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# Grid-Interactive Hybrid Renewable Systems Using Power Electronic Converters

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**Abstract**: *This paper presents the design, integration, and performance analysis of a hybrid power system combining wind energy, solar photovoltaic (PV) energy, and battery storage to deliver a sustainable and reliable energy solution. By leveraging the complementary nature of wind and solar resources, the system ensures continuous power generation under varying environmental conditions. The integration of battery storage enhances reliability by mitigating intermittency and optimizing energy distribution. Key system components are modeled and evaluated in terms of efficiency, cost-effectiveness, and environmental impact. Simulation results validate the system's capability to meet energy demands while reducing dependence on conventional power sources. This study offers valuable insights into the design, optimization, and practical implementation of hybrid renewable energy systems for both grid-connected and off-grid applications.*

**Keywords**: Hybrid power system, wind energy, solar photovoltaic (PV), battery storage, renewable energy integration, energy reliability, sustainable energy, energy management, hybrid system optimization

## I. INTRODUCTION

The growing demand for sustainable and reliable energy solutions has propelled the exploration and integration of renewable energy sources into hybrid power systems. Among these, wind energy and solar photovoltaic (PV) systems stand out as complementary sources due to their availability in diverse environmental conditions. However, the intermittent nature of these sources necessitates effective energy management and storage solutions to ensure continuous and reliable power supply. The integration of battery storage systems within hybrid energy configurations provides a viable approach to addressing these challenges by stabilizing power output and enhancing energy utilization.This paper focuses on the design, integration, and performance analysis of a hybrid power system that combines wind energy, solar PV, and battery storage. By leveraging the inherent strengths of each component, the proposed system offers a balanced and efficient solution for renewable energy utilization in both grid-connected and off-grid scenarios. The study examines the system's ability to meet energy demands under varying environmental conditions while minimizing reliance on conventional energy sources and reducing environmental impact.Simulation-based analysis is conducted to evaluate the efficiency, cost-effectiveness, and sustainability of the system. The findings highlight the potential of hybrid renewable energy systems in addressing global energy challenges, paving the way for innovative solutions in energy management and renewable energy integration. This paper provides a comprehensive framework for designing and optimizing hybrid power systems to meet the evolving energy needs of modern society.

## II. LITERATURE SURVEY

The increasing global focus on sustainable energy systems has driven significant advancements in hybrid power systems integrating renewable energy sources such as wind, solar photovoltaic (PV), and battery storage. This section reviews key studies that have contributed to the understanding, design, and optimization of hybrid renewable energy systems.

The inherent variability of renewable energy sources is a significant challenge to their widespread adoption. Research has demonstrated that combining wind and solar energy can leverage their complementary characteristics to mitigate fluctuations in power generation. Li et al. (2018) analyzed the temporal and spatial complementarity of wind and solar energy, concluding that a well-designed hybrid system could stabilize power supply across seasons and geographic locations [1]. Sharma and Mehta (2019) further explored this concept by simulating hybrid systems in different climatic zones, emphasizing that site-specific design is crucial for maximizing energy output and system reliability [2].Battery storage plays a vital role in addressing the intermittency of renewable energy sources. Kumar et al. (2020) investigated the economic feasibility of integrating advanced battery technologies into hybrid systems, revealing that lithium-ion batteries provide a cost-effective and efficient solution for energy storage [3]. Park et al. (2021) highlighted the importance of battery energy management systems (BEMS) in prolonging battery life and improving energy dispatch in hybrid configurations [4].Effective energy management strategies are critical to optimizing hybrid systems. Chen et al. (2021) proposed an intelligent energy management algorithm that dynamically allocates power between wind, solar, and battery systems based on real-time demand and environmental conditions [5]. Similarly, Rahman et al. (2022) developed a hybrid power management strategy using artificial intelligence (AI) techniques, which demonstrated improved system efficiency and reliability under varying load conditions [6].The cost-effectiveness of hybrid systems is another area of extensive research. Ahmed and Khan (2022) performed a detailed economic analysis, showing that hybrid systems are financially viable when optimized for local energy demands and resource availability [7]. Gupta and Sharma (2019) emphasized the role of government subsidies and policy support in promoting the adoption of hybrid systems, particularly in rural and remote areas [8].Hybrid renewable energy systems offer a promising solution to reducing greenhouse gas emissions and mitigating climate change. Smith et al. (2017) conducted a life cycle assessment of a hybrid wind-solar-battery system, reporting a substantial reduction in carbon emissions compared to traditional fossil fuel-based systems [9]. Chowdhury et al. (2020) evaluated the environmental benefits of hybrid systems deployed in urban areas, demonstrating significant improvements in air quality and reductions in energy-related pollutants [10].Hybrid systems have shown versatility in both grid-connected and off-grid scenarios. Singh et al. (2021) analyzed grid-connected hybrid systems, highlighting their potential to enhance grid stability and reduce peak demand [11]. Das et al. (2020) examined off-grid applications in rural areas, where hybrid systems provide a reliable and sustainable alternative to diesel generators [12].Despite the advancements, several challenges persist in hybrid power system design and deployment. These include high initial costs, limited scalability, and technical complexities in system integration. Patel et al. (2021) identified the need for advanced modeling techniques and robust control systems to address these challenges [13]. Future research is expected to focus on improving energy storage technologies, enhancing system flexibility, and developing innovative financing models to accelerate the adoption of hybrid renewable energy systems.

**Problem Formation**

The present available models are basically designed with the prime aim of power sharing which takes loading conditions as the basis in microgrid system. The voltage regulation of the interlinked microgrids is achieved in other available schemes without considering the specific loading conditions. Therefore, the objectives cannot be fulfilled with the present model.

The islanded and grid connected operation is categorized as major and minor scheduling problem.

For diesel and wind turbine-based power generation in standalone mode requires unified compensation control approach of an energy storage to improve the performance in terms of power and efficiency of the system.

Balancing of supply and demand of energy is achieved with the help of distributed generation and distributed storage which further lead to managing system stability and power quality

## III. METHODOLOGY

The project is implemented using MATLAB Simulink software, with key components designed as follows:

- **Wind Energy System Simulation** – Utilizes the application library within the SimPowerSystems toolbox to model the wind energy system.

- **Solar PV System and MPPT Algorithm Simulation** – Uses SimPowerSystems and commonly available Simulink blocks to simulate the photovoltaic (PV) system along with the Maximum Power Point Tracking (MPPT) algorithm.
- **Inverter Circuit Simulation** – Designed using the power electronics library to facilitate DC-to-AC conversion.
- **Power System and Grid Simulation** – Developed using the SimPowerSystems toolbox to model grid integration.
- **Common Coupling Point Simulation** – Ensures synchronization of the wind and solar systems with the main power grid.
- **Infinite Bus and LC Filter Simulation** – Implemented using SimPowerSystems for grid stability and power quality enhancement.

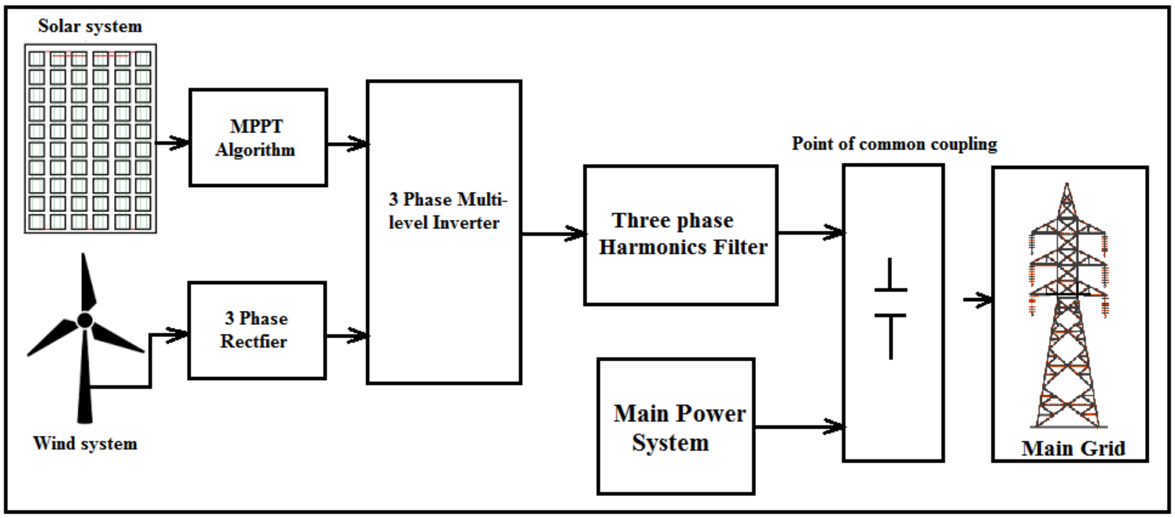


**Fig.3. Block diagram of proposed hybrid power system**

**MATLAB Simulink-Based Implementation**

The proposed methodology, as illustrated in Figure 3, is implemented using MATLAB Simulink, with the SimPowerSystems toolbox playing a crucial role in the development of the hybrid power system. The toolbox is employed for modeling various components, including the wind energy system, solar PV system, battery energy storage, and DC-DC converter subsystem.

Figure 4 presents the complete MATLAB simulation model of the proposed hybrid system. The system generates DC power from both solar PV and wind energy sources. This power is then processed through an MPPT system to extract the maximum available energy. The optimized DC power is subsequently fed into an inverter, which converts it into AC power for grid integration with proper synchronization. Additionally, a battery charging unit is incorporated to store energy for DC applications.

**Solar PV Subsystem Model**

Figure 4 illustrates a solar PV subsystem where the DC output of the solar PV cell is linked to a Maximum Power Point Tracking (MPPT) algorithm block. This algorithm helps in optimizing the solar DC output voltage based on the available irradiation under varying atmospheric conditions.

To achieve the desired electrical ratings, 36 solar cells are interconnected in series and parallel configurations. A diode is connected at the output of the solar cell system to prevent reverse power flow or backfeeding, which could cause damage. This diode, known as a reverse blocking diode, plays a crucial role in stopping reverse current during cloudy or rainy conditions when shading effects may occur.

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### Wind Energy Subsystem Model

The wind energy subsystem consists of a wind turbine that generates three-phase AC power. This power is then passed through a rectifier circuit, which converts it into DC power. Since the solar PV system provides DC output, it is essential to convert the wind-generated AC power into DC of matching magnitude to ensure proper integration of both energy sources. This conversion facilitates seamless coupling of the solar and wind energy systems.

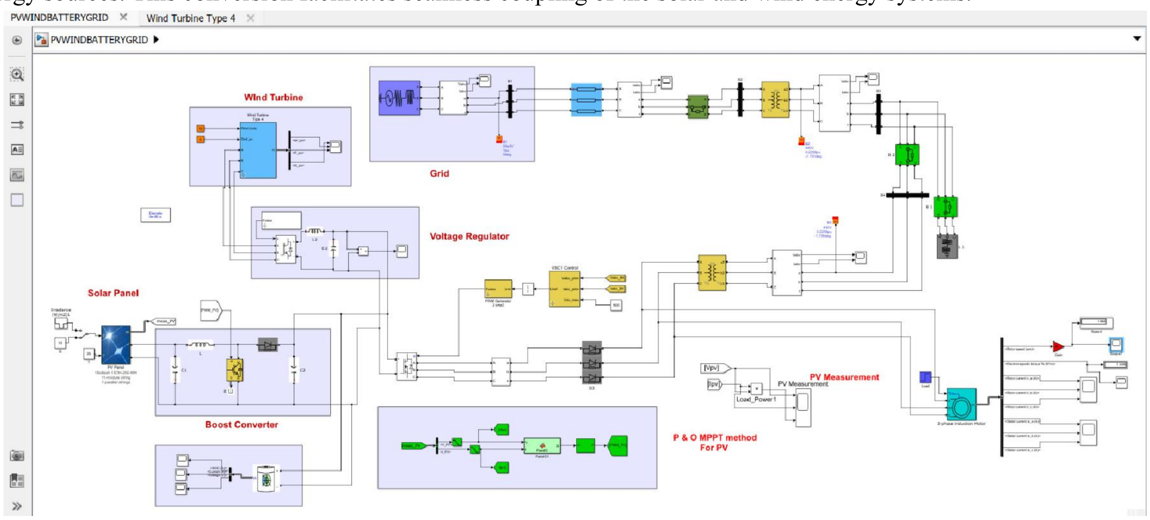


**Fig.5. Solar PV subsystem MATLAB model coupled with MPPT algorithmsubsystem**

## IV. MPPT TECHNIQUE

PV modules experience fluctuations in output due to varying environmental conditions, such as temperature and irradiance. To ensure optimal power extraction regardless of these changes, a control technique is required to maximize power output under all conditions.

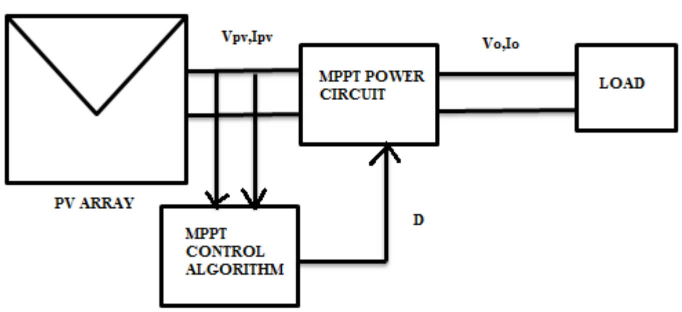


**Fig.6 Block diagram of MPPT control**

### MPPT Control Block Diagram

Figure 4 illustrates the block diagram of the Maximum Power Point Tracking (MPPT) control system. Since photovoltaic (PV) cells exhibit nonlinear behavior, their maximum power point varies with changes in temperature and solar irradiance. To address this, the Perturb and Observe (P&O) method is utilized for tracking and extracting the maximum power under dynamic environmental conditions.

The P&O technique functions by periodically monitoring the voltage and current at the output of the PV array. It introduces a small change in the voltage and observes the corresponding change in power output. Based on the direction of this change, it determines whether to increase or decrease the operating voltage, thereby generating a suitable control

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signal. This control signal adjusts the switching duty cycle, which is governed by the MPPT algorithm. A DC-DC boost converter is also employed to raise the DC voltage level, enhancing the system's overall efficiency.

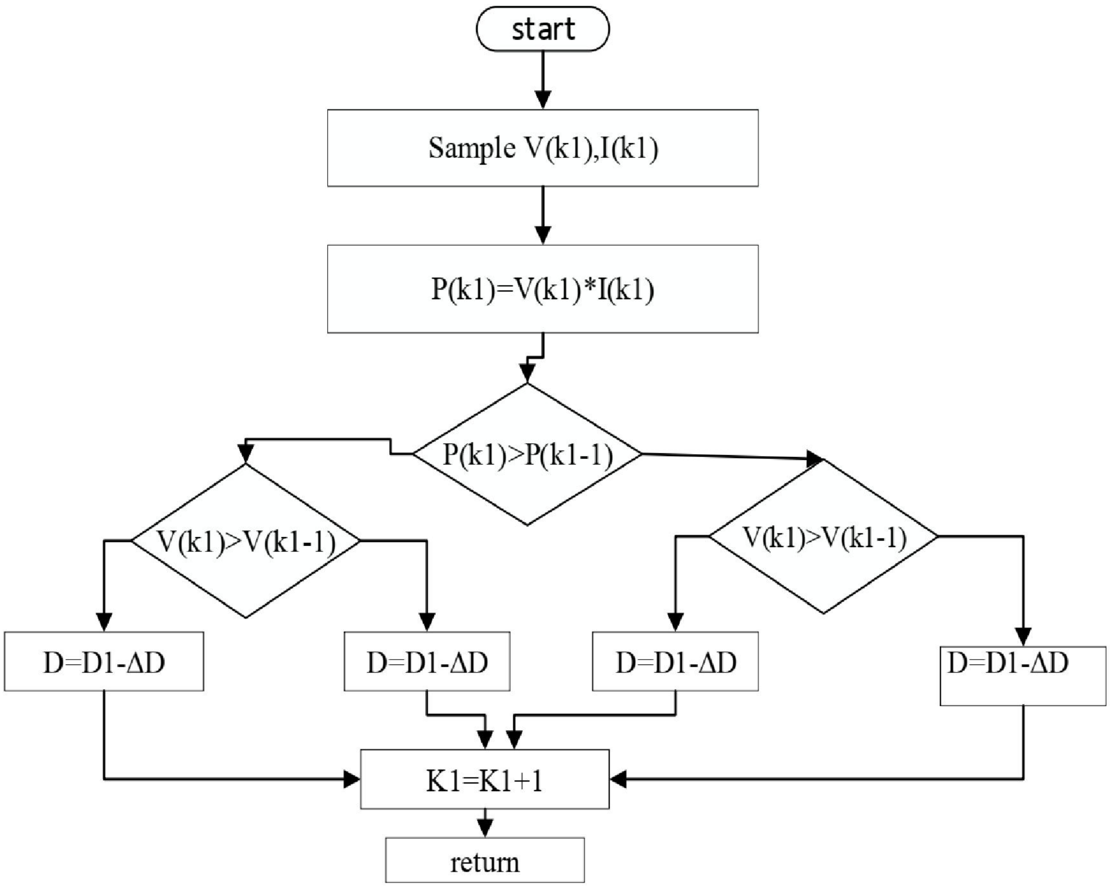


**Fig 7 MPPT Flow Chart**

**Table 3.3: Boost converter parameters**

| Parameter | Description | Parameter | Description |
|---|---|---|---|
| D | Converters witch Duty cycle | $t_{off}$ | MOSFET switch off time |
| $V_{PV}$ | PV output voltage | $T_{on}$ | MOSFET Switch on time |
| $V_0$ | Boost converter voltage | CCM | Continuous Current Conduction |
| $i_L(t)$ | Inductor current | Io | Average output current in ampere |
| $T_s$ | Switching period | $I_i$ | Average input current in ampere |
| R | equivalent load | | |

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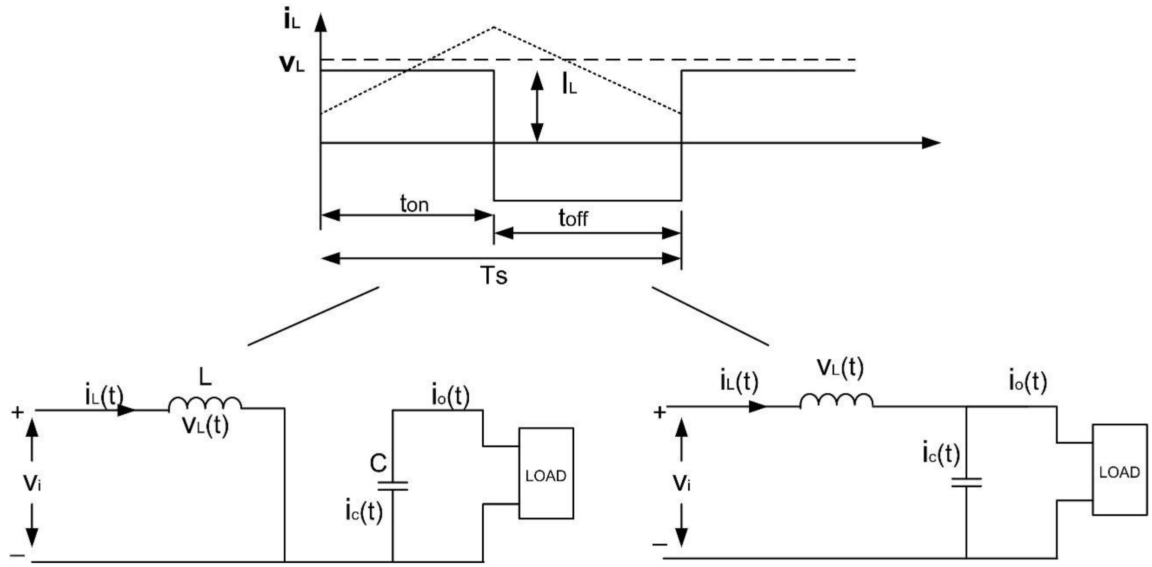


(a) (b)

**Figure 8: Equivalent circuit for boost converter a) mode 1 (0<*t*<*ton*) and b) mode 2 (*ton*<*t*<*Ts*)**

For a lossless circuit, Pi = Po, then

$V_i I_i = V_O I_O$ (3.15)

$\underline{I_O}$ $=1-D$ (3.16)

## V. FACILITIS REQUIRED FOR WORK

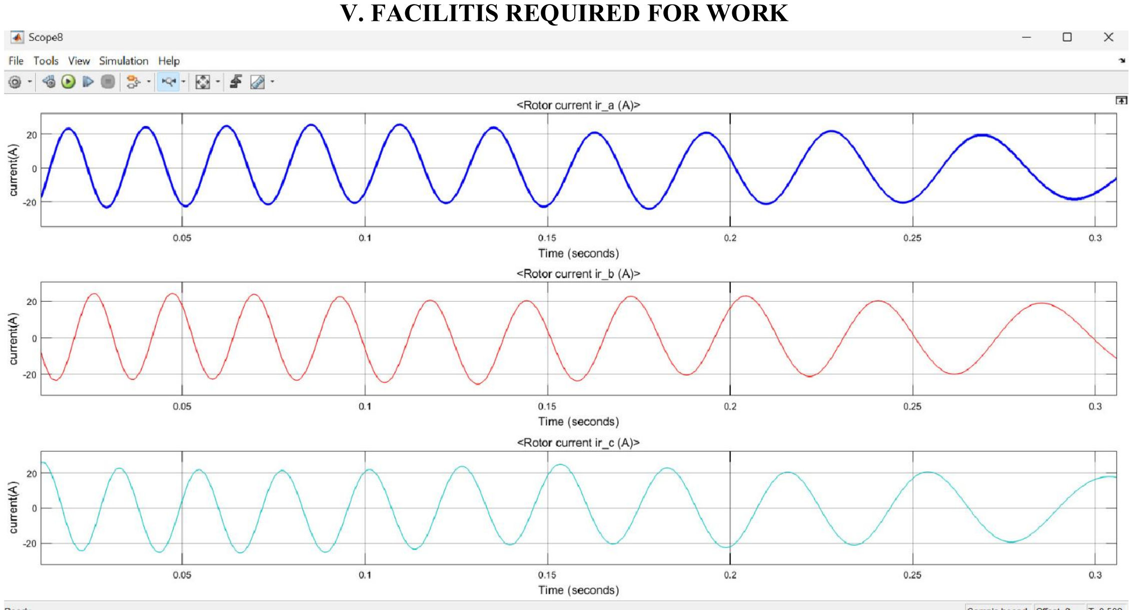


**Fig 8 output waveforms of Rotor current when hybrid system connected to grid**

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The image displays a Simulink Scope output showing the three-phase rotor currents of an electrical machine, likely an induction motor or a synchronous motor. The three graphs represent the rotor currents for phases A, B, and C (ir_a, ir_b, and ir_c) over time. Each waveform is a sinusoidal signal, with a peak value close to ±25 A, and they are clearly 120 degrees out of phase with each other, indicating a balanced three-phase current system. The time axis spans from 0 to 0.3 seconds, during which the amplitudes slightly decrease, suggesting a transient response gradually settling. The blue trace corresponds to phase A, red to phase B, and cyan to phase C, typical of how phase currents are color-coded for clarity. This kind of waveform is typical in simulations involving motor drive systems where the rotor currents are monitored to evaluate performance or control effectiveness.

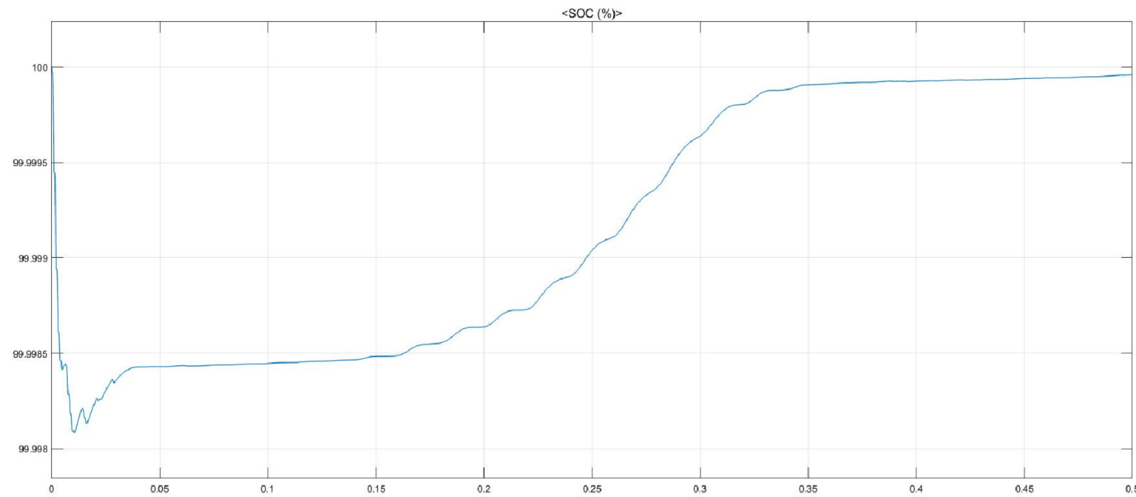


**Fig.9 SOC for the battery connected in system**

The image shows a plot of the State of Charge (SOC) of a battery over time, which is a key parameter in battery management systems. The x-axis represents time (in seconds), while the y-axis represents the SOC in percentage. Initially, the SOC starts slightly below 100%, then experiences a small drop and fluctuation in the first few milliseconds. Following that, it gradually increases in a smooth and consistent manner, indicating that the battery is being charged. The plot shows a significant rise starting around 0.25 seconds, eventually stabilizing close to full charge (100%) by the end of the 0.5-second interval. This kind of behavior is typical in simulations where a controlled charging process is being evaluated, ensuring that the SOCincreases steadily without overshooting or instability.

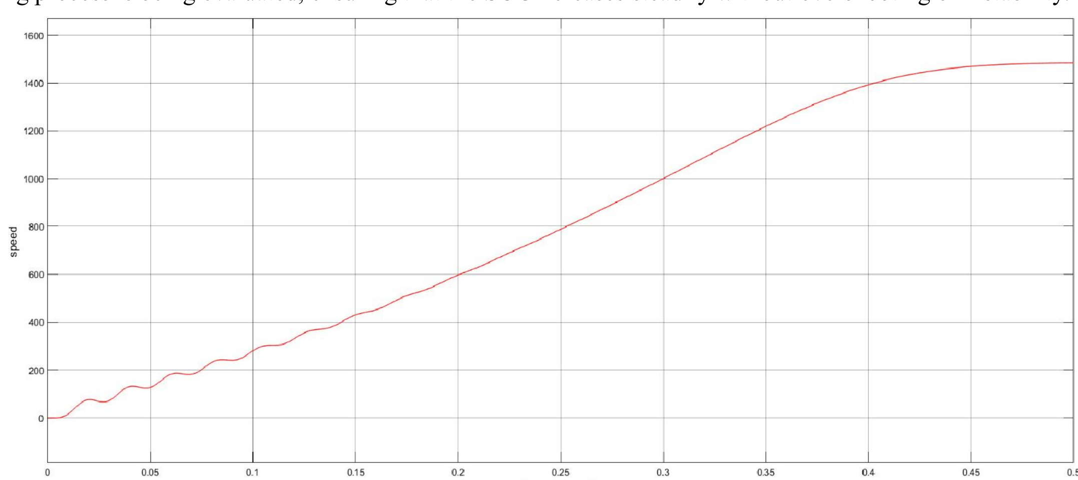


**Fig.10 Speed of the motor connected in system at 1484 RPM**

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The image presents a graph showing the speed response of a system—likely an electric motor—over a time period of 0 to 0.5 seconds. The x-axis represents time in seconds, and the y-axis represents speed, which appears to be measured in revolutions per minute (RPM) or a similar unit. The speed starts near zero and increases steadily in a smooth ramp-like fashion, eventually saturating around the 1500 mark. The slight oscillations early on in the curve suggest the presence of some initial torque ripple or control dynamics as the motor begins to accelerate. This profile is characteristic of a controlled motor startup, where speed increases linearly and then flattens as it reaches a steady-state operating point. This type of response is desirable in many drive applications where smooth acceleration is critical.

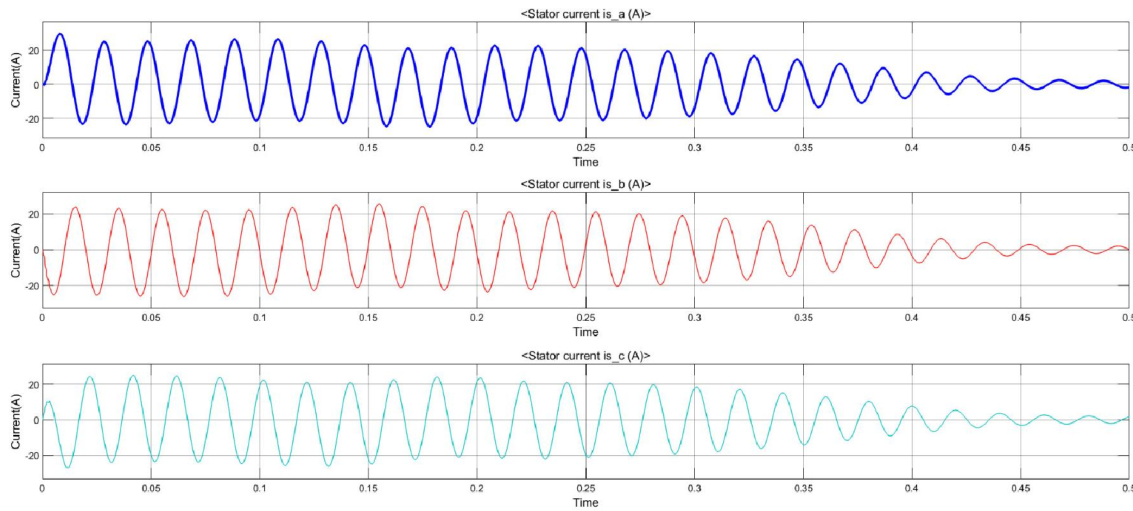


**Fig.11 output waveforms of stator current when hybrid system connected to grid**

After passing through the boost converter, the DC voltage from the PV array is increased to a higher level using the MPPT technique. Meanwhile, the wind turbine, specifically a Permanent Magnet Synchronous Generator (PMSG), produces AC voltage, which is then converted to DC through a rectifier. Figure 13 illustrates the boosted DC voltage after integrating both the PV and wind subsystems.

When the three-phase AC voltage is obtained using an inverter, it initially contains distortions and is not purely sinusoidal. However, once the system is connected to the grid, the three-phase AC voltage stabilizes without fluctuations.

## VI. CONCLUSION

This study introduces a hybrid energy system that combines solar and wind power generation, with its output regulated by a voltage control mechanism. The system's performance is evaluated using MATLAB/Simulink simulations under different environmental conditions, including varying wind speeds and solar irradiance. Specifically, simulations are conducted at a wind speed of 12 m/s and solar irradiance of 1000 W/m², with an ambient temperature of 25°C, over a time interval from 0 to 0.3 seconds. A voltage regulator is employed to maintain a stable combined DC output, ensuring consistent system operation.

The proposed hybrid energy system is particularly suited for supplying electricity to remote or off-grid areas. Simulation results confirm the system's capability to operate effectively under dynamic conditions. Furthermore, the design offers flexibility for expansion, allowing the integration of other renewable energy sources in place of, or alongside, solar and wind. Future enhancements could involve adopting advanced control strategies to replace the voltage regulator, thereby improving inverter performance and system reliability.

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