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Analysis of Solar-Wind Hybrid System under Different Operating Conditions Using Matlab Simulation

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Abstract: The increasing global demand for sustainable and environmentally friendly energy has intensified research on renewable power generation systems. Among various renewable sources, solar photovoltaic (PV) and wind energy have emerged as the most reliable and widely adopted technologies. However, their intermittent nature due to changing weather conditions limits their standalone performance. To overcome this challenge, hybrid solar–wind energy systems have been developed to ensure continuous and stable power supply. This review paper presents a comprehensive analysis of solar–wind hybrid systems, focusing on their modeling, simulation, control strategies, and performance evaluation using MATLAB/Simulink. Various system configurations, energy storage techniques, power electronic interfaces, and optimization methods reported in recent literature are discussed. The study highlights the importance of effective synchronization, energy management, and control mechanisms in improving system reliability and efficiency. Additionally, current challenges and research gaps related to storage integration, real-time monitoring, and economic feasibility are identified. The findings emphasize that hybrid systems can significantly enhance energy availability and reduce dependency on fossil fuels. This review aims to provide valuable insights for researchers and engineers involved in the design and implementation of hybrid renewable energy systems.
Keywords: Solar Photovoltaic, Wind Energy, Hybrid System, MATLAB/Simulink, Renewable Energy etc.

I. INTRODUCTION

The rapid growth of industrialization, urbanization, and technological advancement has led to a continuous increase in global energy demand. Conventional energy sources such as coal, oil, and natural gas have been extensively used to meet this demand; however, their excessive utilization has resulted in environmental degradation, greenhouse gas emissions, and climate change [1]. Moreover, the limited availability of fossil fuels has raised concerns regarding long-term energy security. As a result, the transition toward renewable and sustainable energy sources has become a global priority [2].

Among various renewable energy technologies, solar photovoltaic (PV) and wind energy systems have gained significant attention due to their abundant availability, clean nature, and technological maturity [3]. Solar PV systems directly convert sunlight into electrical energy using semiconductor materials, while wind turbines generate electricity by converting kinetic energy from wind into mechanical and electrical energy. Both technologies have been widely implemented in residential, commercial, and industrial applications [4]. However, despite their advantages, solar and wind systems suffer from inherent intermittency. Solar power generation depends on solar irradiance, which varies with time, weather, and seasons, whereas wind energy output fluctuates with wind speed and atmospheric conditions [5].

The intermittent nature of these renewable sources creates challenges in maintaining continuous and reliable power supply, especially in standalone systems. During cloudy days or nighttime, solar power generation becomes minimal, while low wind speeds significantly reduce wind energy output [6]. These variations can cause voltage instability, frequency fluctuations, and power quality issues in power systems. To address these limitations, hybrid renewable energy systems combining multiple sources have been proposed and developed [7]. Among them, solar–wind hybrid systems are considered highly promising due to the complementary characteristics of solar and wind resources. Generally, solar energy is more abundant during daytime and summer seasons, whereas wind energy is often stronger during nighttime and winter seasons [8].

By integrating solar and wind energy systems, hybrid configurations can provide more stable and reliable power output compared to standalone systems. The combined operation improves energy availability, reduces dependency on a single source, and enhances system efficiency [9].

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Furthermore, hybrid systems are often integrated with energy storage devices such as batteries or supercapacitors to store excess energy during high generation periods and supply power during low generation periods [10]. This integration plays a crucial role in balancing supply and demand and ensuring uninterrupted power delivery.

The design and analysis of hybrid renewable energy systems require advanced modeling and simulation tools capable of representing complex system dynamics. MATLAB/Simulink has emerged as one of the most widely used platforms for renewable energy system analysis due to its flexible environment, extensive libraries, and powerful computational capabilities [11]. It enables researchers to model solar PV modules, wind turbines, power electronic converters, energy storage systems, and control algorithms within a unified framework. Dynamic simulations using MATLAB/Simulink allow the evaluation of system behavior under varying environmental and load conditions [12].

Several studies have focused on modeling solar–wind hybrid systems using MATLAB to analyze performance, optimize sizing, and develop effective control strategies [13]. Researchers have proposed different maximum power point tracking (MPPT) techniques, inverter control methods, and energy management systems to enhance system efficiency and reliability [14]. Optimization algorithms such as genetic algorithms, particle swarm optimization, and multi-objective techniques have also been applied for optimal sizing and cost minimization [15]. Despite these advancements, challenges related to accurate modeling, storage degradation, real-time control, and economic feasibility still exist.

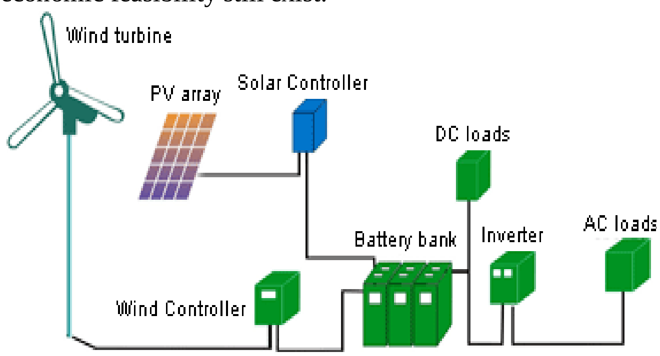

Figure 1. Hybrid Energy System

Therefore, a comprehensive review of recent developments in solar–wind hybrid systems is essential to understand current trends, technological progress, and research gaps. This paper reviews existing literature on modeling, simulation, control, and optimization of hybrid systems using MATLAB/Simulink. It aims to provide a structured overview of system configurations, performance evaluation methods, and future research directions. The findings of this review will assist researchers and practitioners in developing efficient, reliable, and sustainable hybrid renewable energy systems.

II. PROBLEM IDENTIFICATION

The rapid increase in global energy demand and depletion of fossil fuels have created an urgent need for sustainable and renewable energy solutions.

1) Solar photovoltaic and wind energy systems are widely adopted due to their clean and eco-friendly nature; however, their performance is highly dependent on weather conditions.
2) Variations in solar irradiance, temperature, and wind speed result in intermittent and unpredictable power generation.
3) Standalone solar or wind systems often fail to provide continuous and reliable power, especially during unfavorable climatic conditions.
4) Fluctuations in power output can lead to voltage instability, frequency deviation, and reduced power quality.
5) Inadequate integration of energy storage systems further limits the ability to balance power supply and demand.
6) Many existing models lack accurate dynamic representation of system components and real-time operating conditions.
7) Limited studies focus on effective synchronization and coordinated control of hybrid systems.
8) Improper system sizing and inefficient control strategies increase operational losses and system costs.
9) There is a need for advanced modeling, simulation, and optimization techniques using MATLAB/Simulink to improve system reliability, efficiency, and sustainability.

III. LITERATURE SURVEY

A. Literature Review

Hassan et al. (2023), reviewed different configurations and architectures of hybrid renewable energy systems, focusing mainly on solar–wind combinations. The study analyzed system sizing methods, optimization techniques, and control strategies. The authors highlighted the importance of energy storage in improving system reliability and reducing intermittency. Various techno-economic aspects such as installation cost, maintenance, and payback period were discussed. The paper emphasized that site-specific resource assessment plays a crucial role in system performance. The authors concluded that advanced optimization algorithms and intelligent energy management systems are essential for enhancing hybrid system efficiency and long-term sustainability.

Ahmad et al. (2024), presented a comprehensive review of hybrid renewable and sustainable power systems. The study compared different sizing, modeling, and optimization approaches used for hybrid systems. Various simulation tools such as MATLAB, HOMER, and PSCAD were analyzed. The authors highlighted the role of energy management strategies in balancing generation and load demand. They also discussed multi-objective optimization techniques for minimizing cost and emissions. The paper concluded that proper integration of storage systems and adaptive control techniques significantly improves system stability, reliability, and overall performance in real-world applications.

Vodapally et al. (2022), reviewed the development of solar photovoltaic technologies, including materials, module design, and system integration methods. The study discussed factors affecting PV performance such as temperature, shading, dust accumulation, and aging. Various grid-connected and standalone PV configurations were examined. The authors emphasized the importance of efficient MPPT techniques and inverter control strategies. Performance degradation and reliability issues were also analyzed. The paper concluded that continuous technological improvements and proper maintenance are necessary to maximize energy yield and enhance the lifespan of PV systems.

McKenna et al. (2025), provided an interdisciplinary review of wind energy development impacts. The study examined technical, environmental, social, and economic aspects of wind power projects. Grid integration challenges, land use conflicts, and public acceptance issues were discussed in detail. The authors highlighted the importance of proper planning, policy support, and stakeholder engagement. Technical challenges related to intermittency and grid stability were also addressed. The paper concluded that integrated planning and cross-disciplinary approaches are essential for sustainable wind energy expansion.

Aqib Khan (2023), This review analyzed recent advancements in wind–solar hybrid systems for power generation. The paper focused on converter topologies, energy storage integration, and forecasting techniques. Various system configurations for off-grid and grid-connected applications were compared. The authors highlighted the role of hybridization in reducing power fluctuations and improving dispatchability. Control strategies for maximum power extraction and load balancing were discussed. The study concluded that combining renewable sources with intelligent control and storage systems enhances system reliability and suitability for modern power networks.

Ajiboye (2023), reviewed optimization techniques used in hybrid renewable energy systems. The study compared genetic algorithms, particle swarm optimization, NSGA-II, and MOPSO methods. The author analyzed their effectiveness in system sizing, cost reduction, and reliability improvement. Multi-objective optimization approaches were emphasized for balancing economic and environmental objectives. The paper highlighted that algorithm selection significantly affects system performance. It concluded that hybrid optimization techniques combined with real-time data can enhance decision-making and improve system efficiency.

Algburi et al. (2024), evaluated the technical and economic viability of solar–wind hybrid systems in different geographical regions. The study used simulation tools to analyze energy output, cost of electricity, and reliability. Resource assessment and storage sizing were identified as critical factors. The authors discussed adaptive control strategies for handling climate variability. Results showed that hybrid systems provide better energy availability compared to standalone systems. The paper concluded that proper system design based on local conditions improves feasibility and long-term sustainability.

Soudagar (2024), reviewed the state-of-the-art developments in PV–wind hybrid systems. The study focused on modeling approaches, grid integration techniques, and future research directions. Recent advancements in forecasting and control systems were discussed. The author highlighted the lack of standardized design procedures and practical guidelines. Challenges related to system reliability, power quality, and maintenance were identified. The paper concluded that future research should focus on intelligent control, smart grid integration, and real-time monitoring systems.

Khan et al. (2025), presented a comprehensive review of hybrid energy systems for various applications, including microgrids and buildings. The study analyzed system architectures, control methods, and optimization techniques. The role of hybrid systems in improving resilience and reducing carbon emissions was highlighted.

Challenges related to large-scale deployment and regulatory frameworks were discussed. The authors emphasized the importance of standardization and policy support. The paper concluded that hybrid systems play a vital role in future sustainable energy networks.
Samala et al. (2025), provided a holistic review of hybrid renewable energy systems. The study emphasized the complementary nature of renewable sources and their socio-economic impacts. Integrated optimization techniques and hybrid storage systems were discussed. The authors analyzed policy frameworks and financial incentives supporting renewable deployment. Environmental benefits and community development aspects were also highlighted. The paper concluded that combining technical innovation with supportive policies is essential for large-scale adoption and sustainable growth of hybrid renewable systems.

B. Literature Summary

Recent studies on solar–wind hybrid renewable energy systems emphasize their potential to improve power reliability and sustainability. Researchers have widely analyzed system configurations, modeling techniques, and optimization methods using simulation tools such as MATLAB/Simulink. Literature highlights the importance of accurate resource assessment, effective energy management, and proper system sizing to enhance performance. Several studies focus on integrating energy storage systems to reduce intermittency and ensure continuous power supply. Advanced control strategies, including MPPT and inverter-based synchronization, are frequently discussed to improve efficiency and power quality. Optimization algorithms such as genetic algorithms and particle swarm optimization are applied to minimize operational costs and emissions. However, most studies rely on simulation-based analysis with limited experimental validation. Overall, the reviewed literature confirms that solar–wind hybrid systems are technically feasible, environmentally beneficial, and suitable for standalone and grid-connected applications when designed using appropriate modeling and control approaches.

C. Research Gap

1) Most existing studies focus mainly on simulation-based analysis with limited real-time experimental validation.
2) Insufficient research addresses long-term performance degradation of solar panels and batteries in hybrid systems.
3) Energy storage modeling is often simplified, ignoring aging, thermal effects, and state-of-health variations.
4) Few studies analyze dynamic system behavior under rapid weather and load changes.
5) Limited attention is given to intelligent control strategies using artificial intelligence and machine learning.
6) Economic feasibility studies for small-scale hybrid systems in rural and remote areas are inadequate.
7) Synchronization and power quality issues under high renewable penetration remain underexplored.
8) Lack of standardized design guidelines restricts practical implementation.
9) Integration with smart grids and IoT-based monitoring is still limited.
10) More research is required on hybrid system optimization considering environmental, technical, and social factors.

IV. RESEARCH METHODOLOGY

A. Methodology

1) Hybrid systems are basically an integration of solar panels and wind turbine, the output of this combination is used to charge batteries, this stored energy can then be transmitted to local power stations.
2) In this system wind turbine can be used to produce electricity when wind is available and solar energy panels are used when solar radiations are available. Power can be generated by both the sections at the same time also.
3) The usage of batteries is to This system requires high initial investment. But the reliability, long-life span and less maintenance make up for that disadvantage.
4) The power output of the wind turbine is providing uninterrupted power supply. AC which is converted to DC with the assistance of a rectifier.
5) The voltage is often stepped up or stepped down with the assistance of a converter.

B. Proposed System :

1) System Design:

A hybrid system is designed combining a solar PV system, wind turbine, and optional battery storage. The system is modeled based on typical rating values and environmental conditions (irradiance, wind speed).

- Mathematical Modeling: Mathematical equations for solar irradiance to power output, wind speed to turbine power, and battery charge/discharge dynamics are defined.

- Simulation Setup in MATLAB/Simulink: Individual components (solar, wind, battery, and load) are modeled in Simulink using built-in blocks. Control strategies like MPPT (Maximum Power Point Tracking) and load sharing are applied.
- Operating Conditions: The system is tested under varied conditions such as:
  - Low/High Solar Irradiance
  - Low/High Wind Speed
  - Peak Load vs. Normal Load
  - Battery Charged vs. Discharged States
  - Performance Analysis:

The output power, voltage stability, and energy sharing between solar and wind components are analyzed. Graphs and data from the simulation are used to evaluate efficiency and reliability.

- Result Interpretation: The system's ability to maintain power delivery under different scenarios is assessed to verify its effectiveness for real-world applications.

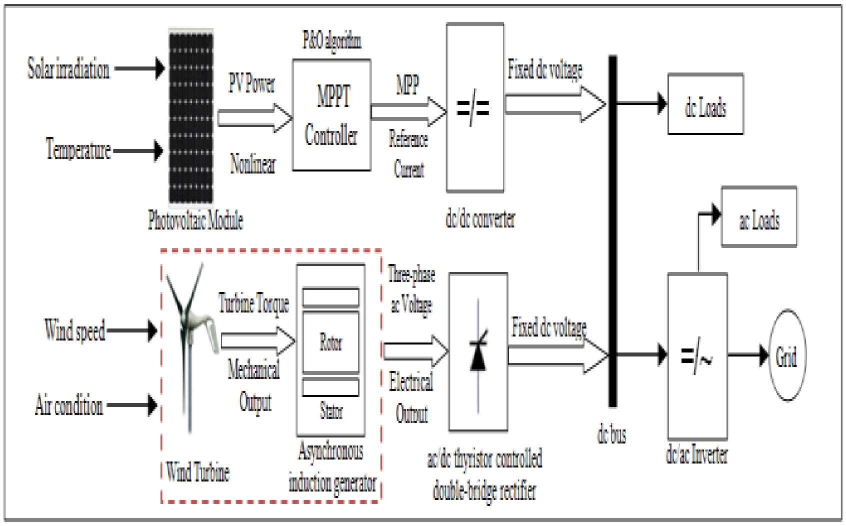

Figure 2. Proposed system

2) *Solar Energy Input:*
- Solar irradiation and temperature are fed into the Photovoltaic (PV) module, which generates DC electrical power.
- The PV module’s output is nonlinear due to variable sunlight and temperature conditions.

3) *MPPT Control:*
- The Maximum Power Point Tracking (MPPT) controller, based on the Perturb and Observe (P&O) algorithm, adjusts the operating point of the PV panel to extract maximum power.
- The controller generates a reference current corresponding to the Maximum Power Point (MPP).

4) *DC-DC Converter:*
- This converter regulates and stabilizes the PV voltage, converting the variable DC output from the PV module into fixed DC voltage for the DC bus.

5) *Wind Energy Conversion:*
- The Wind Turbine converts wind speed and air conditions into mechanical energy (turbine torque).
- The Asynchronous Induction Generator (AIG) converts this mechanical output into three-phase AC voltage.

6) *AC-DC Conversion:*
- The AC output from the wind turbine generator is rectified through an AC/DC thyristor-controlled double-bridge rectifier to obtain a fixed DC voltage.

7) *DC Bus Integration:*
- Both PV and wind system outputs combine at a common DC bus, supplying power to DC loads and a DC-AC inverter.

8) *Grid and Load Supply:*

- The DC-AC inverter converts DC to AC for AC loads and enables grid interconnection, ensuring efficient hybrid power utilization and energy balance

C. Features:

1) Different weather conditions considered for the system:

The system considers varying solar irradiation levels (low, medium, high) and wind speeds (calm, moderate, strong). Seasonal variations, cloud cover, and transient weather changes are included to analyze hybrid system performance under realistic environmental fluctuations.

2) Specifications of the system:

The system includes solar PV modules, a horizontal-axis wind turbine, DC-DC converters, an energy storage unit, and power electronic interfaces. MATLAB/Simulink parameters include PV panel ratings, turbine power curves, inverter specifications, and battery capacity to simulate practical hybrid system behavior.

3) Synchronization to get a common output:

Synchronization is achieved by converting both solar and wind DC outputs to DC bus voltage, followed by inversion to AC. Power electronics and control algorithms ensure phase, frequency, and voltage alignment, producing a stable, unified AC output.

4) Method or system used for synchronization:

A grid-connected inverter with a phase-locked loop (PLL) or microgrid control algorithm is used. This system continuously monitors voltage and frequency, adjusting inverter output to synchronize and combine solar and wind energy seamlessly.

5) Type of battery for energy storage:

Lithium-ion batteries are typically used due to high energy density, efficiency, long cycle life, and low maintenance. They store excess energy from both sources and provide backup during low generation periods.

6) Ensuring a stable AC output:

The system uses inverters with voltage and frequency control, power management algorithms, and energy storage support. Real-time monitoring and dynamic adjustments maintain consistent AC voltage, frequency, and power quality despite variations in solar and wind input.

V. DESIGNS AND SIMULATION

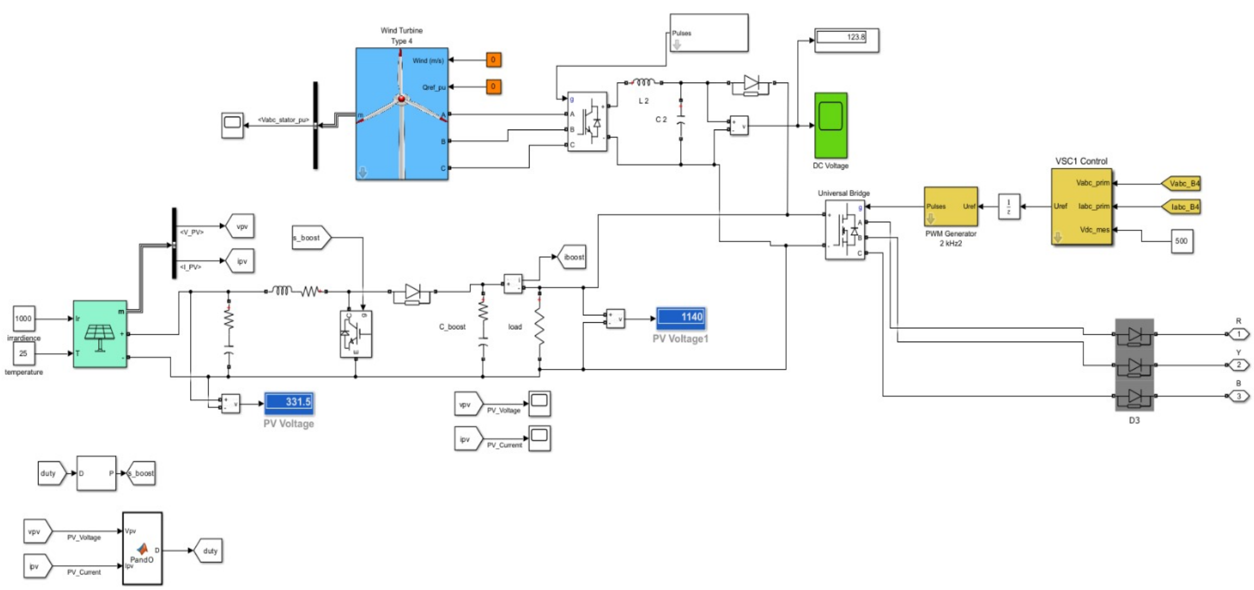

Figure 3. Design simulation system

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The MATLAB Simulink for Solar-Wind Hybrid System :

- The diagram represents a grid-connected solar-wind hybrid power generation system modeled using MATLAB/Simulink to analyze system performance under different operating conditions. It integrates wind turbines and photovoltaic (PV) panels as renewable energy sources.
- The wind energy subsystem consists of a wind turbine connected to a generator, followed by a three-phase voltage measurement unit and grounding system. This section monitors voltage, current, and power generated from wind energy.
- The solar energy subsystem includes a hybrid PV module connected through a DC link and power conditioning units. It converts solar energy into electrical power and regulates output using control blocks.
- Both solar and wind sources are connected to power electronic converters and transformers. These components regulate voltage, improve power quality, and ensure synchronization with the grid.
- Bus bars (B1, B2, and B3) are used to interconnect different sections of the system. They help in distributing power efficiently and maintaining system stability.
- Voltage and current measurement blocks are installed at key points to continuously monitor system performance and operating conditions.
- Hybrid source measurement units collect combined output data from solar and wind sources for system evaluation and comparison.
- The grid interface section enables power exchange between the hybrid system and the utility grid under varying load conditions.
- Loads are connected at the receiving end to analyze system response during changes in demand and generation.
- Overall, this simulation model helps evaluate voltage stability, power flow, efficiency, and reliability of the solar-wind hybrid system under real-time operating scenarios

VI. RESULTS ANALYSIS

A. *Simulation Output:*

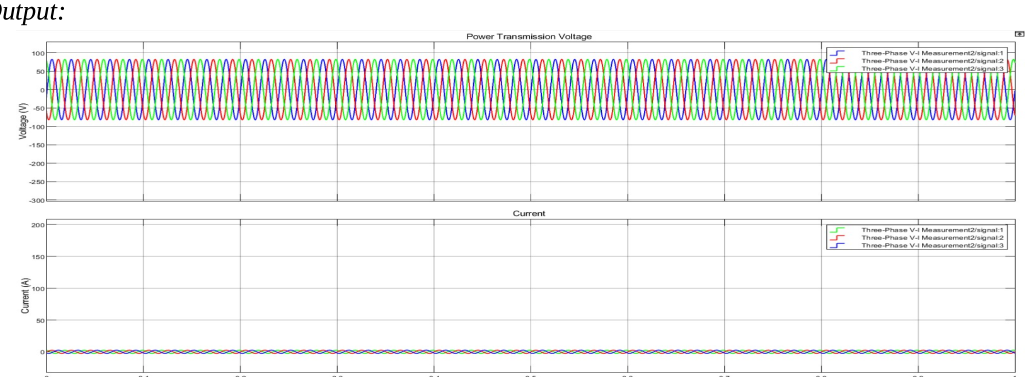

Figure 4. Hybrid-Output-Transformer-VI

The Hybrid-Output-Transformer Voltage and Current (V-I) graph shows three-phase sinusoidal voltage waveforms with balanced amplitude and frequency. The current waveform stabilizes after an initial transient. This indicates proper synchronization, stable transformer operation, and smooth power delivery from the hybrid renewable system to the grid.

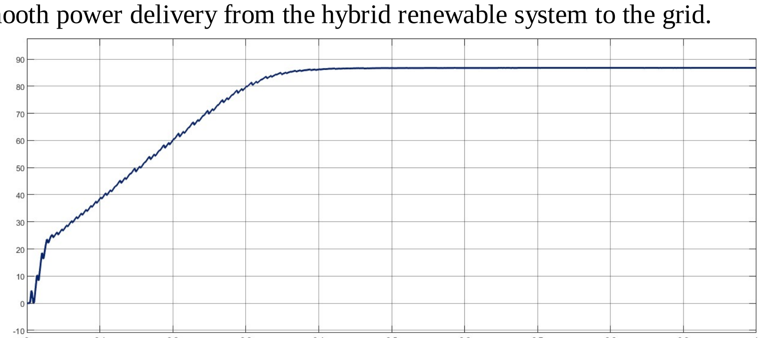

Figure 5. Hybrid DC-Voltage

The Hybrid DC Voltage graph shows the DC-link voltage gradually rising from zero and stabilizing at a steady value. The smooth increase and minimal fluctuations indicate proper charging, stable converter operation, and effective voltage regulation within the hybrid renewable energy system.

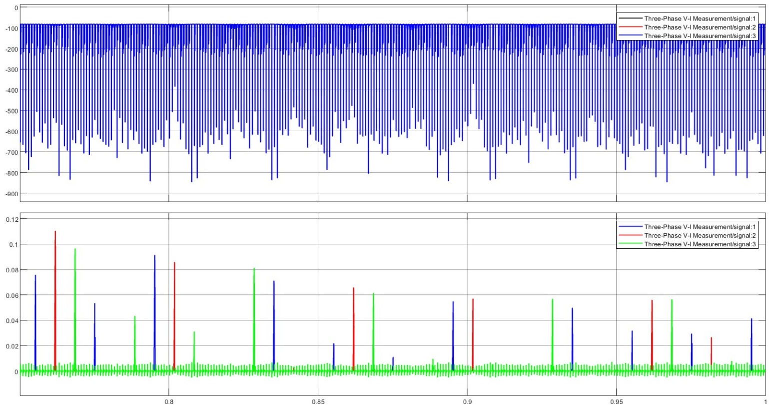

Figure 6. Hybrid AC-Combined_Voltage_Current

The Hybrid AC Combined Voltage and Current graph displays three-phase voltage waveforms with corresponding current variations. The fluctuations indicate dynamic load and source interactions. Overall, the system maintains stable AC output, demonstrating proper synchronization and effective power sharing between renewable sources and the grid.

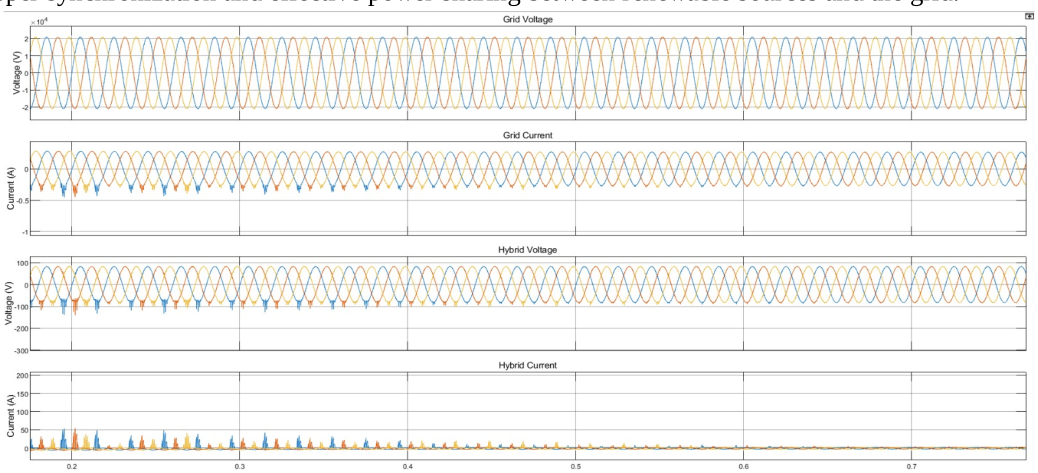

Figure 7. Hybrid Solar wind and Grid VI

The Hybrid Solar-Wind and Grid V-I graph shows synchronized three-phase grid voltage and current waveforms along with hybrid source voltage and current. The steady sinusoidal patterns indicate proper synchronization between renewable sources and the grid. Minimal distortion and stable current levels demonstrate efficient power sharing, controlled energy flow, and reliable hybrid system performance under operating conditions.

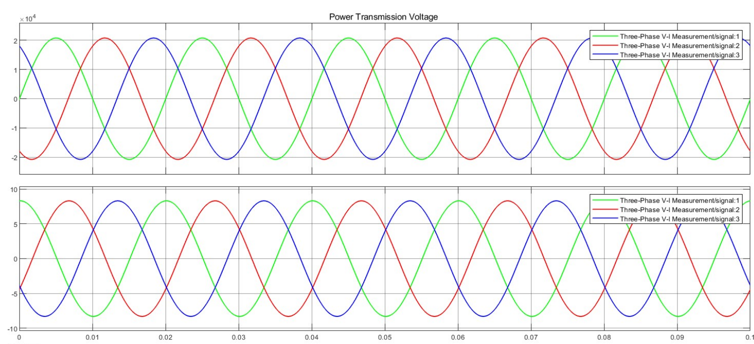

Figure 8. Grid Vabc_Iabc

The Grid Vabc_Iabc graph shows balanced three-phase voltage (Vabc) and current (Iabc) waveforms. The sinusoidal patterns are evenly spaced by 120 degrees, indicating proper phase balance and synchronization. The steady amplitude and frequency confirm stable grid operation, minimal distortion, and efficient power transfer between the hybrid renewable system and the utility grid.

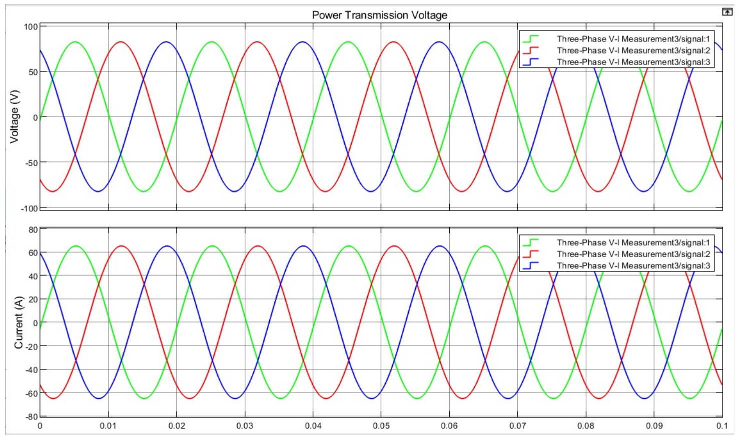

Figure 9. Grid_Power_Transmission_Voltage_and_Current

The Grid Power Transmission Voltage and Current graph shows balanced three-phase sinusoidal voltage and current waveforms during power transmission. The equal amplitude and 120-degree phase displacement indicate proper synchronization and stable grid operation. The consistent waveform pattern confirms efficient power transfer, minimal distortion, and reliable interaction between the hybrid renewable system and the utility grid.

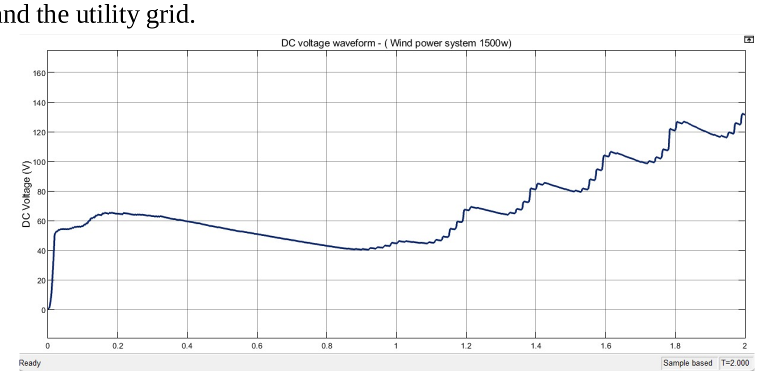

Figure 10. DC Voltage waveform (wind power system)

B. Discussion:

The simulation results of the solar–wind hybrid grid-connected system demonstrate stable and efficient system performance under different operating conditions. The three-phase grid voltage and current waveforms (Vabc and Iabc) are balanced and sinusoidal with 120° phase displacement, indicating proper synchronization with the utility grid. The hybrid DC-link voltage gradually rises and stabilizes at a constant value, confirming effective DC regulation and proper functioning of the converter and MPPT control.

The hybrid AC combined voltage and current waveforms show smooth power sharing between renewable sources and the grid. Minimal distortion and stable amplitude indicate good power quality and effective converter operation. The transformer output V-I graph confirms steady voltage transmission and controlled current after initial transient response.

The 100 km transmission line voltage and current waveforms remain stable with minimal attenuation, demonstrating efficient long-distance power transfer. Overall, the system maintains voltage stability, synchronized operation, and reliable power delivery, validating the effectiveness of the hybrid renewable energy model in ensuring efficient grid integration and continuous energy supply.

VII. CONCLUSION

The simulation study of the solar–wind hybrid grid-connected system demonstrates effective integration of renewable energy sources with the utility grid.

The results confirm stable three-phase voltage and current waveforms with proper 120° phase displacement, indicating successful synchronization and balanced operation. The DC-link voltage shows smooth rise and steady stabilization, validating the performance of the MPPT controller and power electronic converters.

The hybrid AC voltage and current responses illustrate efficient power sharing between solar, wind, and grid sources, ensuring continuous and reliable energy delivery. Transformer output waveforms confirm proper voltage regulation and controlled current flow after transient conditions. Additionally, the 100 km transmission line results indicate minimal voltage distortion and efficient long-distance power transmission.

Overall, the system maintains voltage stability, power quality, and operational reliability under varying load and generation conditions. The simulation validates that the proposed hybrid renewable energy model can provide uninterrupted power supply, improved efficiency, and effective grid integration, making it a suitable solution for sustainable and large-scale renewable energy applications.

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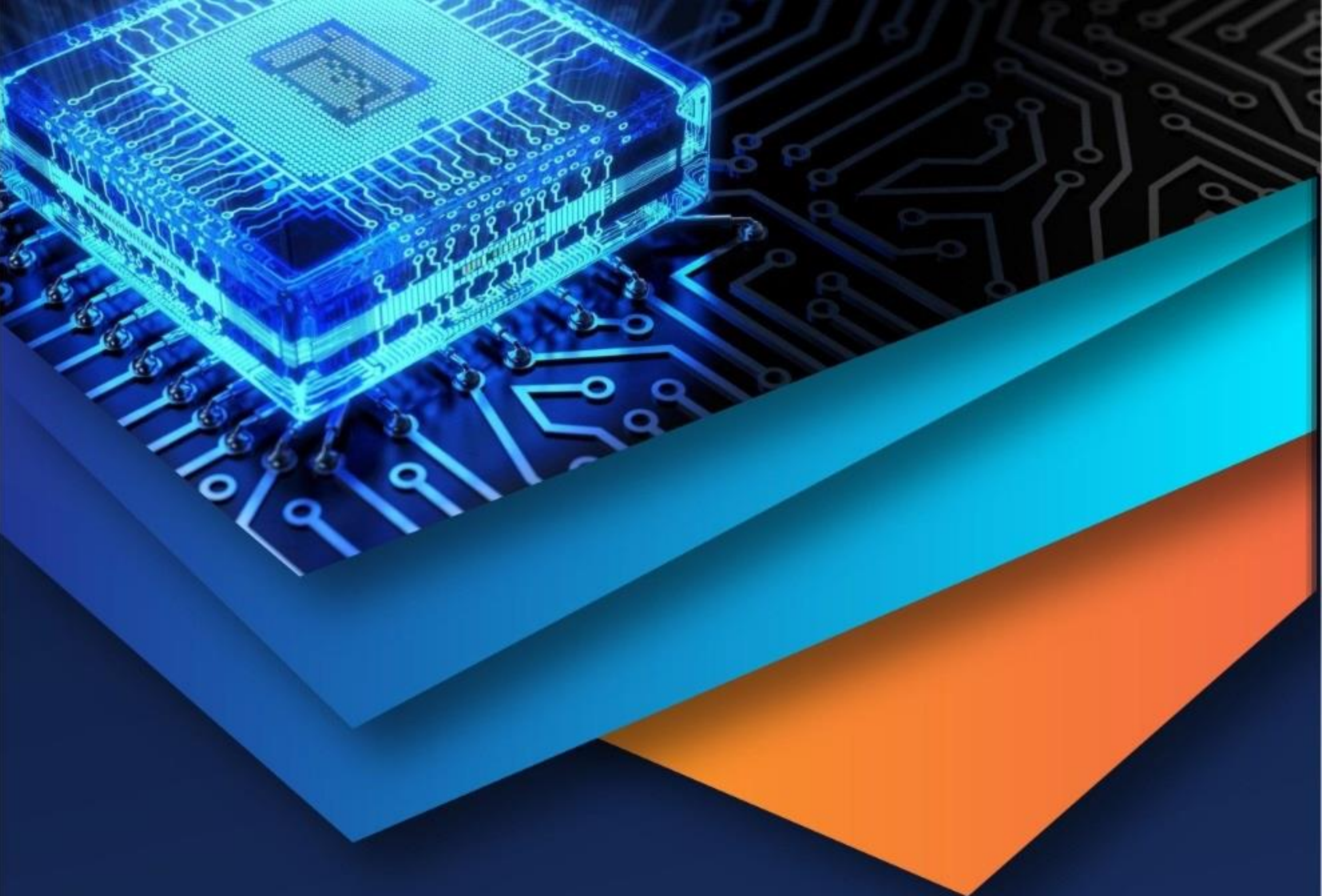

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