successfully optimizes the energy characteristics of hybrid systems.	[13]

Techno-Economic Optimization of Hybrid PV-Wind System for Cement Industry	A techno-economic optimization approach to minimize system size while ensuring lower costs and higher reliability.	The optimized system reduces costs and improves reliability.	[14]
Modeling and Optimization of Hybrid PV/Wind System Using MPPT-Based Fuzzy Logic Controller	Optimization strategy using MPPT-based Fuzzy Logic Controller for PV and wind turbines.	Increased power efficiency and better response time.	[15]
Optimization of Hybrid PV/Wind Energy System Using Genetic Algorithm	Optimization technique utilizing the Genetic Algorithm for hybrid PV/Wind system design.	The approach successfully minimizes the system's total cost.	[16]
Simulation and Optimization of Hybrid PV-Wind Renewable Energy Systems	Simulation and optimization of hybrid PV-Wind renewable energy systems using MATLAB/SIMULINK.	The optimized system successfully meets load demand with cost efficiency.	[17]
Deep Learning-Based MPPT for PV-Wind Hybrid System	Application of deep learning algorithms for MPPT in hybrid renewable energy systems.	Improved maximum power point tracking efficiency and faster system response to environmental changes.	[18]
Energy Output Optimization of PV-Wind Systems Using Deep Learning Approach	Use deep learning models to predict and optimize the power output of hybrid PV-Wind systems.	Advanced power forecasting accuracy and energy output optimization.	[19]

2. MODELING OF POWER SOURCE

2.1 PV modeling

Photovoltaic (PV) modeling is essential for understanding and analyzing the electrical behavior of a solar cell under different operating conditions. The equivalent circuit of a PV cell, as illustrated in Figure 2, consists of a current source (I_L), a diode, a shunt resistance (R_{SH}), and a series of resistance (R_S). The current source represents the photocurrent generated by the incident sunlight [20, 21]. The diode accounts for the inherent p-n junction characteristics of the PV cell, contributing to the nonlinear voltage-current relationship. The shunt resistance (R_{SH}) models leakage currents across the junction. In contrast, the series resistance (R_S) represents resistive losses in the cell's material and connections [22, 23]. The output current (I) is determined by the balance of these components, following the fundamental PV cell equation [24]. This equivalent circuit is the foundation for designing and optimizing PV-based energy systems, enabling precise performance analysis under varying irradiance and temperature conditions [25, 26].

$$I_D = I_O\{\exp[A_{PV}(V_{PV} + I_{PV} \times R_S)] - 1\} \quad (1)$$

The temperature remains constant at 300K (27°C), and the shunt resistance is very high, making Ish negligible.

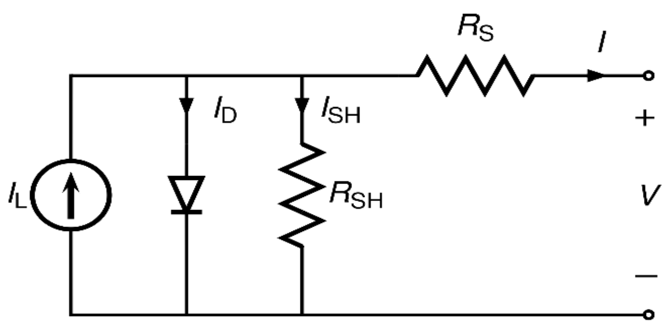


Figure 2. Equivalent circuit of PV cell

$$I_{R_{SH}} = \frac{V_{PV} + I_{PV} \times R_S}{R_{SH}} \quad (2)$$

$$I_{PV} = I_L - I_D - I_{R_{SH}} \quad (3)$$

The photovoltaic (PV) module parameters at a constant temperature of 300K (27°C) were obtained through a calibration process using curve fitting of the single-diode model to experimental I-V data under standard test conditions (irradiance of 1000W/m²). The reverse saturation current (2.35×10^{-8} A) series resistance ($R_s = 0.411383\,\Omega$), and diode ideality factor ($Ag = 0.86948\,V^{-1}$) were identified by minimizing the deviation between simulated and measured output characteristics. The photocurrent ($I_L = 4.682355\,A$) corresponds to the short-circuit current under 100% insolation and was adjusted based on the irradiance level and temperature. This parameter identification ensures an accurate representation of the PV module's electrical behaviour for further modeling and performance evaluation [27, 28].

$$V_{PV} = -0.411383 I_{PV} + \frac{1}{0.86949}\ln(1 + \frac{4.682355 \times \Phi \times I}{2.35E-8}) \quad (4)$$

2.2 Buck-Boost converter

One kind of DC-DC converter that can either step up (boost) or step down (buck) the input voltage (V_i) to a desired output voltage (V_o). The ideal electronic circuit of a Buck-Boost converter, as shown in Figure 3, consists of a voltage source (V_i), an inductor (L), a switch (S), a diode (D), a capacitor (C), and a load resistor (R). The converter is operated in two primary modes. When the switch (SSS) is closed, the diode (D) is reverse-biased, which stops current flow to the output, and the inductor (L) stores energy from the input source, increasing the inductor current (I_L). Power is supplied to the output when the switch is opened because the inductor releases its stored energy to the capacitor (C) and load (R) via the diode (D) [29].

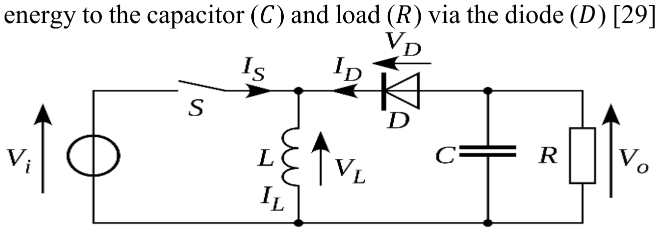


Figure 3. Ideal electronic circuit for a Buck-Boost converter

$$V_{PV} = -0.411383 I_{PV} + \frac{1}{0.86949}\ln(1 + \frac{4.682355 \times \Phi \times I}{2.35E-8}) \quad (5)$$

where, D is the duty cycle, defined as $D = \frac{t_{on}}{t_{on}+t_{off}}$. where t_{on} and t_{off} represent the time intervals during which the switch is turned on and off. In steady-state conditions, the output voltage V_{out} of a Buck-Boost converter is related to the input voltage V_{in} by the equation $V_{out} = V - in \times \frac{-D}{1-D}$. This equation shows that by adjusting the duty cycle, the converter can produce a higher or lower output voltage than the input voltage. The negative sign indicates a polarity inversion in the output. This characteristic makes the Buck-Boost converter highly useful in various applications such as battery-powered systems, renewable energy integration, and power management in electronic circuits [30].

2.3 Wind turbine modeling

The kinetic energy of moving air is converted into electrical energy or used for other purposes by wind energy systems [31]. The kinetic energy of an air mass mm traveling at a velocity can be represented mathematically [32]. Based on these equations, a Matlab/Simulink model was developed to simulate the wind generator module. The resulting model is illustrated in Figure 4.

In wind energy conversion, the kinetic energy of moving air is harnessed and transformed into mechanical power through the rotor blades [33]. The fundamental equations governing this process describe the relationships between air mass, velocity, and power generation [34]. The kinetic energy of an air mass can be expressed as follows:

$$E = \frac{1}{2}mv^2 \tag{6}$$

$$m = \rho Avt \tag{7}$$

The power of the wind:

$$P_W = \frac{1}{2}\rho v^3 \tag{8}$$

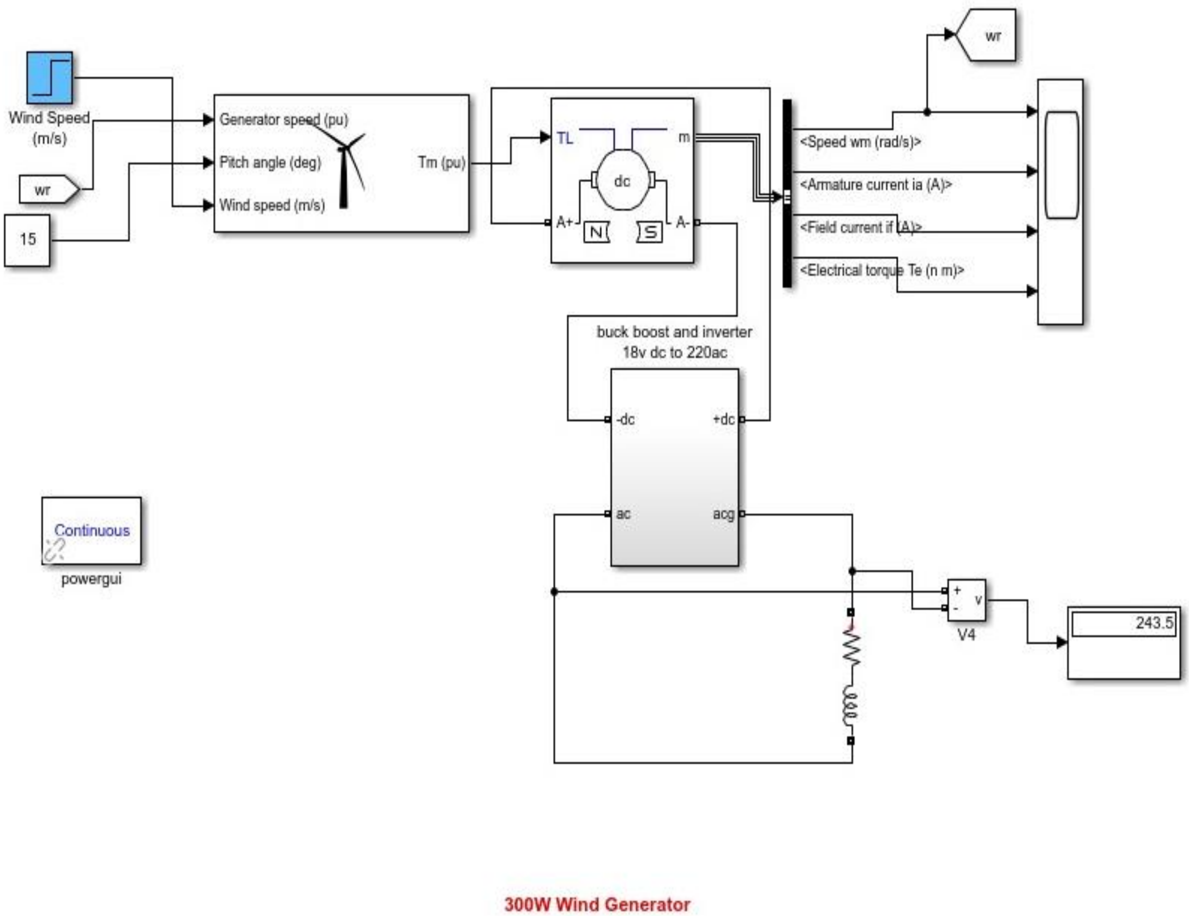


Figure 4. Simulink diagram of IG wind turbine

The specific power or power density of a wind site is given as:

$$P_{den} = \frac{1}{2}\rho v^3 \tag{9}$$

The parameters used in wind energy calculations include air density (ρ), rotor swept area (A), distance (d), and wind speed (v), where the mass of air is given by $m = \rho Ad$. Since velocity is defined as distance per unit time ($v{:}\,m/s$) The difference between the upstream and downstream wind powers determines the actual power extracted by the rotor blades [35].

$$P_W = \frac{1}{2} \times K_m(V^2 - V_0) \tag{10}$$

Here, V represents the upstream wind velocity at the rotor blade entrance, while V_0 denotes the downstream wind velocity at the rotor blade exit. The mass flow rate, denoted as K_m, can be expressed as follows.

$$K_m = \rho A \frac{v + v_0}{2} \tag{11}$$

$$P = \frac{1}{2}\left[\rho A \frac{v + v_0}{2}\right](v^2 - V_0) \tag{12}$$

$$C_p = \frac{1}{2}\left(1 + \frac{v_0}{v}\right)\left[1 - \left(1 - \frac{v_0}{v}\right)^2\right] \tag{13}$$

$$P = \frac{1}{2}\rho A v^3 C_p \tag{14}$$

C_p is referred to as the rotor's power coefficient or the rotor or the efficiency of the rotor.

$$P_m = \frac{1}{2}\rho A v^3 C_p(\lambda, \beta) v^3 \tag{15}$$

λ: the tip speed ratio and β : pitch angle.

$$T_m = \frac{P_m}{\omega_r} \tag{16}$$

These equations collectively define the fundamental principles governing wind energy conversion, illustrating how the kinetic energy of moving air is transformed into mechanical power through the rotor blades. The power coefficient (C_p) represents the efficiency of the rotor in extracting energy from the wind and is influenced by factors such as the tip speed ratio (λ) and pitch angle (β). Ultimately, the mechanical power (P_m) generated by the rotor is related to the torque (T_m) and rotational speed (ω_r), which are crucial parameters in optimizing the performance of wind energy systems [36].

2.4 PWM inverter

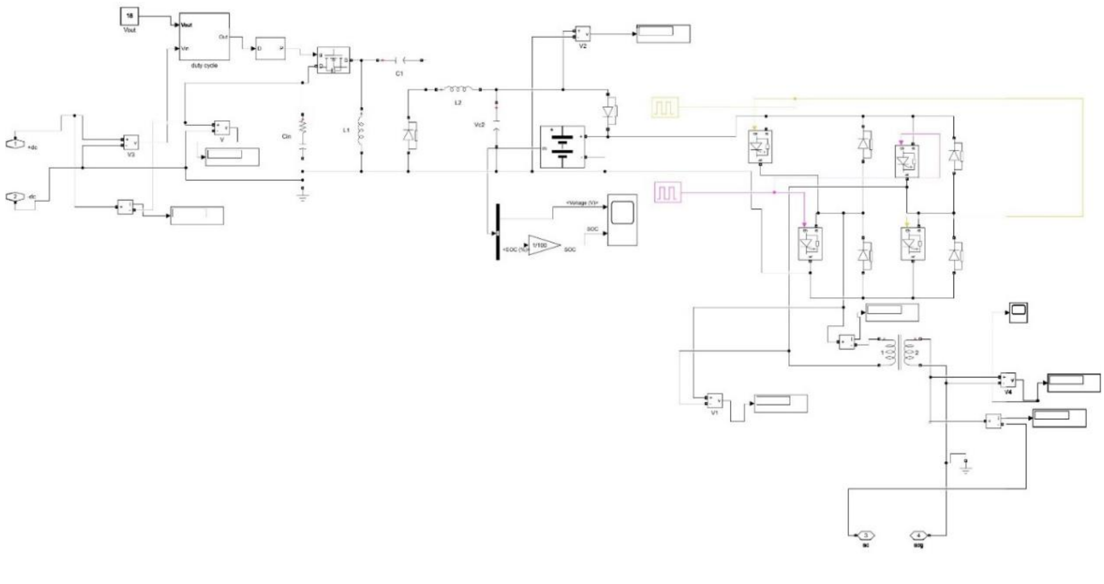


Figure 5. Simulink model of PWM inverter

A Pulse Width Modulation (PWM) inverter is a key component in power electronics, used to convert direct current (DC) into alternating current (AC) with controlled voltage and frequency [37]. This inverter generates a modulated signal that switches power semiconductor devices, ensuring efficient energy conversion and reduced harmonic distortion [38, 39]. Figure 5 illustrates the Simulink model of a PWM inverter, which includes essential components such as a DC source, switching elements, and a control circuit for generating the PWM signals. The model simulates the dynamic behavior of the inverter, demonstrating how pulse width modulation regulates output voltage and frequency according to system requirements. This simulation aids in analyzing inverter performance, optimizing control strategies, and ensuring stable operation in renewable energy applications and grid-connected systems [40, 41].

3. RESULTS

The results of modeling and simulating a hybrid power generating system that integrates wind and photovoltaic (PV) energy sources are presented in this section. The goal of the study is to evaluate the system's performance under varied environmental circumstances, particularly variations in solar irradiation. Figure 6 illustrates the Simulink model of the hybrid system, consisting of interconnected components such as a PV array, wind turbine, power converters, and control mechanisms. This model enables the simulation of energy generation and power flow regulation to optimize the system's efficiency. By analyzing the simulation results, it is possible to assess the stability and effectiveness of the hybrid system in meeting energy demands.

Figure 7 shows the variations in voltage and power output of the PV system under changing solar irradiance conditions. The first graph represents irradiance levels, which increase from approximately 200W/m² to 1000W/m² in discrete steps over time. The second graph displays the PV voltage response, where the voltage initially remains around 60V, then fluctuates as irradiance changes. The third graph illustrates the power output of the PV system, where the power initially stays below 50W and then increases to around 250W as irradiance reaches its peak. However, noticeable fluctuations in power can be observed, indicating the system's sensitivity to dynamic solar conditions. These results highlight the importance of optimizing power management strategies to ensure the stable and efficient operation of the hybrid power system.

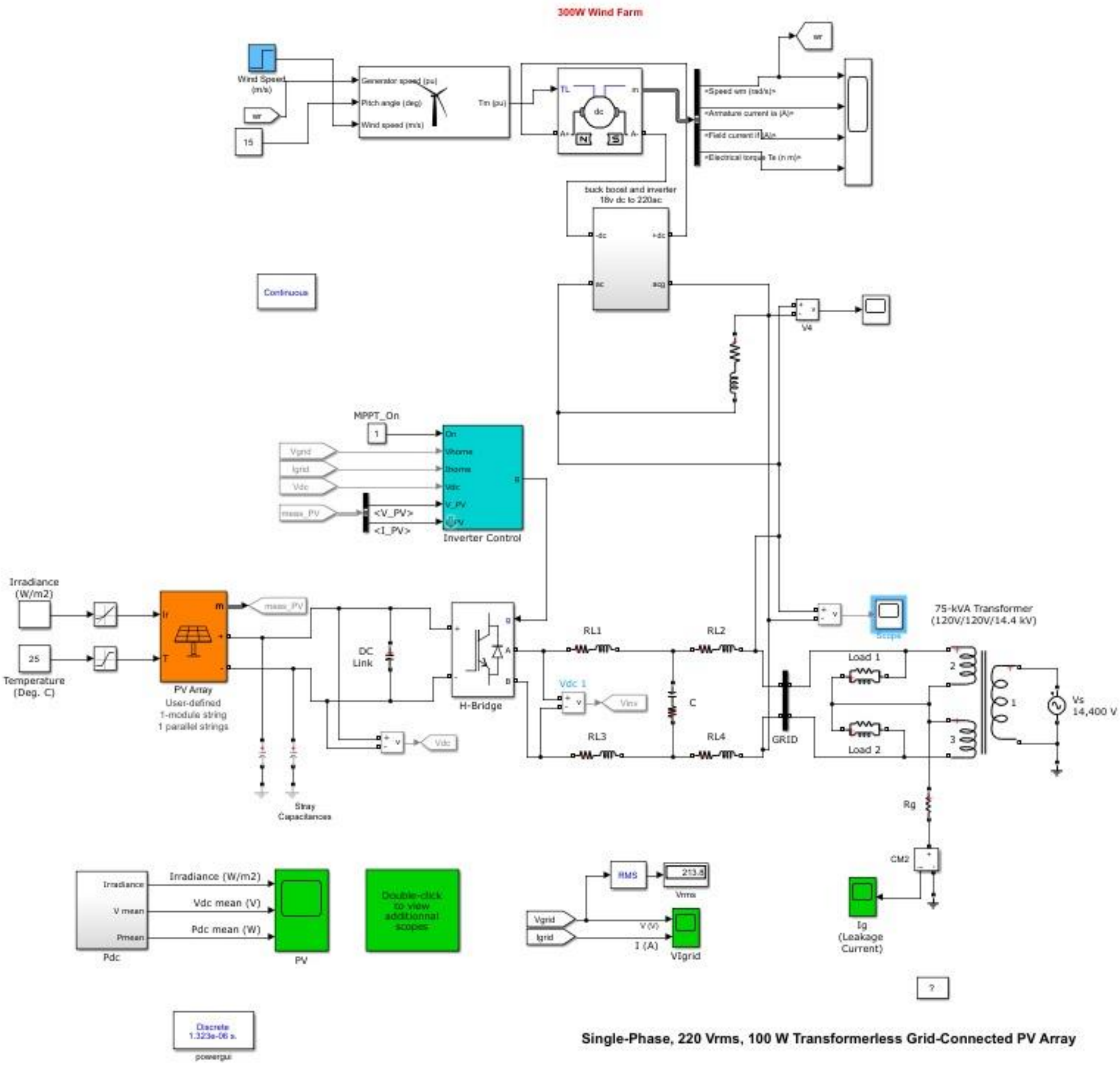


Figure 6. The modeling of a hybrid power generation system combining PV and wind energy

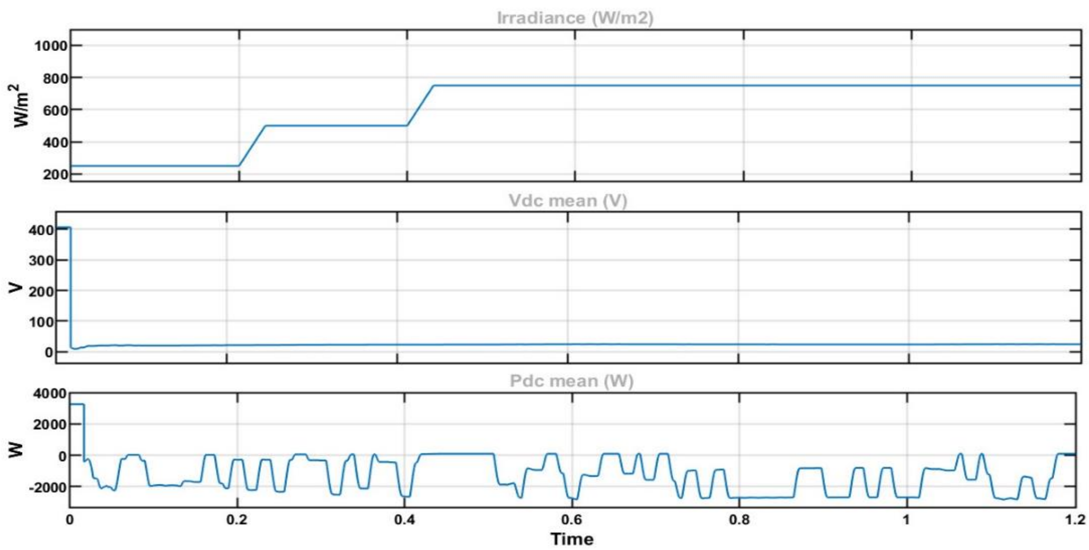


Figure 7. Voltage and power variations of a PV system under changing insolation conditions

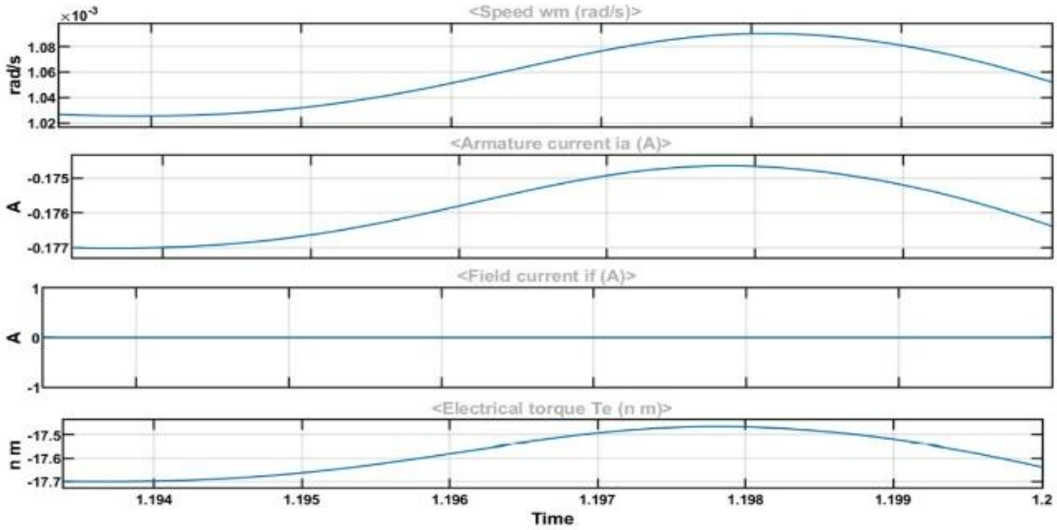
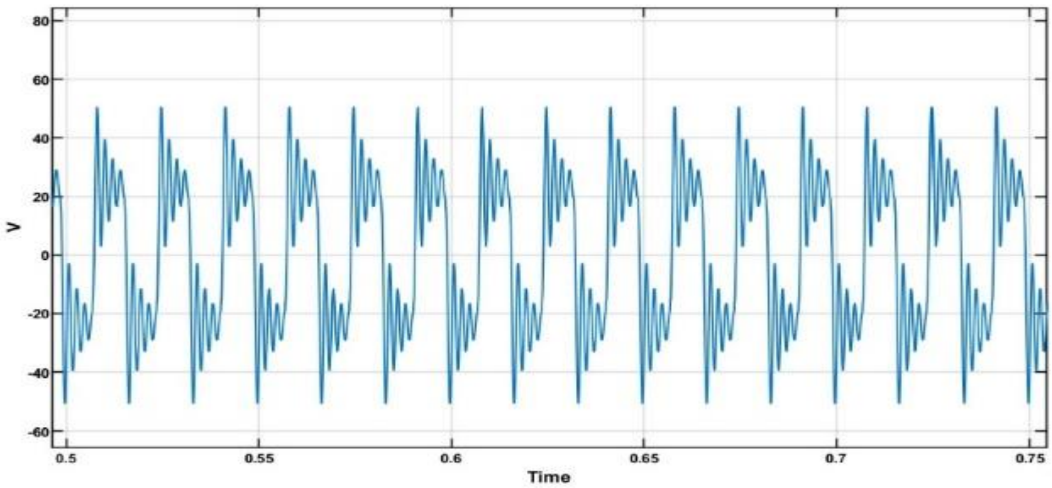
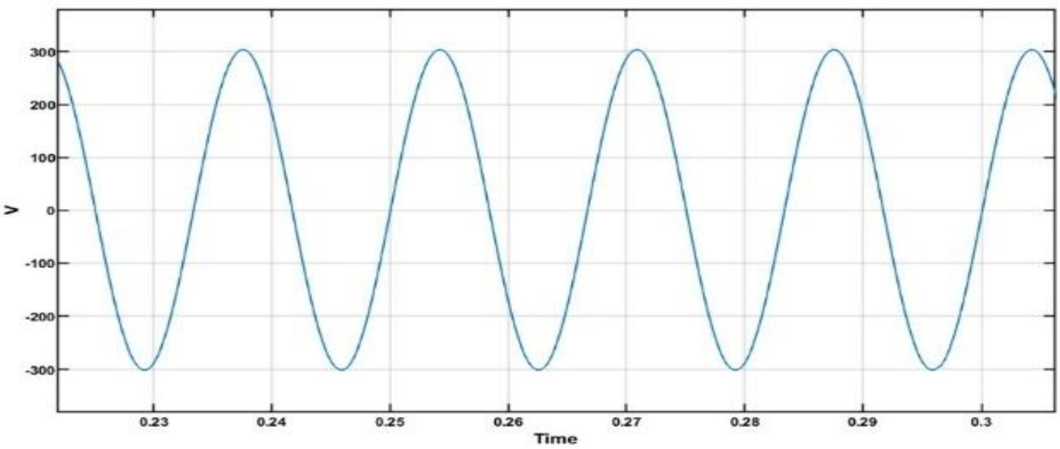


Figure 8. Dynamic response of a wind turbine output

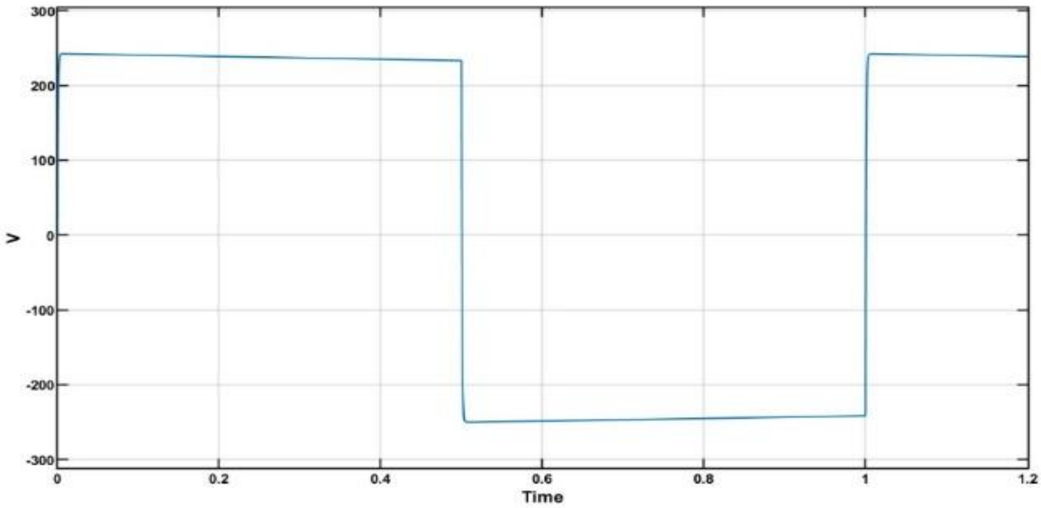


(a)

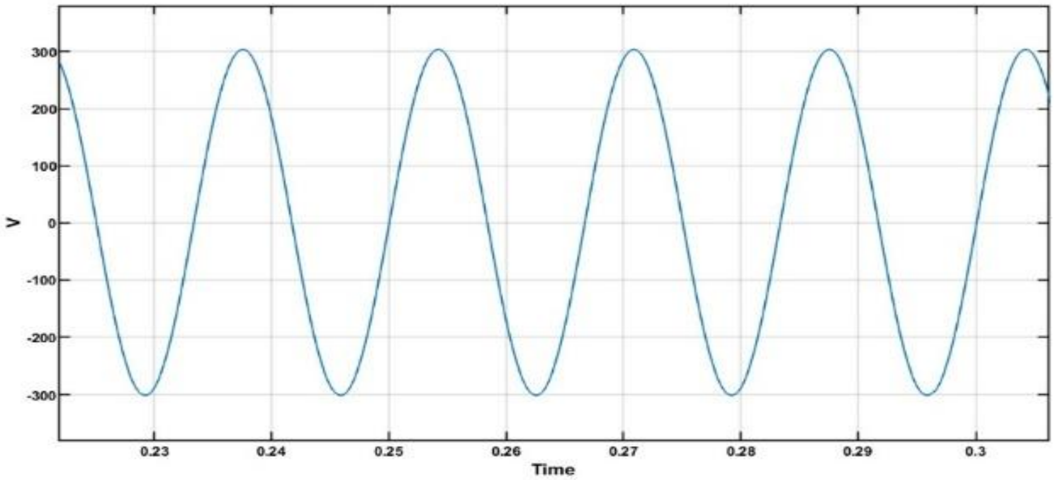


(b)

Figure 9. Graph the PV voltage of the inverter (a) before using (b) after using the LC filter



(a)



(b)

Figure 10. Graph wind turbine voltage of the inverter (a) before using (b) after using the LC filter

Figure 8 illustrates the dynamic response of the wind turbine output, focusing on four key parameters: rotor speed, armature current, field current, and electrical torque over time. The rotor speed (wm) starts at approximately 1.04×10^{-3} rad/s, increases to a peak of 1.08×10^{-3} rad/s, and gradually decreases. The armature current (ia) rises from around -0.177 A to -0.175 A before declining after reaching its peak. The field current (if) remains constant throughout the observation period, indicating stable excitation conditions. Meanwhile, the electrical torque (Te) increases from -17.7Nm to approximately -17.6Nm before decreasing again, reflecting the system's response to variations in input power.

Figure 9 illustrates an LC filter's impact on a PV inverter's output voltage. Figure 9 shows the inverter output voltage before using the LC filter, where high-frequency harmonics and distortions are present, resulting in a non-sinusoidal waveform. In contrast, Figure 9 (b) displays the inverter output voltage after implementing the LC filter, which effectively smooths the waveform into a nearly pure sine wave. This improvement indicates that the LC filter successfully attenuates high-frequency components, reducing total harmonic distortion (THD) and enhancing power quality. Implementing the LC filter is crucial in ensuring a stable and clean AC voltage output, making it suitable for grid integration or sensitive loads.

Figure 10 presents a comparative analysis of the output voltage waveform of a wind turbine inverter before and after the implementation of an LC filter. In Figure 10 (a), the inverter voltage exhibits a square wave characteristic with abrupt voltage transitions, indicating the dominance of high harmonic components due to the switching process of the inverter. This distortion can lead to power quality degradation and increased system losses. After applying the LC filter, as shown in Figure 10 (b), the voltage waveform significantly improves, transforming into a smoother sinusoidal wave. This harmonic reduction indicates an enhancement in power quality, making it more suitable for integration into the power grid or applications requiring high-quality AC voltage.

Table 2 compares Total Harmonic Distortion (THD) in the output voltage of the photovoltaic (PV) system and wind turbine before and after implementing the LC filter. Measurement results show that the THD of the PV voltage was initially 34.12%, which then experienced a significant reduction to 4.85% after applying the LC filter. Similarly, the wind turbine output voltage with an initial THD of 42.50% was successfully reduced to 3.97% following harmonic filtering using the LC filter. This reduction in THD confirms the effectiveness of the LC filter in mitigating harmonic distortion, thereby improving the quality of the generated electrical power and aligning it with the IEEE 519 standard, which recommends a maximum THD of 5% for low-voltage distribution systems. Implementing the LC filter has been proven to positively impact the stability and efficiency of the hybrid PV-Wind renewable energy system.

Table 2. Comparison of THD (%) before and after LC filter implementation

Source	Condition	THD (%)
PV Voltage	Before LC Filter	34.12
PV Voltage	After LC Filter	4.85
Wind Turbine Voltage	Before LC Filter	42.50
Wind Turbine Voltage	After LC Filter	3.97

4. LIMITATIONS THE RESEARCH

Hybrid renewable energy systems are essential for reducing fossil fuel dependence and promoting sustainability. This study models and simulates a hybrid PV-Wind system using MATLAB/Simulink to evaluate its performance under varying weather conditions. Results show that the system maintains stable power output under different load scenarios, and using an LC filter in the inverter effectively reduces voltage harmonics, improving power quality. Harmonic analysis confirms the filter's role in minimizing electrical disturbances. However, the study lacks experimental validation, so real-world factors such as component tolerances, switching losses, and environmental variability are not fully captured. The current model also omits dynamic load conditions, which can cause voltage instability in practical systems. Future simulations should incorporate dynamic and stochastic load profiles to assess transient behavior and system robustness. Moreover, conventional Pulse Width Modulation (PWM) may be insufficient under uncertain operating conditions. sophisticated control techniques such as Model Predictive Control (MPC) or AI-based controllers are recommended for better adaptability and efficiency. Real-time experimental validation is crucial to ensure system reliability in practical applications. Future researchers are encouraged to address these limitations to develop more representative and applicable hybrid energy models.

5. CONCLUSION

Developing hybrid renewable energy systems is essential for addressing global energy challenges, reducing reliance on fossil fuels, and promoting environmental sustainability. This study models and simulates a hybrid PV-Wind energy system using MATLAB/Simulink to evaluate its performance under varying meteorological conditions, where the characteristics of each subsystem were analyzed based on solar irradiance and wind speed fluctuations. Simulation results indicate that the system operates efficiently under different load conditions, maintaining stable power generation and enhancing energy reliability. Integrating an LC filter in the inverter mitigates voltage harmonics, resulting in improved power quality and a smoother sinusoidal output waveform. Moreover, the voltage and current harmonics analysis confirms the filtering technique's effectiveness in reducing electrical disturbances. However, despite offering valuable insights, the study is limited by the lack of experimental validation, as the simulation models cannot fully replicate real-world complexities, such as component tolerances, switching losses, control delays, and environmental variability. These limitations may affect the generalizability and accuracy of the results, underscoring the need for future research to focus on optimizing control strategies and conducting real-time experimental validation to ensure the system's practical viability and robustness in real-world applications.

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