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# DESIGN AND IMPLEMENTATION OF A SMART HYBRID SOLAR-WIND POWER SYSTEM WITH MPPT ALGORITHMS FOR IMPROVED ENERGY EFFICIENCY

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**Abstract**
*The increasing demand for sustainable and efficient energy systems has led to the development of hybrid solar-wind power generation systems. This paper presents the design and implementation of a smart hybrid solar-wind power system optimized with Maximum Power Point Tracking (MPPT) algorithms for improved energy efficiency. The system integrates solar and wind energy sources with a battery storage system to address the intermittency of renewable energy and ensure stable power supply. A supervisory control system manages power flow, peak shaving, and energy storage, adapting to variations in supply and demand. To enhance system performance, a fuzzy logic-based control algorithm is introduced for intelligent power management. The hybrid system utilizes separate MPPT techniques for both solar panels and wind turbines, maximizing power extraction under changing environmental conditions. A novel hybrid MPPT algorithm adjusts to fluctuations in solar irradiance and wind speed, optimizing overall efficiency. Simulation results and performance analysis demonstrate a significant improvement in energy efficiency compared to standalone solar or wind systems. This study highlights the potential of integrating advanced MPPT control in hybrid renewable energy systems, providing a promising solution for sustainable and reliable power generation in remote and off-grid areas.*

## INTRODUCTION

The global shift towards sustainable energy solutions is becoming increasingly critical in addressing environmental challenges such as climate change and fossil fuel depletion. Among the renewable energy sources, solar and wind energy are considered to be the most promising due to their abundance, environmental benefits, and scalability. However, both solar and wind energy are inherently intermittent, with output variations influenced by changing weather conditions, time of day, and seasonal fluctuations. This intermittency poses significant challenges for maintaining a reliable and continuous power supply, particularly in remote and off-grid areas where energy storage options are limited. To address these challenges, hybrid solar-wind power generation systems have emerged as a promising solution. By integrating both solar and wind energy sources, hybrid systems can compensate for the weaknesses of each individual energy source, improving overall energy reliability and stability [1]. These systems are particularly advantageous in regions where solar and wind conditions complement each other. Despite their potential, optimizing the energy efficiency of hybrid systems remains a complex task, largely due to the varying nature of solar irradiance and wind speed.

There are many researches on examining the role of energy storage systems and fuel cells (FC's) in "hybrid renewable energy system" (HRES). According to reference [2], due to their fast ramping capabilities, fuel cell systems mitigate the problems related to the intermittent power generation of Distributed Generators (DGs). This phenomenon is observed in reference [3], where computer model for simulating a transient's operation of a tubular solid oxide fuel cell was proposed. A non-linear mathematical model of an internal reforming molten carbonate fuel cells plant was proposed in [4], to evaluating the cell responses to varying load demands and to define transient limitation and control requirements. A fuzzy logic based supervisory controller was proposed in [5], with FC's providing power to the load and ultracapacitors (UCs) assisting during the transients. The issue of slow response of batteries can overcome by taking the advantage of the fast response features of the fuel cell's [6]. A comprehensive analysis of various methods [7], pointed out that there are many problems which needs to be addressed, related to failure's affecting the end consumers. Additionally, work on storage and FC's and storage can found in [8], where an electric circuits of fuel cells generation system for control purpose based on fuzzy logic controller (FLC) was developed and proposed. According to reference [8], many tests are conducted on the phosphoric acid (H3PO4) fuel cells plant install in Germany. The reported results mainly focused on the response time for load change from 25% of rated power to full load [9]. According to this contribution, novel fuzzy logic controller for HRES with multiples types of storage is explained. The proposed scheme solves problems regarding to the requirements of consumers pointed out in [10]. The solution focuses on satisfactory supply of the consumer side with providing the safety of lithium-ion battery and making the system efficient and reliable. The evaluation of the proposed objective and validity of its effects are conducted in MATLAB SimPowerSystems™ by the use of real solar power, wind, and load data. Maximum Power Point Tracking (MPPT) is a well-established technique used to maximize the energy harvested from solar and wind power systems [11]. MPPT algorithms allow for continuous tracking of the optimal operating points of photovoltaic (PV) panels and wind turbines, ensuring that both systems operate at their maximum power potential under fluctuating environmental conditions. However, in a hybrid system, the integration of MPPT for both energy sources presents additional challenges, including the need for adaptive control strategies to efficiently manage power generation, storage, and distribution [12].

This paper presents the design and implementation of a Smart Hybrid Solar-Wind Power System optimized with advanced MPPT algorithms for improved energy efficiency. The proposed system integrates solar and wind power generation with a battery storage system, enabling energy storage during times of excess generation and supply during periods of low production. To optimize energy management, the system employs a supervisory control algorithm that dynamically adjusts to fluctuations in both supply and demand, ensuring a stable and continuous power output. In addition, a fuzzy logic-based control algorithm is introduced to intelligently manage power flow and battery charge/discharge cycles, enhancing the overall system's performance. The hybrid system incorporates separate MPPT techniques for both the solar and wind components, maximizing the energy extraction from each source. A novel hybrid MPPT algorithm is developed that dynamically adjusts to changes in solar irradiance and wind speed, optimizing the overall system efficiency. The significance of this study lies in its contribution to advancing the performance of hybrid renewable energy systems through innovative MPPT control techniques. By combining solar and wind power with intelligent control algorithms and energy storage, the proposed system offers a promising solution for improving energy efficiency, particularly in off-grid and remote areas where reliable power generation is crucial.

## 1- Research Objective:

The primary objective of this research is to design, implement, and optimize a smart hybrid solar-wind power system that improves energy efficiency through advanced Maximum Power Point Tracking (MPPT) algorithms. The specific objectives of the study are as follows:

**Design of a Hybrid Solar-Wind Power System**:
To develop a hybrid renewable energy system integrating solar and wind power sources with a battery storage unit, aimed at addressing the intermittency challenges associated with each energy source individually [13].

**Development and Integration of MPPT Algorithms**:
To design and implement separate MPPT algorithms for both the solar and wind components of the system, ensuring maximum power extraction under varying environmental conditions such as solar irradiance and wind speed.

**Optimization of Energy Management with Fuzzy Logic**:
To enhance system performance through the implementation of a fuzzy logic-based control algorithm, allowing intelligent management of power flow, peak shaving, and energy storage for improved overall efficiency and adaptability to changing supply and demand.

**Design of a Novel Hybrid MPPT Algorithm**:
To propose and implement a novel hybrid MPPT algorithm that can dynamically adjust to fluctuations in solar irradiance and wind speed, optimizing the combined efficiency of both energy sources in the hybrid system [14].

**Simulation and Performance Analysis**:
To simulate the proposed system and evaluate its performance in comparison to standalone solar or wind power systems. The analysis will focus on key performance metrics such as energy efficiency, system stability, and power generation reliability.

**Assessment of the System's Feasibility for Off-Grid and Remote Applications**:
To assess the practical feasibility and potential applications of the hybrid solar-wind system with MPPT algorithms in off-grid and remote areas, with a focus on providing sustainable and reliable power generation solutions.

## 2- MPPT Algorithm:

Maximum Power Point Tracking is used to obtain the maximum power from systems. In these applications, the load can demand more power than the PV system can deliver. There are many different approaches to maximizing the power from a PV system, those range from using simple voltage relationships to more complexes multiple sample based analysis. The tracking algorithm works based on the fact that the derivative of the output power P with respect to the panel voltage V is equal to zero at the maximum power point as in Figure 1. The derivative is greater than zero to the left of the peak point and is less than zero to the right.

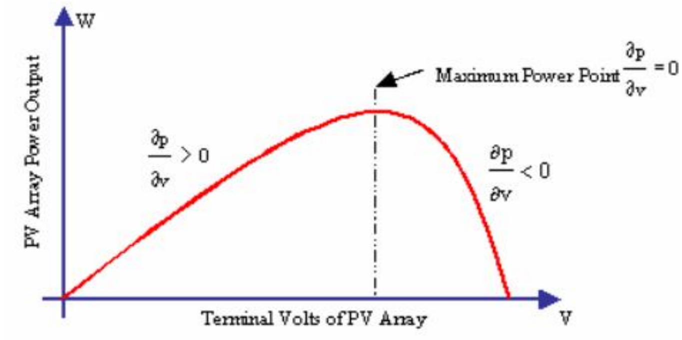


**Figure 1:** P-V characteristic of module [15]

∂P/∂V = o for V = Vmp
∂P/∂V > o for V < Vmp
∂P/∂V < o for V >Vmp

Various MPPT algorithms are available in order to improve the performance of PV system by effectively tracking the MPP. There are some conventional methods for MPPT [16]. Some of them are listed here

(1) Constant Voltage method
(2) Open Circuit Voltage method
(3) Short Circuit Current method
(4) Perturb and Observe method
(5) Temperature Parametric method
(6) Fuzzy Logic method

### 3.1- Fuzzy logic controller for MPPT:

Fuzzy logic or fuzzy set theory is a new method of controlling the MPPT in obtaining the peak power point. Typical fuzzy logic based MPPT controller includes three basic components, fuzzification module, inference engine, and defuzzification module; as shown in figure 2.



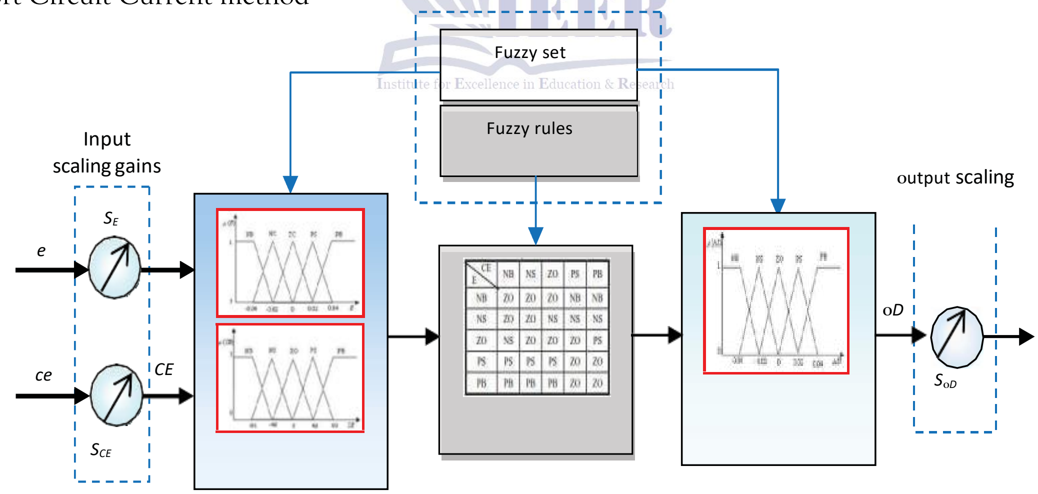


**Figure 2:** Structure of Fuzzy logic Controller [17].

### 3.2- Defuzzification:

It was seen that the inference methods provide a function for the resulting membership variable; it thus acts of fuzzy information [18]. Being given that converter DC-DC requires a precise control signal D at its entry it is necessary to envisage a transformation of this fuzzy information into deterministic information, this transformation is called defuzzification. Defuzzification can be performed normally by two algorithms: Center of Area (COA) and the Max Criterion Method (MCM). The most used defuzzification method is that of the determination of the center of gravity (COG) of final combined fuzzy set [19]. The final combined fuzzy set is defined by the union of all rule output fuzzy set using the maximum aggregation method. For a sampled data representation, the center of gravity (COG) is computed point-wise by,

$$\Delta D = \frac{\sum_{j=1}^{n} \mu(\Delta D_j) \cdot \Delta D_j}{\sum_{j=1}^{n} \mu(\Delta D_j)}$$

Once the fuzzy controller output, which is the change of duty ratio ΔD (k), is defuzzified by (8) and scaled by the gain SoD, it is converted to the actual duty ratio D (k) by

$$D(k) = D(k-1) + S_{\Delta D} \cdot \Delta D(k)$$

## 3- Methodology:

The methodology for designing and implementing the **Smart Hybrid Solar-Wind Power System** with Maximum Power Point Tracking (MPPT) algorithms involves several key steps: system modeling, integration of renewable energy sources, MPPT optimization, energy storage management, and simulation and analysis [20]. This section outlines the approach used to model, design, and evaluate the system for improved energy efficiency. Figure 3 shows the block diagram of the system.

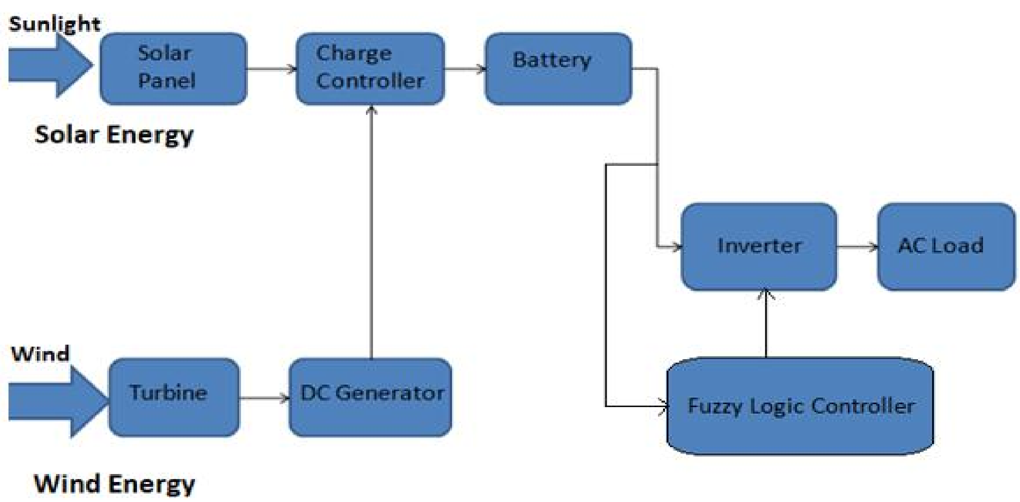


**Figure 3:** Block Diagram of the system

### 4.1- System Design and Components:

The proposed hybrid power system consists of three main components: **solar photovoltaic (PV) panels, wind turbines,** and a **battery storage system**. These components work together to ensure a reliable and continuous power supply, even in the face of intermittent energy generation.

#### 4.1.1- Solar PV System:

The solar energy component consists of a set of PV panels connected in series and parallel to achieve the desired output voltage and current. The solar panel array's power output is dependent on solar irradiance, which varies throughout the day. Only absorbed energy from sunlight produce electricity [21]. The energy absorbed from sunlight is moved to electrons of the atoms of photovoltaic cell. Special manufacturing makes the visible surface of the cell more available to free electron, so the electrons obviously transfer to the surface. Electrons get this energy and escape from normal condition of their atoms. These electrons cause to flow current in circuit. Built-in electrical field is the possessions of the photovoltaic cell that provides force which is necessary for only absorbed energy from sunlight produce electricity [22]. The energy absorbed from sunlight is moved to electrons of the atoms of photovoltaic cell. Special manufacturing makes the visible surface of the cell more available to free electron, so the electrons obviously transfer to the surface. Electrons get this energy and escape from normal condition of their atoms. These electrons cause to flow current in circuit. Built-in electrical field is the possessions of the photovoltaic cell that provides force which is necessary for an external load to drive current through it. Two different layers of semiconductor material are used to produce 'built-in electric field' in photovoltaic cell. To increase the properties of material, specific chemicals are used. This is called doping. 'N-type' semiconductor layer is doped with small amount of pentavalent element like phosphorus.

This produce additionally free –ive charge called 'electrons'. 'N-type' semiconductor have –ive electrical charge. 'P-type' semiconductor layer is doped with trivalent element usually silicon. This produce additionally free moving +ive charge called 'holes'. 'P-type' semiconductor layer has +ive electrical charges [23]. 'Holes' are formed when electrons leave their place. When 'P-type' and 'N-type' layers put together, the electrons and holes pull each other. They create an electrical field called 'p-n junction'. Figure 4 shows the P-N junction of PV cell. When p-type and n-type semiconductors come into interaction, additional electrons transfer from n-type to p-type side. 'Depletion zone' is the area around p-n junction where production of current happens. When light photon is absorbed by atoms in n-type material, it will eliminate an electron. This process will create a hole and a free electron. The free electron and hole has enough energy to jump out the 'depletion zone'. A potential difference is produce between back and front surfaces of the cell when electrons pass through the front surface of the cell like negative and positive terminals of battery. The stream of electrons is pushed by to produce voltage which is direct current to joins at the back and front of the cell. Electricity flows through load when both surfaces are connected [24].

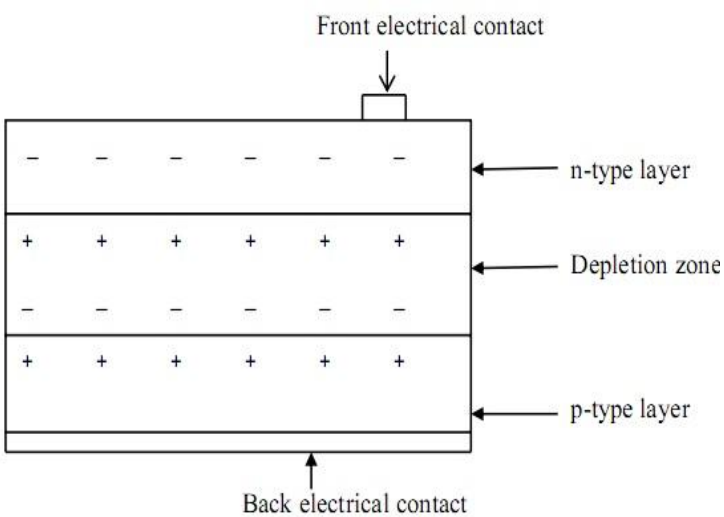


**Figure 4:** P-N junction of PV cell [24].

**4.1.2- Wind Turbine System:**

The wind energy component includes a horizontal-axis wind turbine (HAWT), which converts wind kinetic energy into electrical power. The wind turbine's power generation is influenced by the wind speed, which fluctuates with time and location. A HAWT has same configuration like windmill, it contain razor sharp edges that is similar to propeller that rotate on the x-axis. Rotor shaft and generator located on horizontal axis of turbine at the upper side of tower, and their direction should be towards the wind [25]. The Small turbines are connected by the wind vane which make the square with rotor while large turbines contain wind sensor with servo engine to make the turbine to contact towards the wind. Most large wind turbines contain gearbox, which rotate rotor from the axis very fast that run an electrical generator. The turbine is located in the opposite direction of wind with the tower due to the distortion produce by the tower. Figure 5 shows the schematic overview of wind turbine components. Turbine blades are made tough to make the blades of steels from being pushed towards the tower by high winds. Moreover, the turbine blades are separated at significant distance in front of tower [26]. Machines have been produced in the direction of wind, with the issue of disorder, and really they don't have to trouble with an additional part for making them in accordance with the wind. Additionally, in high winds the extremely sharp edges can be allowed to bend which diminishes their cleared region and subsequently their wind resistance. Since turbulence prompts shortcoming and trustworthiness of most HAWTs are upwind machines [27]. A wind tower can be as high as 120/150 meters. As wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity. Generally output power of the wind system increase with increase in height and also reduces the turbulence in wind.

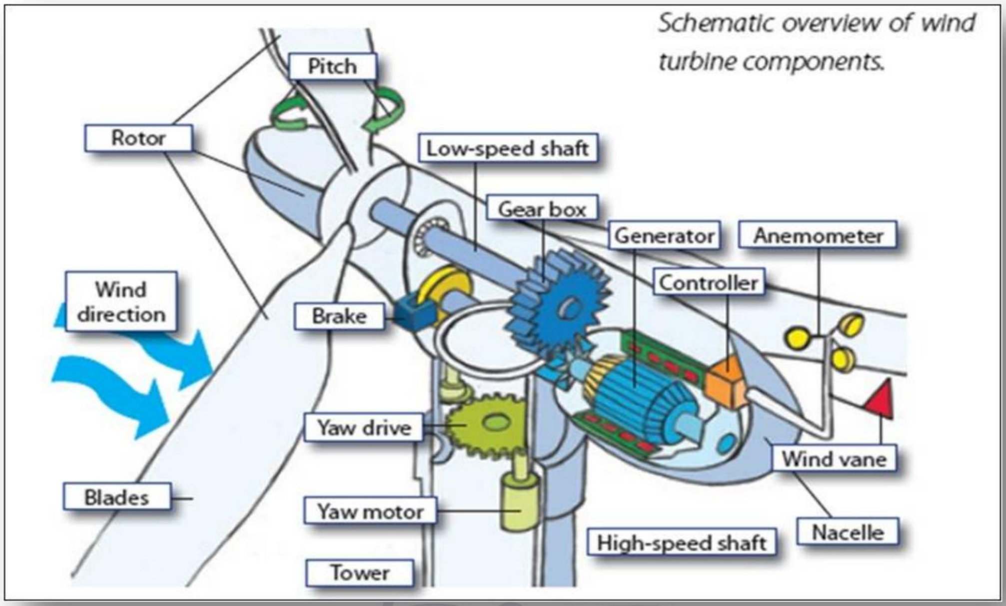




**Figure 5:** Schematic overview of wind turbine components [28].

The power in the wind increases as the cube of the wind speed,

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

where $\boldsymbol{\rho}$ is the air density
$\boldsymbol{v}$ is the wind speed
$\boldsymbol{A}$ is the area covered by the rotor
Effect of wind is more prominent due to its cubic relationship with power.
Power also depends on the elevation and temperature because air density is a function of these parameters $\rho$= $(H)$
The actual power produced by a rotor would be decided by the efficiency of energy transfer from wind to the rotor. This efficiency is usually termed as Power Coefficient $(CP)$/ Capacity Factor. Thus the mechanical power and mechanical torque on the wind turbine rotor shaft are given by

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

$$T = \frac{1}{2\omega}\rho A C_p v^3$$

**4.1.3- Battery Storage System:**

To manage the variability in both solar and wind generation, a **battery storage system** is incorporated. The battery stores excess energy generated during high production periods and provides power to the load during times of low renewable energy output. Battery is used to store energy [29]. Generally, it consists of a cathode, an anode and an electrolyte. Electrolyte is a substance that reacts chemically with cathode and anode. When the cathode and anode of a battery is linked in a circuit, due to connection, between the electrolyte and anode a chemical reaction take place. In battery, the chemical reaction reasons to produce electrons. This creates a potential difference among cathode and anode. This potential difference causes to flow current through a wire connected to anode and cathode. Battery provides limited amount of power [30]. Battery can't produce electricity when cathode and anode is not extended to be used in the reaction or if they are consumed. Than battery is said to be 'dead'. In case of recharging of a battery, the direction of flowing electrons change by using other power source. Process occur in reverse direction and anode and cathode restore to their original state [31].

### 4.2- Maximum Power Point Tracking (MPPT) Algorithms:

The key to optimizing the efficiency of the hybrid system is the use of **MPPT algorithms.** These algorithms track the maximum power point of both the solar PV system and the wind turbine, ensuring that both energy sources operate at their peak efficiency.

- **Solar MPPT**: For the solar PV system, the **Perturb and Observe (P&O)** algorithm is implemented [32]. This algorithm perturbs the voltage or current of the solar panel, and based on the resulting changes in power output, it determines the optimal operating point that maximizes power generation.
- **Wind MPPT**: The wind system uses the **Tip-Speed Ratio (TSR)** algorithm, which adjusts the wind turbine's rotational speed to maintain the optimal TSR. This technique maximizes the power generated by the wind turbine by adjusting its operational characteristics based on real-time wind speed data [33].

### 4.3- System Integration and Simulation:

The system components, including the solar PV system, wind turbine, battery storage, and control algorithms, are integrated into a unified model using **MATLAB/Simulink** for simulation purposes. The simulation environment allows for real-time performance analysis under various environmental and load conditions.

- **Simulation Conditions**: The system is tested under varying conditions of solar irradiance (200 to 1000 W/m²) and wind speed (3 to 15 m/s). The load profile is designed to simulate typical daily energy consumption patterns [34].
- **Performance Metrics**: Key performance indicators such as **energy efficiency, system reliability, battery state of charge (SOC),** and **power output** are evaluated. These metrics are used to compare the performance of the hybrid system with standalone solar or wind systems.

## 4- Simulation and Result:

In this section, presents the results of the simulation and implementation of the Smart Hybrid Solar-Wind Power System integrated with Maximum Power Point Tracking (MPPT) algorithms. The system was tested under varying solar irradiance and wind speed conditions to assess the effectiveness of the proposed hybrid MPPT algorithms, energy management strategies, and the overall system performance in terms of energy efficiency and stability [35]. The Simulation of Hybrid (Solar & Wind) Based Fuzzy Logic MPPT in MATLAB is given in figure 6.

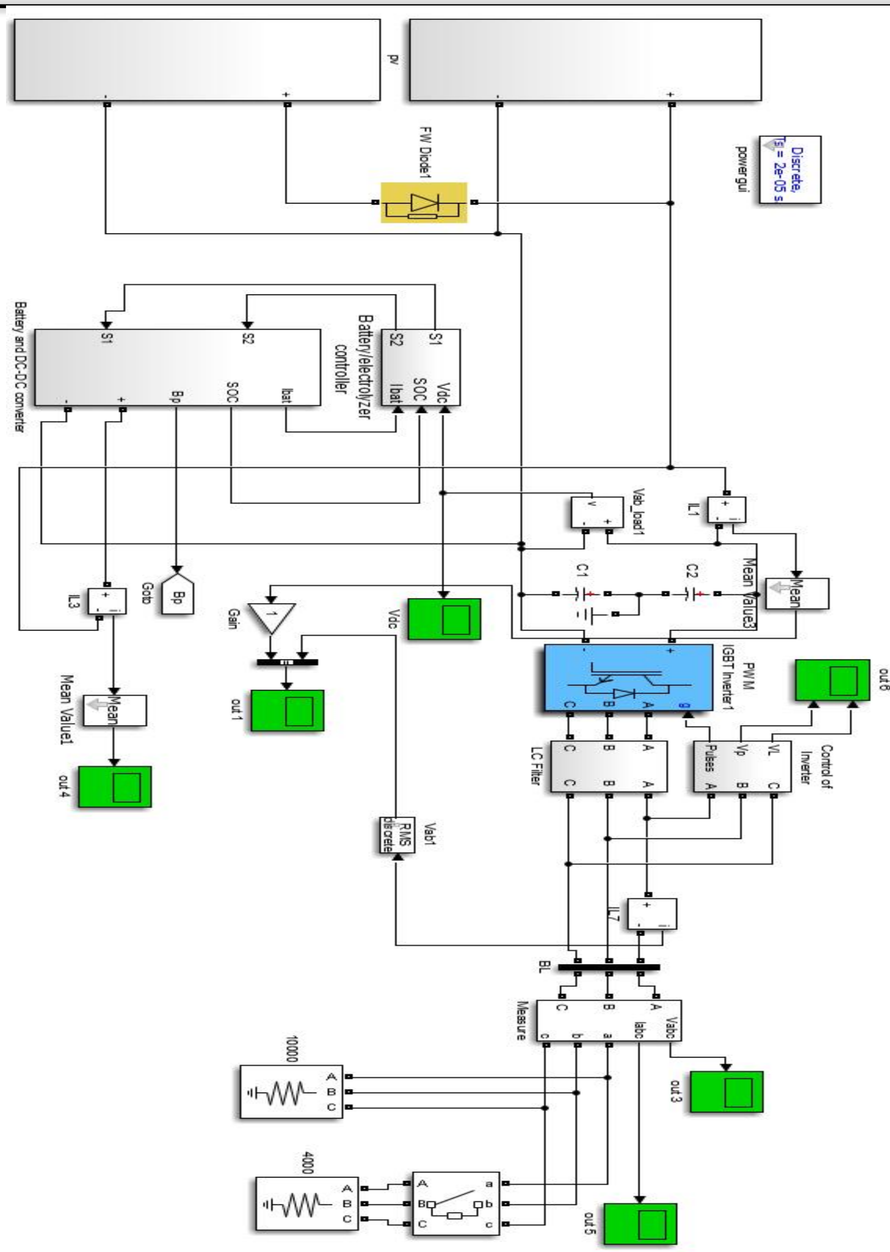


**Figure 6:** Simulation of Project

**Case # 1:**

During the daytime, when both solar and wind power generation meet the load requirements, Figure 7 illustrates the solar voltage, approximately 640V. Figure 8 displays the power generated by the solar system. Figure 9 depicts the wind voltage, around 640V, while Figure 10 shows the power generated by the wind turbines [36–37]. Figure 11 presents the battery's state of charge, and Figure 12 indicates the output voltage at the load, approximately 230V. Finally, Figure 13 illustrates the output current flowing through the load, around 15A.

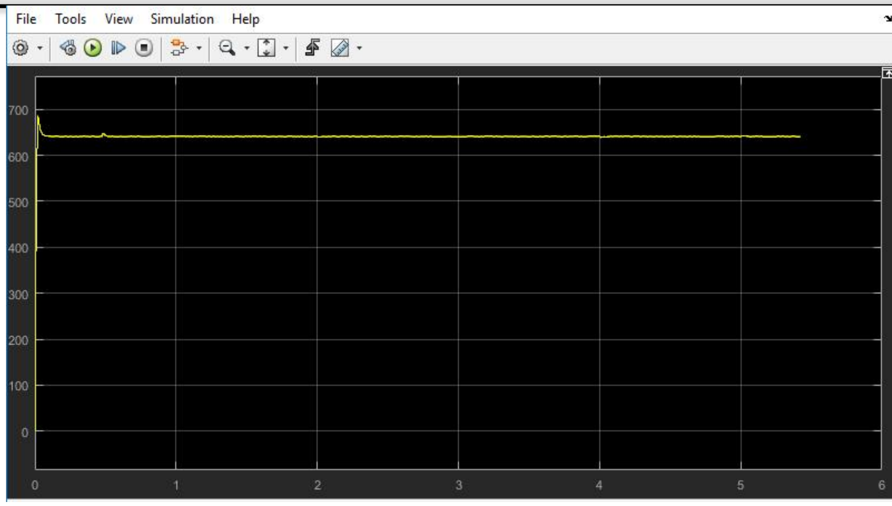

**Figure 7:** Solar Voltages approx. 640V

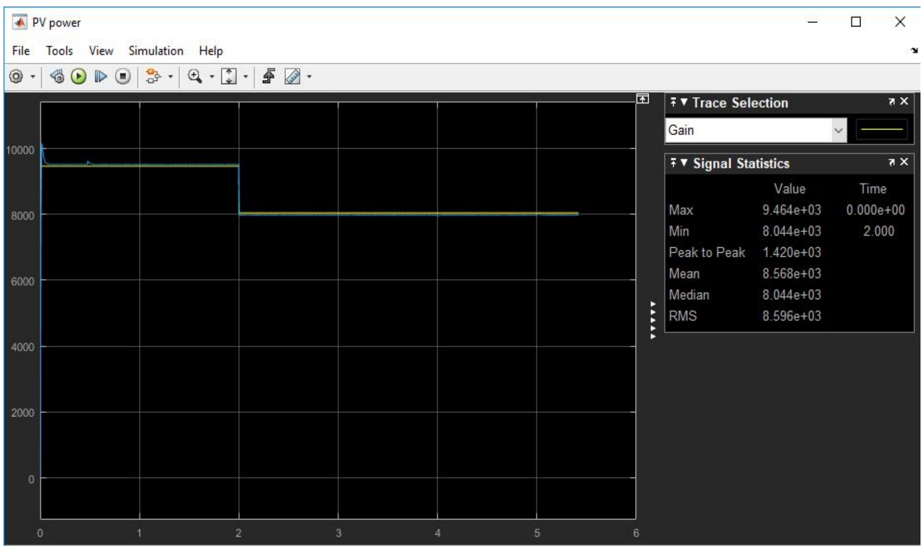

**Figure 8:** Generated Power from Solar

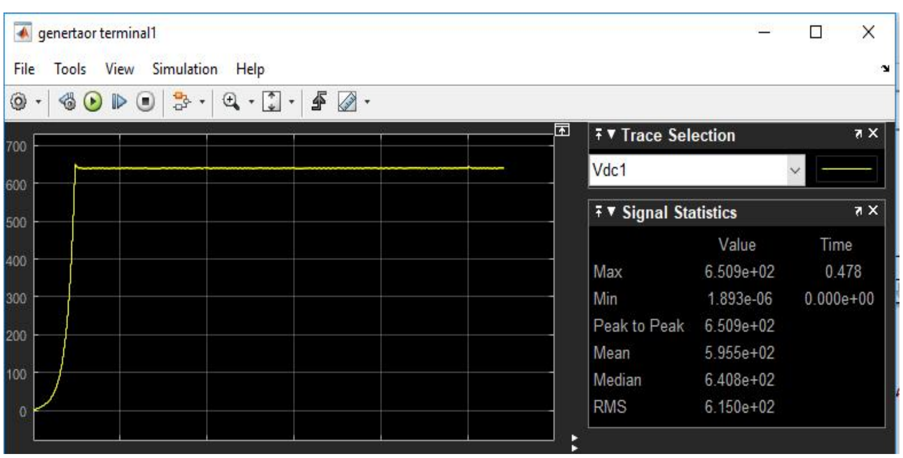

**Figure 9:** Wind Voltages approx. 640V

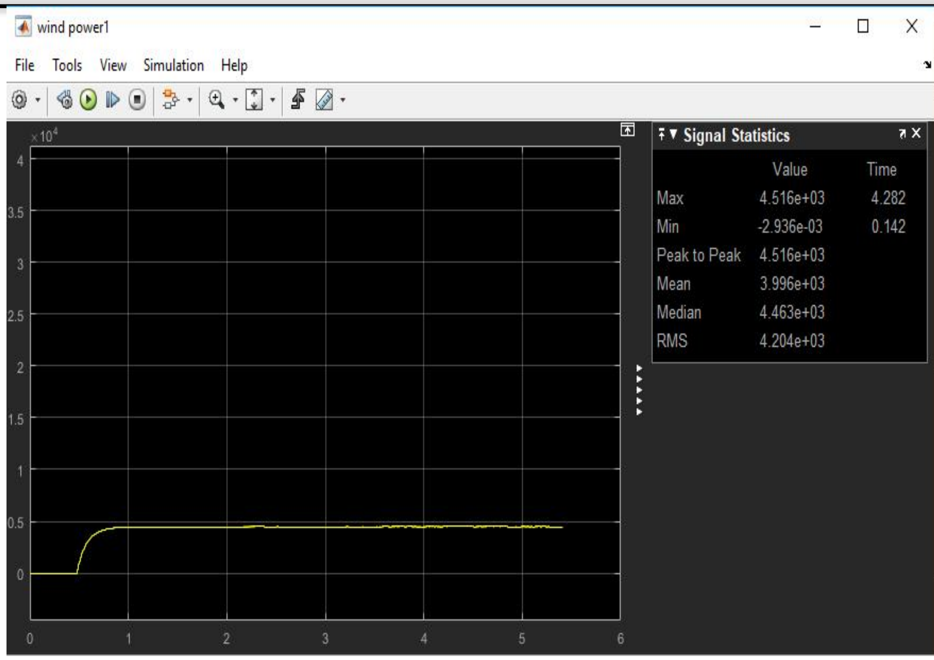

**Figure 10:** Wind Power

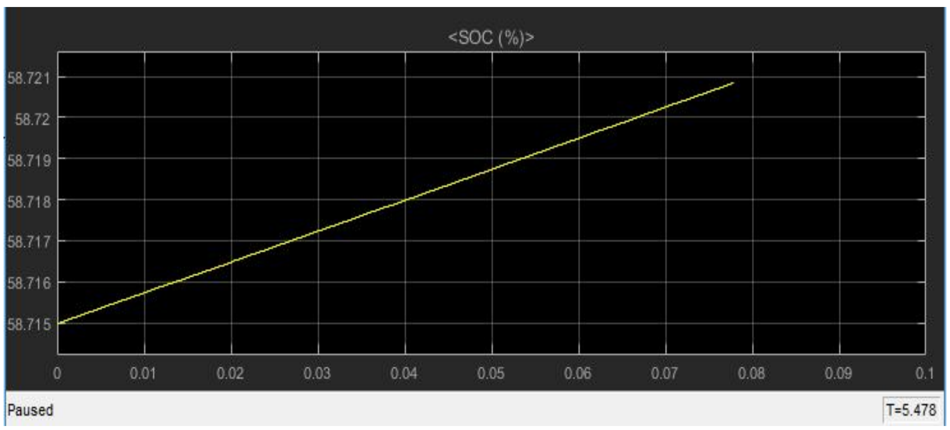

**Figure 11:** State of Charge of Battery

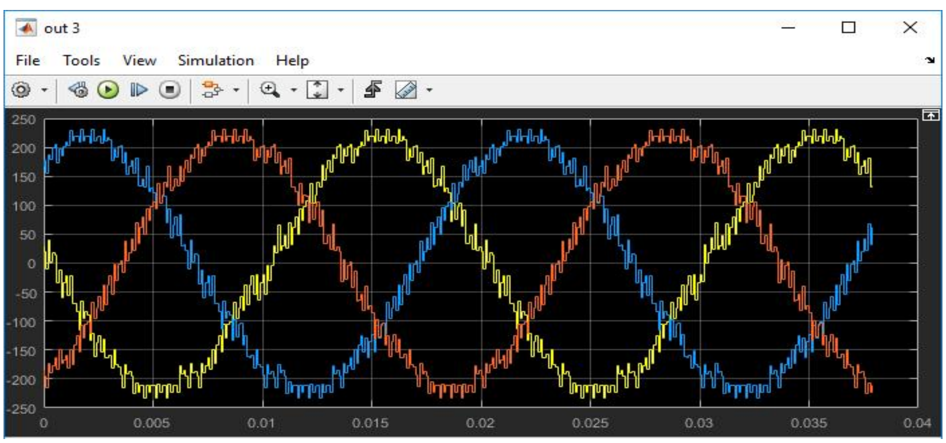

**Figure 12:** Output Voltages at Load in this Case approx. 230V

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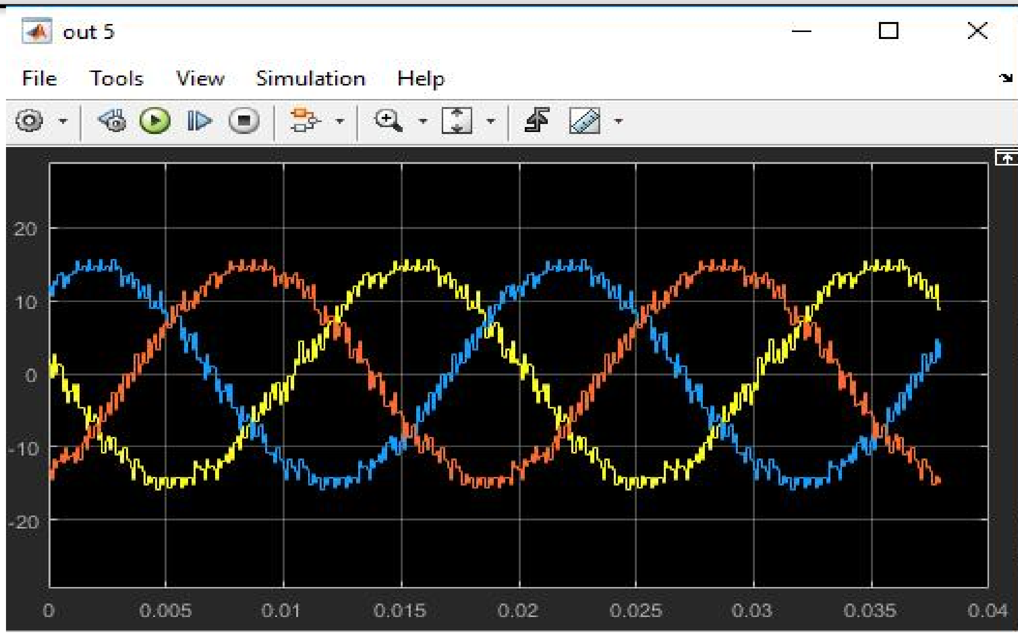


**Figure 13:** Output Current through Load approx. 15A

In this Case, the Solar Radiations are from 1000 to 850W/m$^2$. In this report the analysis based on three years wind data has been presented along with the wind generated electric power at Karachi, Sindh. At 50 meters the annual average wind speed of 4.2 m/s. Both the Sources produces electrical energy and meet the requirement of load [38]. The State of Charge (SOC) shows that graph is upward and the extra energy is stored in battery.

**Case # 2:-**

In this case, the additional load of (4000W) is attached with the system in same condition as described above, the output current is increased by 5A, but the voltage remain constant at 230V. Figure 14 and 15 shows the Output Current through Additional Load and Output Voltage



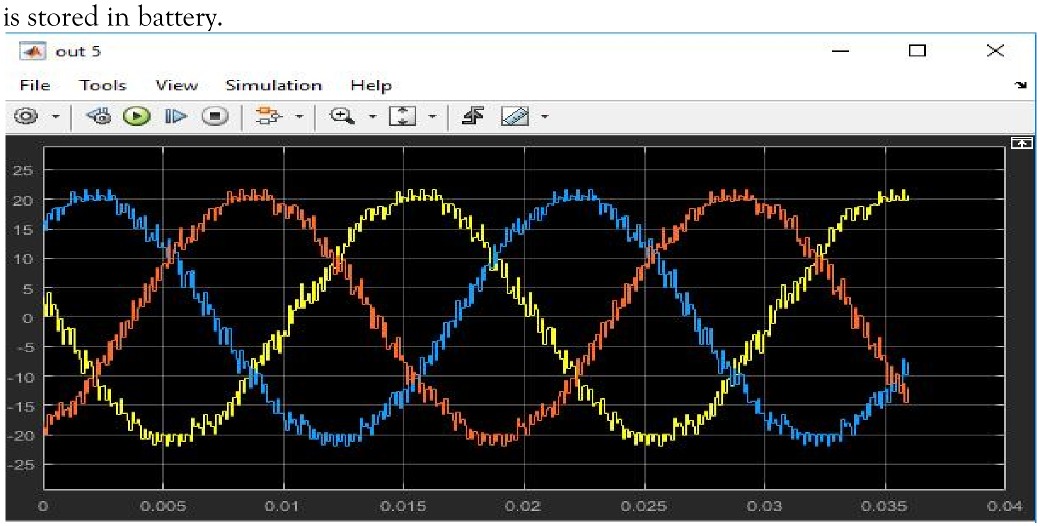


**Figure 14:** Output Current through Additional Load

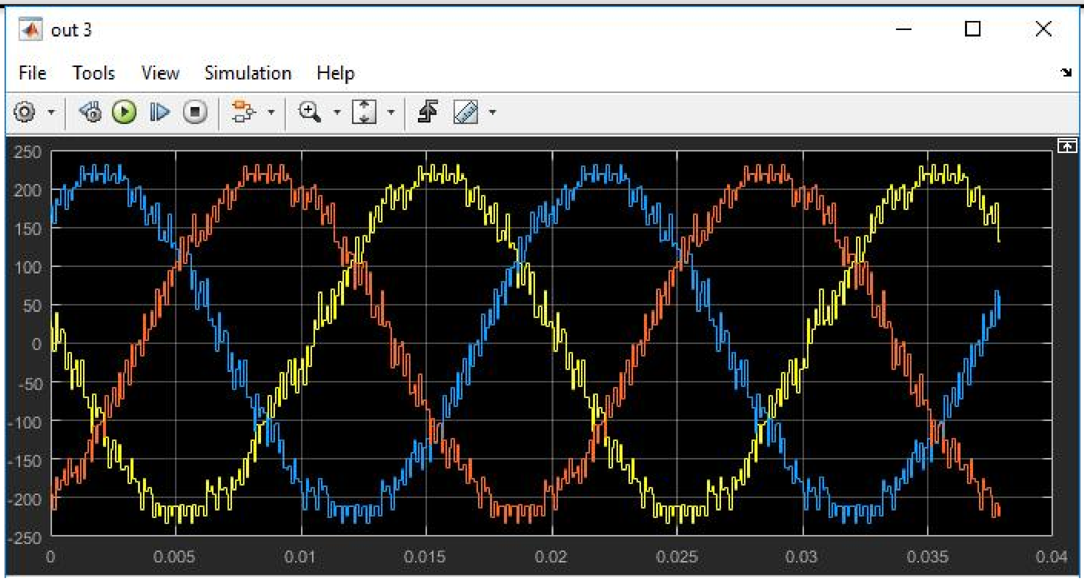


**Figure 15:** Output Voltage

**Case # 3:-**

During the night, when solar energy is unavailable, the wind turbine and battery supply the power required to meet the load demand. As a result, the State of Charge (SOC) graph shows a downward trend, indicating that the battery is discharging to provide energy. Under these conditions, Figure 16 displays the solar voltage at 0V [39]. Figure 17 illustrates the wind power generation. Figure 18 shows the SOC graph decreasing. Figure 19 depicts the output voltage at the load during the night, and figure 20 illustrates the output current flowing through the load.

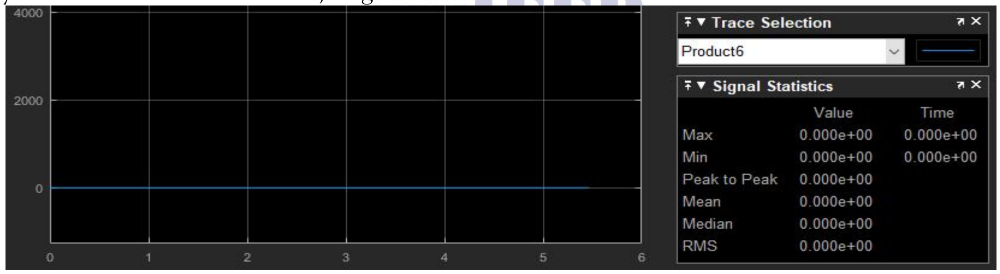


**Figure 16:** Solar Voltages 0V in Night

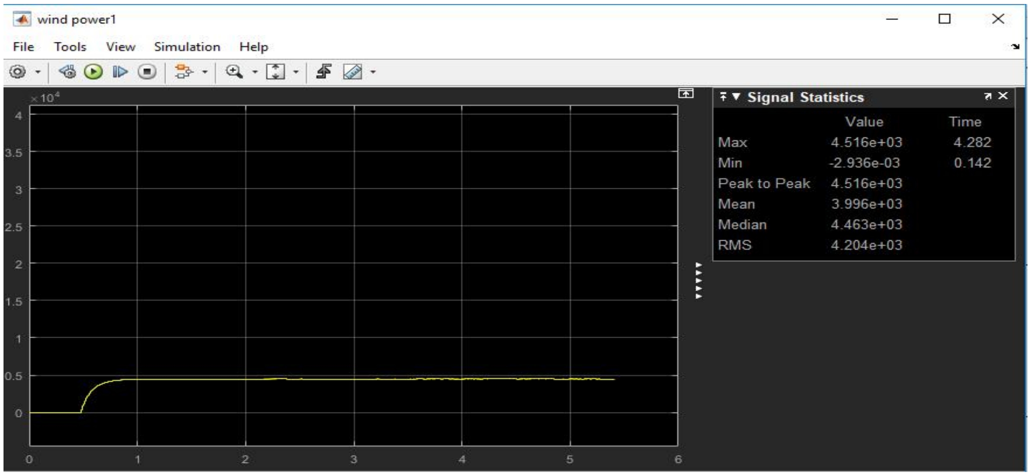


**Figure 17:** Wind power

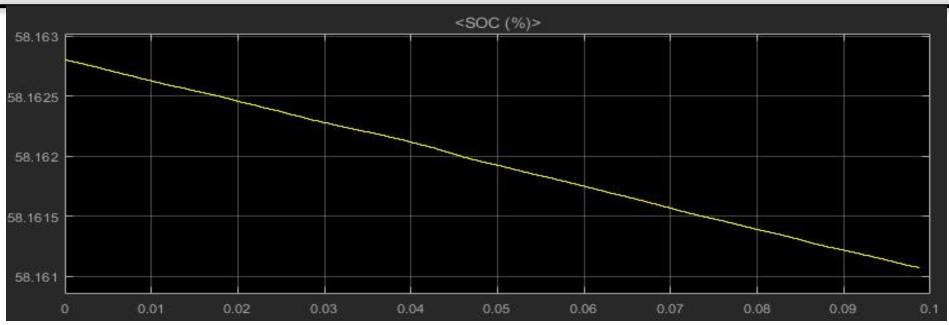


**Figure 18:** State of Charge (SOC) graph decreasing

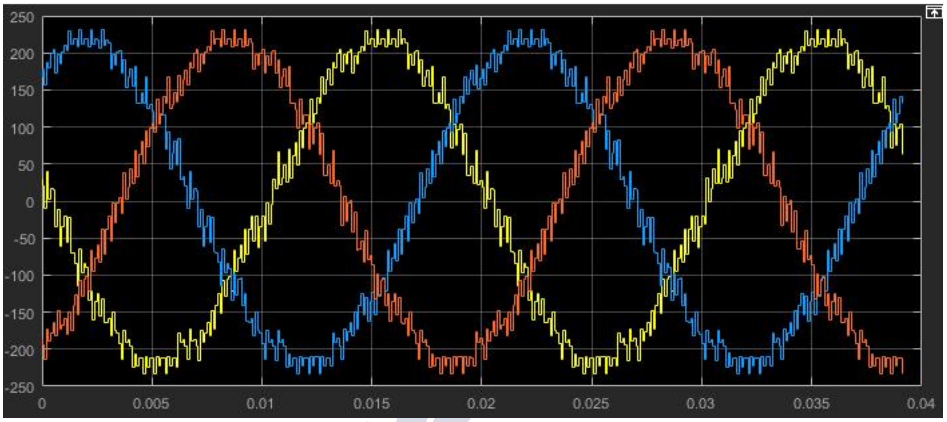

**Figure 19:** Output Voltage at load in Night

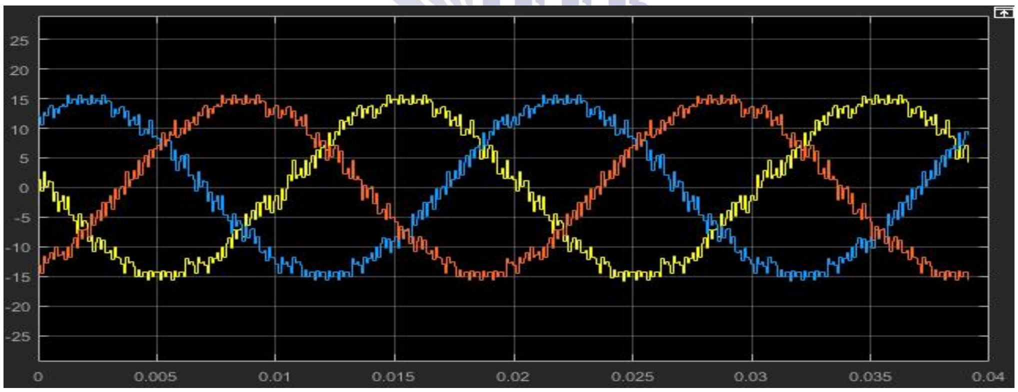

**Figure 20:** Output Current

## 5- Future Work:

While the proposed hybrid solar-wind power system demonstrates significant improvements in energy efficiency and reliability, there are several avenues for future research and development to further optimize its performance.

1. **Integration of Additional Renewable Sources**: Future work could explore the integration of other renewable energy sources, such as biomass or hydro, into the hybrid system to further increase energy generation flexibility and reliability.

2. **Advanced Energy Storage Solutions**: The current system uses battery storage for short- to medium-term energy storage [40]. Research into advanced storage technologies, such as supercapacitors, flywheels, or hydrogen storage, could offer higher efficiency, longer lifetimes, and better scalability for large-scale systems.

3. **Real-time System Optimization**: Implementing real-time optimization algorithms using machine learning techniques or predictive analytics could improve the system's adaptability to dynamic environmental conditions, load demands, and grid interactions. This would further enhance the efficiency and economic viability of the system.

4. **Grid Integration and Smart Grids**: Further research could focus on optimizing the hybrid system for grid-connected applications, exploring how it could be integrated with smart grids for demand-response management, distributed power generation, and enhanced grid stability [41].

5. **Improved MPPT Algorithms**: While the current hybrid MPPT algorithm effectively adjusts to variations in solar irradiance and wind speed, future work could investigate more advanced techniques, such as deep learning-based MPPT algorithms, for even faster and more accurate maximum power extraction.

6. **Prototype Development and Testing**: Building and testing a physical prototype of the proposed system in a real-world setting would provide valuable insights into the system's performance under actual operating conditions [42–43]. This would also allow for better validation of simulation results and identification of practical challenges in system design and deployment.

By addressing these areas, future research can further enhance the performance, scalability, and commercial viability of hybrid renewable energy systems, contributing to their widespread adoption and the global transition to sustainable energy.

## 6- Conclusion:

In conclusion, this paper presents a smart hybrid solar-wind power system optimized with MPPT algorithms to improve energy efficiency and stability. By integrating solar and wind energy sources with a battery storage system, the system addresses renewable energy intermittency and ensures a reliable power supply. A fuzzy logic-based supervisory control system effectively manages power flow, peak shaving, and energy storage, adapting to fluctuating supply and demand. The hybrid system employs separate MPPT techniques for solar panels and wind turbines, maximizing energy extraction under variable environmental conditions. A novel hybrid MPPT algorithm dynamically adjusts to changes in solar irradiance and wind speed, enhancing overall system performance. Simulation results show significant efficiency improvements compared to standalone solar or wind systems. This work demonstrates the potential of advanced MPPT control for sustainable and reliable energy generation, particularly in off-grid and remote areas, contributing to the transition toward clean energy solutions.

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