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"Advanced Control Strategies for Grid-Connected Renewable Energy Systems using Power Electronics and Artificial Intelligence"

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ABSTRACT

This paper focuses on the simulation and performance analysis of a grid-connected hybrid renewable energy system developed in MATLAB/Simulink. The proposed system combines solar photovoltaic (PV) and wind energy sources using a common DC-link configuration and supplies power to the grid through a three-phase inverter. Separate models of the solar and wind subsystems are first designed and then integrated using a regulated 700 V DC bus. The behavior of the system is evaluated under different environmental conditions and load variations. Key performance indicators such as DC-link voltage stability, inverter output characteristics, and power flow are examined. The simulation results indicate that the system operates reliably, maintains voltage stability, and delivers improved power quality, demonstrating its suitability for modern grid-connected renewable energy applications.

Keywords: Renewable Energy; Energy Efficiency; Solar Power Generation ; MATLAB/Simulink; Energy Management System

1. INTRODUCTION

The increasing demand for electrical energy, combined with the rapid depletion of fossil fuel resources and growing environmental concerns, has encouraged the global transition toward renewable and sustainable energy systems. Conventional power generation methods based on coal, oil, and natural gas contribute significantly to greenhouse gas emissions, environmental pollution, and climate change. As a result, governments, industries, and researchers around the world are focusing on cleaner and more efficient energy alternatives. Renewable energy sources such as solar photovoltaic (PV) systems and wind energy conversion systems have emerged as promising solutions due to their availability, sustainability, and low environmental impact.

In modern power systems, renewable energy sources are increasingly being integrated into residential, commercial, and industrial applications through distributed generation systems and microgrids. A microgrid is a localized energy system that consists of interconnected loads, renewable energy sources, energy storage systems, and control units capable of operating either in coordination with the utility grid or independently in islanded mode. Microgrids provide several advantages, including improved reliability, reduced transmission losses, increased energy efficiency, and enhanced utilization of renewable energy resources.

Unlike conventional synchronous generators, renewable energy systems typically produce variable and intermittent electrical power. Solar PV systems generate electricity depending on solar irradiance and temperature conditions, while wind turbines depend on fluctuating wind speeds. Because of this variability, renewable energy sources are connected to the grid through power-electronic converters and inverter systems. These converters are essential components responsible for converting DC power or variable-frequency AC power into stable AC electricity suitable for grid integration and residential consumption.

Power-electronic converters perform several important functions, including voltage regulation, frequency synchronization, harmonic suppression, reactive power compensation, and power flow control. However, the increasing penetration of inverter-based renewable energy systems introduces significant challenges to power system stability and operation. Variations in renewable generation can lead to voltage fluctuations, frequency instability, reduced system inertia, harmonic distortion, poor power quality, and difficulties in maintaining grid reliability. These challenges become more severe under weak-grid conditions, rapidly changing load demands, and fault situations.

Traditional controller designs such as proportional-integral (PI), proportional-derivative (PD), and proportional-resonant (PR) controllers are commonly used in renewable energy systems due to their simplicity and ease of implementation. However, these conventional controllers often have fixed control parameters and limited adaptability. As renewable energy systems operate under highly nonlinear and uncertain conditions, fixed-gain controllers may not provide satisfactory performance during sudden environmental changes, disturbances, or dynamic load variations. To address these limitations, this project proposes the development of a Renewable Energy-Based Micro grid Power Management System using intelligent and AI-based control techniques. The project focuses on designing advanced control strategies capable of improving the performance, efficiency, and reliability of renewable energy systems under dynamic operating conditions. Artificial intelligence and modern control methods offer the ability to adapt automatically to changing system behaviour, making them suitable for complex and nonlinear renewable energy applications.

The proposed system integrates multiple energy sources, including solar photovoltaic panels, wind turbines, battery energy storage systems (BESS), and utility grid supply into a single residential microgrid framework. The system is designed to manage energy generation, storage, and consumption efficiently while maintaining stable power delivery to residential loads. The main objective of the project is to minimize electricity costs, maximize renewable energy utilization, reduce dependence on conventional grid power, and ensure uninterrupted power supply.

A major component of the project is the development of an intelligent Energy Management System (EMS). The EMS acts as the supervisory controller responsible for monitoring system parameters such as solar power generation, wind power availability, battery state of charge, load demand, and grid conditions in real time. Based on these inputs, the EMS determines the optimal power-sharing strategy among the available energy sources. For example, during periods of high solar irradiance, the EMS prioritizes solar energy utilization while charging the battery storage system with excess energy. During low renewable generation periods, the EMS can draw power from the battery or utility grid to maintain continuous supply to residential loads.

The project also investigates advanced inverter control techniques using artificial intelligence and data-driven methods. Intelligent control approaches such as fuzzy logic control, artificial neural networks (ANN), adaptive control, genetic algorithms, machine learning optimization, and hybrid control systems are explored to improve system performance. These controllers can dynamically adjust control parameters according to operating conditions, making them more effective than traditional controllers in handling renewable energy fluctuations and nonlinear system behaviour.

Fuzzy logic controllers are particularly useful because they can mimic human decision-making processes and operate effectively without requiring highly accurate mathematical models. Artificial neural networks can learn system behaviour from training data and provide adaptive responses under varying conditions. Hybrid intelligent controllers combining fuzzy logic and neural networks can further improve accuracy, robustness, and system adaptability.

The inverter control system developed in this project is designed to perform several important functions, including:

- Active and reactive power control
- Voltage and frequency regulation
- Grid synchronization
- Harmonic reduction
- Power quality improvement
- DC-link voltage stabilization
- Dynamic load sharing
- Fault ride-through capability
- Weak-grid operation support

Battery energy storage systems play an important role in the proposed microgrid architecture. Since renewable energy generation is intermittent, energy storage systems help balance generation and consumption by storing excess renewable energy and supplying power during low generation periods. The battery storage system improves system reliability, reduces voltage fluctuations, and supports uninterrupted operation during temporary grid failures or renewable energy shortages.

The entire renewable microgrid system is designed and analysed using MATLAB/Simulink simulation software. Detailed mathematical and simulation models are developed for all system components, including solar PV arrays, wind turbine generators, DC-DC converters, inverter systems, battery storage units, residential loads, and utility grid interfaces. The simulation environment allows the evaluation of system performance under realistic operating conditions.

Several test scenarios are considered during simulation analysis, including:

- Variations in solar irradiance and temperature
- Changing wind speed conditions
- Sudden residential load changes
- Battery charging and discharging cycles
- Grid voltage disturbances
- Weak-grid operation
- Short-duration power interruptions
- Harmonic disturbances
- Peak demand conditions

The system performance is analysed based on important technical and economic parameters such as:

Voltage stability, Frequency regulation, Total harmonic distortion (THD),Renewable energy penetration level, Energy efficiency, Dynamic response time, Battery performance, Power quality improvement, Grid dependency reduction, Electricity cost savings, Carbon emission reduction, System reliability and stability .

The simulation results demonstrate that the proposed intelligent micro grid power management system can effectively improve overall system operation compared to conventional control approaches. The intelligent controllers provide faster dynamic response, better voltage and frequency stability, lower harmonic distortion, and improved adaptability under fluctuating renewable energy conditions. The coordinated operation of solar PV systems, wind turbines, battery storage, and utility grid supply ensures efficient energy utilization and reliable power delivery for residential applications.

The project also highlights the environmental benefits of renewable energy integration. By increasing the utilization of clean energy sources and reducing dependence on fossil fuel-based electricity generation, the proposed system contributes to lower greenhouse gas emissions and supports sustainable energy development. The reduction in electricity consumption from conventional utility grids also leads to lower operational costs for residential consumers.

In addition to residential applications, the concepts developed in this project can be extended to commercial buildings, rural electrification systems, smart cities, electric vehicle charging stations, and industrial micro grids. The integration of artificial intelligence with renewable energy systems represents an important step toward the development of future smart grids capable of autonomous and efficient energy management.

Future enhancements of the project may include the integration of Internet of Things (IOT) technologies, cloud-based monitoring systems, real-time hardware implementation, block chain-based energy trading, and advanced predictive analytics for renewable energy forecasting. Smart communication technologies can further improve coordination among distributed energy resources and enable real-time optimization of microgrid operation.

2. SYSTEM MODELING IN MATLAB/SIMULINK

The complete system is developed using MATLAB/Simulink by modelling individual components and integrating them into a unified framework.

2.1 Solar PV Model

The solar subsystem is modelled using a PV array whose output varies with irradiance and temperature. A DC–DC converter is used to regulate the voltage and extract maximum power before feeding it to the DC bus.

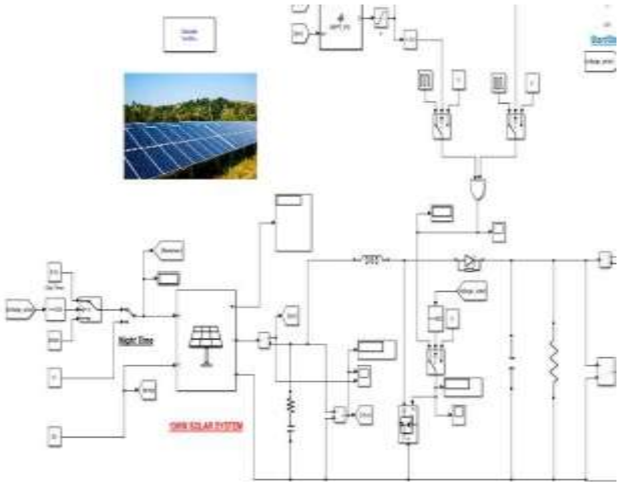


Figure 1: Solar circuit diagram

2.2 Wind Energy Model

The wind subsystem consists of a turbine, generator, and rectifier for energy conversion. The generated AC power is converted to DC and regulated using a DC–DC converter before being supplied to the DC bus.

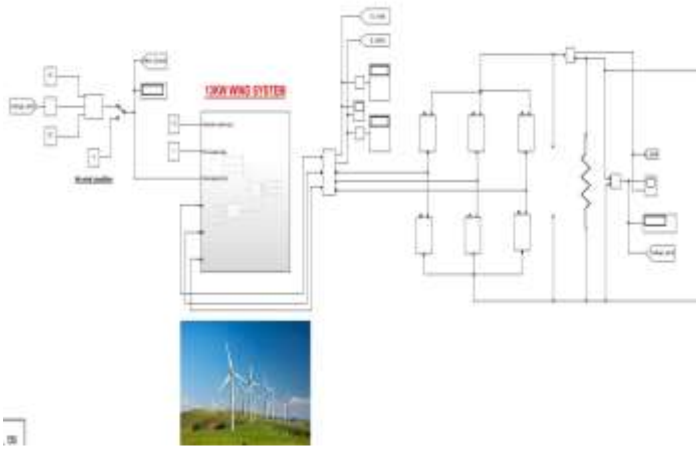


Figure 2 : wind circuit diagram

2.3 Inverter and Grid Connection

A three-phase inverter is used to convert DC power into AC and is connected to both the grid and local load. PWM based control techniques are employed to generate switching pulses and ensure proper operation.

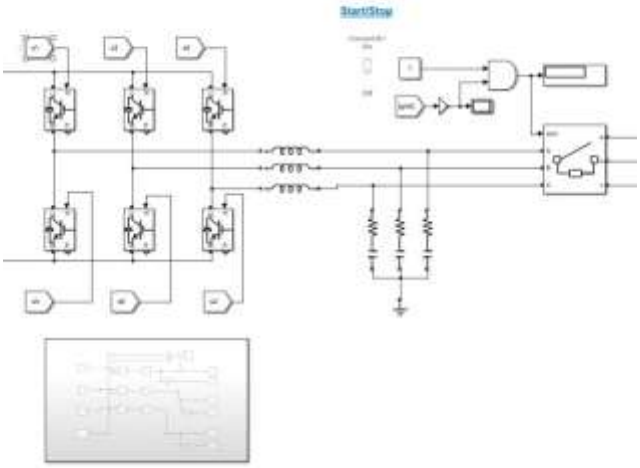


Figure 3: Inverter circuit diagram

2.3.1 LOCAL LOAD

Figure 4 : load circuit diagram

2.3.2 GRID

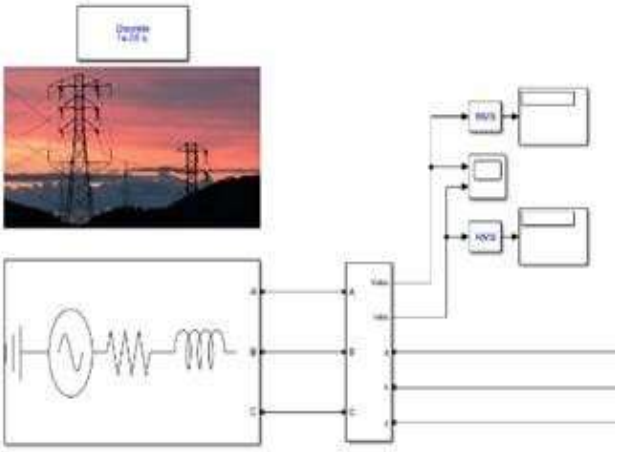


Figure 5 : Grid circuit diagram

3. SIMULATION PARAMETERS

Parameter	Value / Range
DC Bus Voltage	700 V
Solar Irradiance	800 – 1000 W/m²
Wind Speed	8 – 12 m/s
Switching Frequency	5 kHz – 10 kHz (as per design)
Load Type	Three-phase load

4. SIMULATION RESULT AND ANALYSIS

4.1 Different scenario of source

1) **Scenario-1:** Only Grid Power Source available
2) **Scenario-2:** Only Solar Power Source available
3) **Scenario-3:** Only Wind Power Source available
4) **Scenario-4:** Solar + Wind Power Source are available
5) **Scenario-5 :** Solar to Wind or Wind to Solar Power changeover on different condition

Scenario-1: Only Grid Power Source available

Only Grid Power Source available: The grid is supplying power to meet the entire load demand as both solar and wind energy sources are unavailable. Simultaneously, the battery is charging using grid power to ensure energy storage for future use.

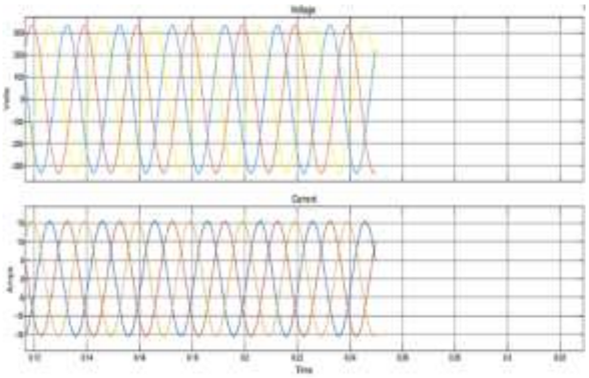
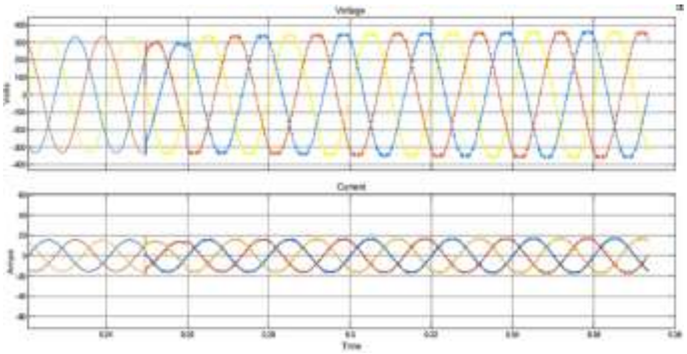


Figure 6: Output Voltage and Current of scenario – 1

- **Scenario-2**: Only Solar Power Source available

Only Solar Power Source available: Solar power is available and supplying the total load while both wind and grid power are unavailable or isolated. Additionally, the battery is being charged using the surplus solar power.

Figure 7 : Output Voltage and Current of scenario – 2



- **Scenario-3**: Only Wind Power Source available

Only Wind Power Source available: The wind power system is operational and supplies the total load demand. Simultaneously, the surplus wind power is utilized to charge the battery, while solar and grid power remain unavailable or isolated.

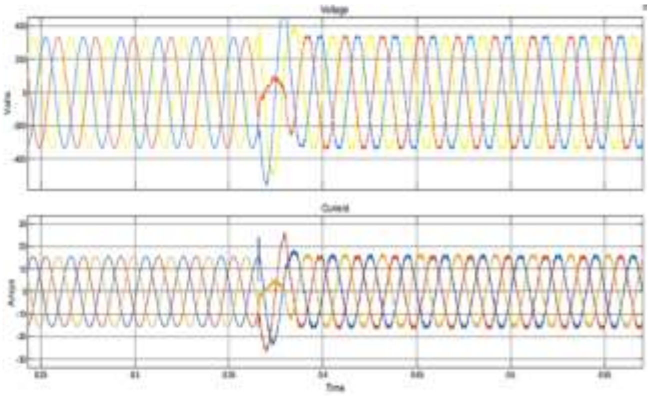
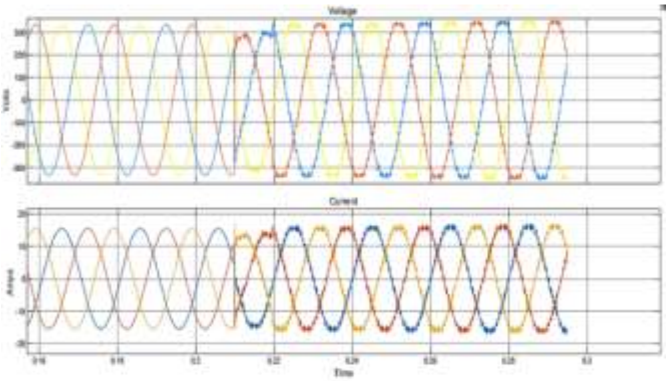


Figure 8 : Output Voltage and Current of scenario – 3

- **Scenario-4**: Solar + Wind Power Source are available

Solar + Wind Power Source are available: Solar + Wind Power Source: Solar and wind power supply the total load while the system operates in isolated mode (grid unavailable). Excess energy from solar and wind sources is used to charge the battery.

Figure 9 : Output Voltage and Current of scenario – 4



- **Scenario-5** : Solar to Wind or Wind to Solar Power changeover on different condition

Solar to Wind or Wind to Solar Power changeover on different condition: When SOLAR fail to tackle the load WIND will be single handed tackle the load & whenever both fail GRID come to picture & tackle the load or vise-versa.

Conditions:

Before

Solar toggle switches → Day time

Wind toggle switch → Normal wind speed

Battery charging → 50%

After

Solar toggle switches → Night time

Wind toggle switch → Normal wind speed

Battery charging → 50%

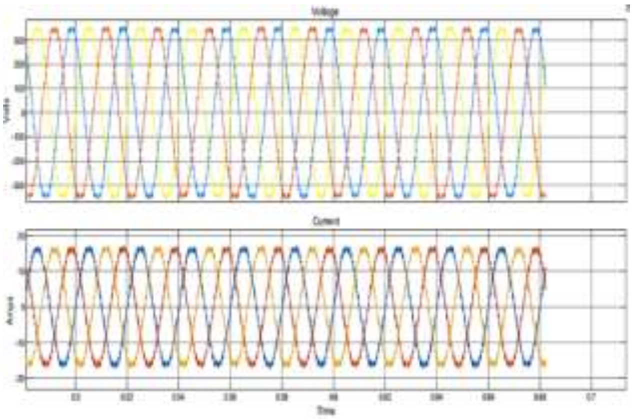


Figure 10 : Output Voltage and Current of scenario – 5

5. Discussion

The obtained simulation results indicate that the designed hybrid renewable energy system operates efficiently across a range of environmental and loading conditions. The shared DC-link configuration effectively combines the energy contributions from both solar and wind subsystems, enabling coordinated and stable operation. Furthermore, the inverter facilitates reliable interaction with the utility grid, ensuring smooth and continuous power transfer. The overall system behaviour reflects strong reliability, stable voltage characteristics, and effective distribution of generated power among the connected sources and loads.

6. Advantages of the Simulation Approach

The application of simulation techniques offers significant advantages during the design and analysis of renewable energy systems. It eliminates the immediate requirement for costly hardware setups in the early stages of development, thereby reducing financial constraints. Additionally, simulation platforms enable evaluation of system performance under diverse and extreme operating scenarios that may not be easily achievable in practical environments. This approach also supports the fine-tuning of system parameters and control methodologies, leading to a more optimized and efficient design prior to physical implementation.

6. Conclusion

This work has presented a comprehensive simulation based study of a grid-connected hybrid renewable energy System developed using MATLAB/Simulink. The findings demonstrate that the integration of solar photovoltaic and wind energy sources through a common DC-link structure allows effective and stable power delivery to the grid. The incorporation of power electronic interfaces along with suitable control strategies ensures efficient energy conversion and dependable system performance. The system maintains stability even under varying environmental inputs, highlighting its potential suitability for real-world power system applications.

7. Future Work

1. **Integration of Advanced Renewable Energy Sources**:
   Expand the microgrid to include emerging renewable energy technologies like biogas, tidal, or geothermal energy. This integration would increase energy diversity and resilience.
2. **Incorporation of Artificial Intelligence and Machine Learning**:
   Employ AI/ML algorithms for predictive analysis, demand forecasting, and adaptive energy management. This can enhance system efficiency by dynamically adjusting to load variations and weather conditions.
3. **Implementation of Smart Grid Technology**:
   Integrate the microgrid with a broader smart grid network for real-time monitoring, improved fault detection, and seamless energy exchange with utility grids.

4. **Energy Storage Advancements**: Incorporate advanced energy storage technologies, such as super capacitors or second-life EV batteries, to improve energy reliability and reduce dependence on the main grid.
5. **IoT-Based Monitoring and Control**: Implement IoT-enabled sensors and devices for real-time data acquisition, remote monitoring, and autonomous system control, improving reliability and ease of use.

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