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Grid Connected Hybrid Energy Storage Structure with Renewable Energy Sources

Mr. Hitendra Kumar Pandey
Assistant Professor, Electrical Engineering, Prabhat Engineering College, Kanpur Dehat
hitendra085@gmail.com

Shivam Savita
Research Scholar. Electrical Engineering, Prabhat Engineering College, Kanpur Dehat
shivamkumar53691@gmail.com

Virendra Kumar Yadav
Research Scholar, Electrical Engineering, Prabhat Engineering College, Kanpur Dehat
virendrakumaryadavmpi@gmail.com

Vishal Gautam
Research Scholar, Electrical Engineering, Prabhat Engineering College, Kanpur Dehat
vishalgautam9936@gmail.com

Yashi Mishra
Research Scholar, Electrical Engineering, Prabhat Engineering College, Kanpur Dehat
mishrayashi674@gmail.com

Abstract-This study presents the design and analysis of a hybrid renewable energy system integrating multiple energy sources such as solar photovoltaic (PV), wind, and hydroelectric power along with advanced energy storage technologies including battery, hydrogen storage, and supercapacitor. The system is supported by a power conversion unit and controlled using an intelligent energy management system (EMS) to ensure efficient power flow and system stability. The proposed model utilizes converters and bidirectional energy flow to interact with the grid, enabling optimal utilization of generated and stored energy. A cooling system is also incorporated to maintain safe operating conditions of storage components. The system is analyzed under varying conditions to evaluate its performance in terms of reliability, efficiency, and stability. The results demonstrate that the proposed hybrid system effectively balances energy generation and consumption, reduces dependency on conventional sources, and ensures continuous power supply.

Keywords-Hybrid Renewable Energy System, Solar PV, Wind Energy, Hydroelectric Power, Battery Storage, Supercapacitor, Hydrogen Storage, Energy Management System (EMS), Power Conversion, Bidirectional Energy Flow

I INTRODUCTION

Renewable energy sources (RESs) like solar, wind, hydro, tidal, and geothermal power offers several environmental benefits [1,2]. These sources help mitigate climate change by reducing greenhouse gas emissions and other harmful pollutants associated with traditional fossil fuel-based energy generation [3]. Renewable energy technologies have lower environmental impacts compared to fossil fuels, contributing to environmental sustainability [6]. Renewable energy systems can also lessen the total environmental effect of energy production, increase biodiversity, and cut greenhouse gas emissions [7,8]. The integration of renewable energy with multi-generation systems can further increase efficiency, reduce pollution emissions, and promote sustainability. Overall, the environmental benefits of utilizing renewable energy include lower emissions, reduced pollution, enhanced biodiversity, and a more sustainable approach to meeting energy needs. Hybrid renewable energy systems play a crucial role in enhancing the efficiency and reliability of off-grid systems. By combining sources like solar, wind, batteries, and diesel generators [9], these systems optimize power generation, minimize fuel consumption, and reduce operational costs [10]. Utilizing diverse renewable sources over extended simulation periods significantly boosts system reliability and resilience, making configurations up to 94% more robust than those based on single-year data [11]. Moreover, experimental analyses demonstrate that hybrid systems, incorporating wind and photovoltaic sources, can cover a substantial portion of energy consumption, with added storage capacity ensuring continuous power supply [12]. However, challenges persist due to the variable nature of solar and wind energies, necessitating careful planning to ensure reliable power supply in off-grid settings [13].

Hybrid System: A hybrid system is a system that uses multiple sources of energy. The integration of systems (wind and solar) has a greater impact on electricity generation. Such a system is called a "hybrid system”. The use of hybrid solar energy is realized in this field, where energy will be consumed throughout the year without any chance of interruption. There may be several energy combinations that meet the energy needs of hybrid power systems, solar and wind energy. The assignment is similar to the power from solar panels and wind turbines. The difference is that it is just an attachment in system. Photovoltaic solar panels or small wind turbines deepen on weather conditions. so, solar or wind energy alone is not enough. If both wind and solar energy are included into a something new body, a lot of renewable energy specialist claim to have a satisfactory hybrid energy source. In summer, when the sun's rays are strong, the wind speed is comparatively small. In winter or sunny days are comparatively short, on the contrary, the wind speed is relatively high. The effectiveness of these renewable systems shows dissimilarity throughout the year. In other words, the two systems must support each other to maintain the permanence of energy production in the system. Depending on the environmental conditions, the energy required by the system can be supplied separately from the wind or solar system, or both resources can be used simultaneously. The control unit determines which power source is used to charge the battery according to the input energy. Wind turbines first convert kinetic energy to mechanical energy and then convert it to electrical energy. The wind turbine in the system consists of a tower, an alternator, a frequency converter (gearbox) and a propeller. And pictures of the hybrid system built. [15]

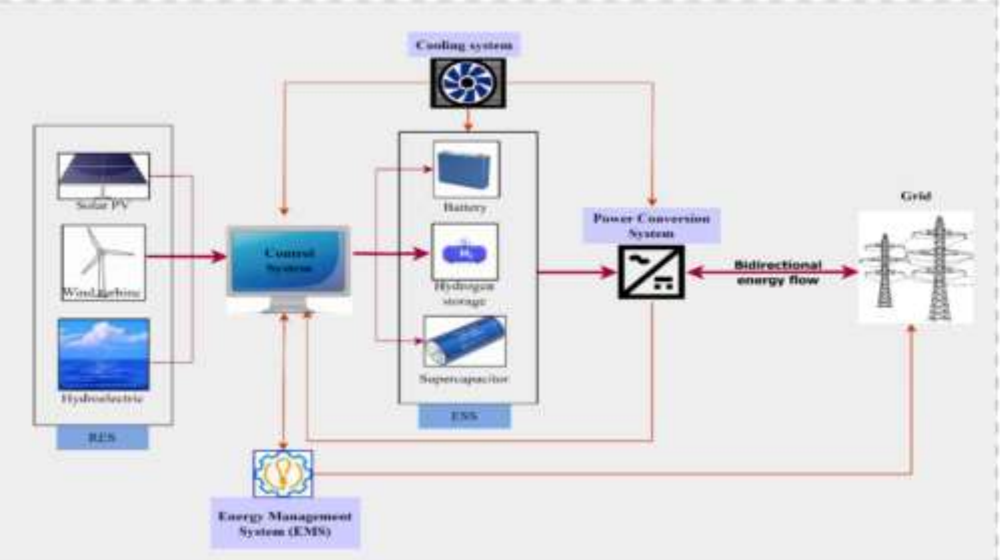

Fig. 1 An overview of hybrid energy storage systems and their components

The diagram 1 represents an integrated hybrid renewable energy system consisting of multiple energy sources, storage units, and control mechanisms to ensure efficient power generation and management. The system includes renewable energy sources (RES) such as solar photovoltaic (PV), wind turbine, and hydroelectric power, which generate electrical energy based on environmental conditions. These sources are connected to a central control system, which monitors and regulates the flow of energy. The generated energy is stored in an Energy Storage System (ESS) that consists of:

- Battery for long-term energy storage
- Hydrogen storage for energy conversion and long-duration backup
- Super capacitor for rapid charge/discharge and transient support

A cooling system is integrated to maintain optimal temperature conditions for the storage components, ensuring safety and efficiency. The stored energy is then supplied to the power conversion system, which converts electrical energy into the required form (AC/DC) for utilization. This system enables bidirectional energy flow, allowing energy to be both supplied to and drawn from the grid as needed. The diagram represents an integrated hybrid renewable energy system consisting of multiple energy sources, storage units, and control mechanisms to ensure efficient power generation and management. The system includes renewable energy sources (RES) such as solar photovoltaic (PV), wind turbine, and hydroelectric power, which generate electrical energy based on environmental conditions. These sources are connected to a central control system, which monitors and regulates the flow of energy.

II LITERATURE REVIEW

Renewable energy systems have gained significant attention in recent years due to increasing energy demand, environmental concerns, and the need for sustainable power generation. Various researchers have explored hybrid renewable energy systems, maximum power point tracking (MPPT), and advanced control techniques to improve system efficiency, stability, and reliability.

M. O. Abed El-Raouf et al. (2023) emphasized the importance of integrating renewable energy sources such as solar and wind into modern power grids. The study proposed the use of a Unified Power Flow Controller (UPFC) with an optimized FOPID controller to enhance system stability and performance. Simulation results demonstrated improved voltage regulation, reduced harmonic distortion, and enhanced power quality under varying operating conditions. [16]

A. Abbas et al. (2025) focused on improving the efficiency of photovoltaic (PV) systems through different MPPT techniques. The study compared standalone and hybrid MPPT algorithms such as Perturb and Observe (P&O), Particle Swarm Optimization (PSO), and Fuzzy Logic (FL). The results indicated that hybrid controllers significantly improve tracking efficiency, with a proposed triple hybrid MPPT achieving up to 99.5% efficiency. [17]

M. S. Endiz et al. (2025) provided a comprehensive review of MPPT techniques used in PV systems. The study analyzed various traditional and advanced MPPT methods based on parameters such as tracking speed, efficiency, cost, and implementation complexity. It concluded that advanced MPPT techniques offer higher efficiency, especially under partial shading conditions, though they involve increased complexity. [18]

S. A. Mohamed et al. (2021) investigated hybrid systems combining solar PV and wind energy. The study highlighted the importance of dynamic modeling and control strategies to ensure grid stability. Using MATLAB simulations, the system demonstrated stable voltage at the point of common coupling and efficient power injection into the grid under varying climatic conditions. [19]

H. Al-Najjar et al. (2022) explored Hybrid Renewable Energy Systems (HRES) using photovoltaic and biomass sources. The study employed HOMER Pro software to determine the optimal system configuration based on energy efficiency, system sizing, and economic factors. Results showed that hybrid systems can provide cost-effective and sustainable energy solutions. [20]

D. Kumar et al. (2025) proposed an advanced hybrid energy management system integrating solar, wind, battery storage, and microturbines. The study introduced a Quantum-Inspired Multiverse Optimization (QI-MVO) algorithm, achieving 99.9% efficiency and reducing power losses significantly. The system demonstrated improved reliability, faster convergence, and better energy distribution. [21]

III PROPOSED SYSTEM

The proposed system is a hybrid renewable energy system that integrates multiple energy sources such as solar, wind, battery storage, supercapacitor, and diesel generator to ensure reliable and continuous power supply. In this system, the solar photovoltaic (PV) source generates DC power, which is regulated using a DC–DC converter to maintain a stable voltage. The wind energy system and diesel generator produce AC power, which is converted into DC using AC–DC rectifiers. All generated DC power is collected at a common DC bus. The battery acts as the main energy storage unit, storing excess energy and supplying power during low generation periods. The supercapacitor provides fast charging and discharging capability, helping to handle sudden load variations and improving system stability. The DC power from the DC bus is converted into AC using a DC–AC inverter, which supplies power to different loads such as residential and industrial loads through the AC bus. A control system is implemented to monitor system parameters, manage power flow, and ensure system stability and protection. It coordinates between different energy sources and storage units to optimize performance and maintain uninterrupted power supply.

Battery Module

The battery acts as the primary energy storage unit. It stores excess energy generated from renewable sources and supplies power during low generation periods or high demand. It ensures continuity of power and improves system reliability.

Solar (PV) Module

The solar photovoltaic system converts sunlight into DC electrical energy. A DC–DC converter is used to regulate the output voltage and ensure maximum power extraction (MPPT), improving efficiency.

Diesel Engine Module

The diesel generator serves as a backup power source. It provides electricity during insufficient renewable energy generation and ensures uninterrupted power supply. The generated AC power is converted into DC using an AC–DC rectifier.

Wind Energy Module

The wind turbine converts wind energy into electrical energy (AC). This AC power is converted into DC using an AC–DC rectifier before being supplied to the DC bus.

DC–DC Converter Module

This converter regulates and stabilizes the DC output from the solar PV system. It ensures proper voltage levels for integration into the DC bus and improves energy transfer efficiency.

AC–DC Rectifier Module

The rectifier converts AC power from the wind turbine and diesel generator into DC power, allowing integration with the DC bus.

DC Bus

The DC bus acts as a common connection point where all DC power sources (solar, battery, wind, diesel) are combined. It ensures efficient power distribution within the system.

8. DC–AC Inverter Module

The inverter converts DC power from the DC bus into AC power, which is required for supplying AC loads such as residential and industrial systems.

AC Bus

The AC bus distributes AC power from the inverter to various loads. It serves as the main supply line for end-user applications.

AC Load Modules

- AC Load 1: Represents residential or household loads
- AC Load 2: Represents industrial or commercial loads

These loads consume the electrical power supplied by the system.

Super capacitor Module

The super capacitor provides fast charging and discharging capability. It handles sudden load changes and transient conditions, improving system stability and reducing stress on the battery.

Control System Module-The control system monitors and manages the entire system. It:

- Controls power flow
- Maintains voltage and frequency stability
- Ensures protection and efficient operation
- Coordinates between all modules

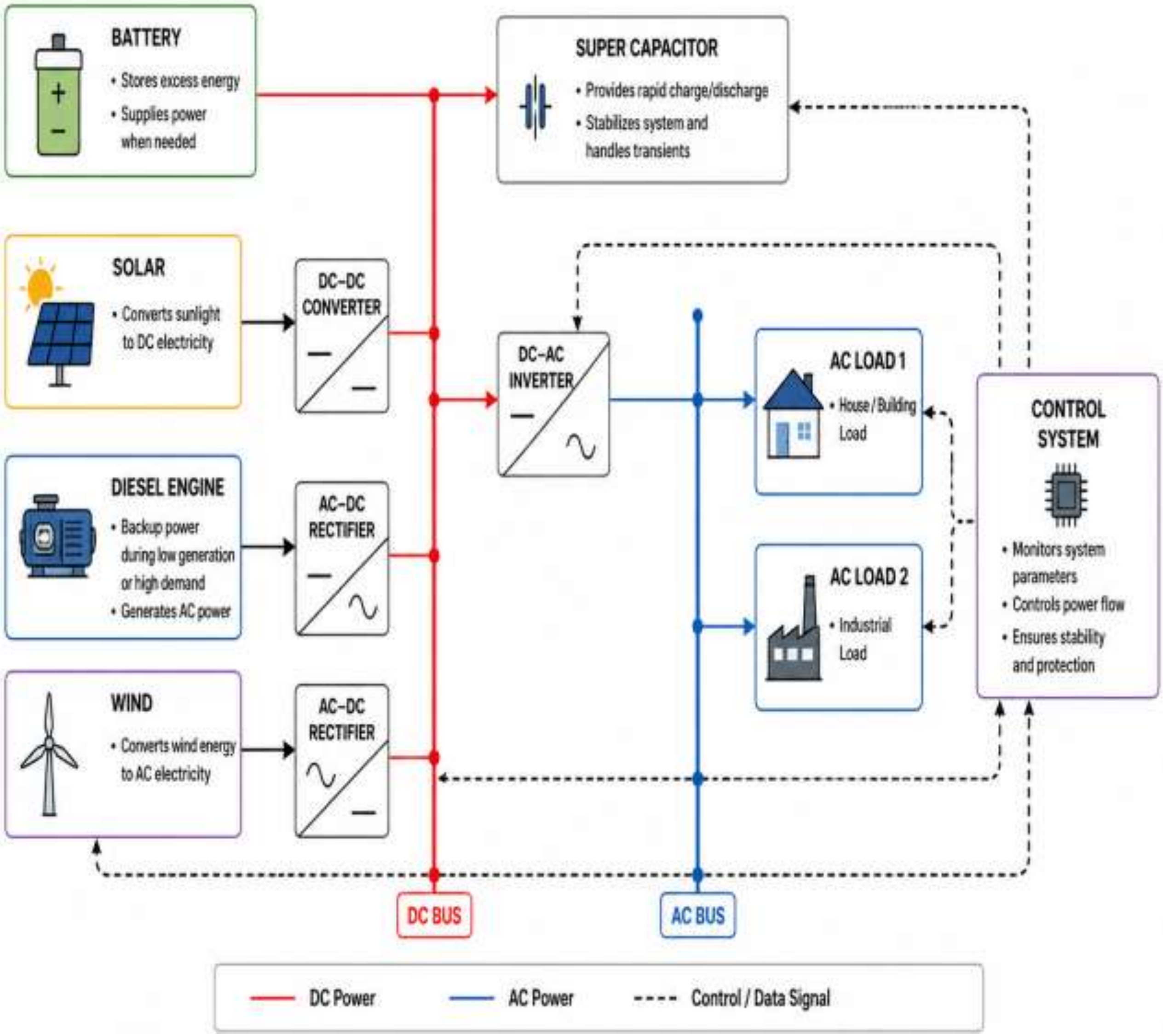

Fig. 2 proposed block diagram

SOLAR PHOTOVOLTAIC (PV)

The figure 3 represents a solar photovoltaic (PV) based DC–DC boost converter system. The solar panel generates DC power from sunlight, which is fed into the circuit. A current measurement (CM) block is used to monitor the input current. The inductor (L) stores energy when the switch (MOSFET M1) is turned ON and releases energy when the switch is turned

OFF. The diode allows current to flow in one direction, preventing backflow, while the capacitor (C) smooths the output voltage. The MOSFET switch (M1) is controlled to regulate the voltage and boost the input voltage to a higher level at the output terminals. This system ensures efficient energy conversion and is commonly used with MPPT techniques to maximize power extraction from the solar panel.

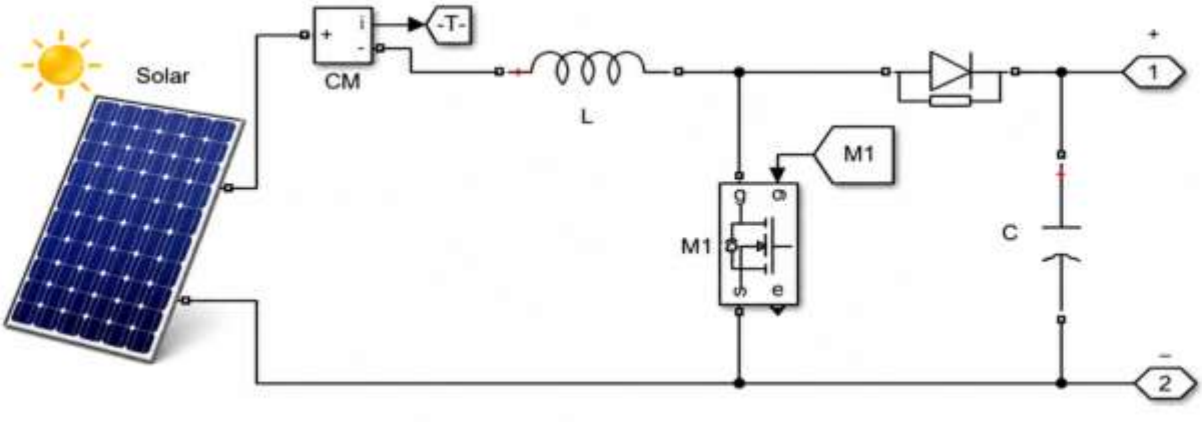

Fig. 3 Solar Panel

The inverter used in the grid-connected photovoltaic system is responsible for controlling DC bus voltage, grid-connected synchronization, and injecting high-quality electrical energy. The inverter used on the grid side of the present invention is called a voltage source converter (VSC) and is responsible for synchronizing the system voltage with the mains voltage. The mains voltage and frequency are used to operate the DC-AC inverter (inverter).

WIND TURBINE Doubly-fed electric machines are mostly electric machines that are fed ac currents into both the stator and the rotor windings. Most doubly-fed electric machines in industry today are three-phase wound-rotor induction machines.

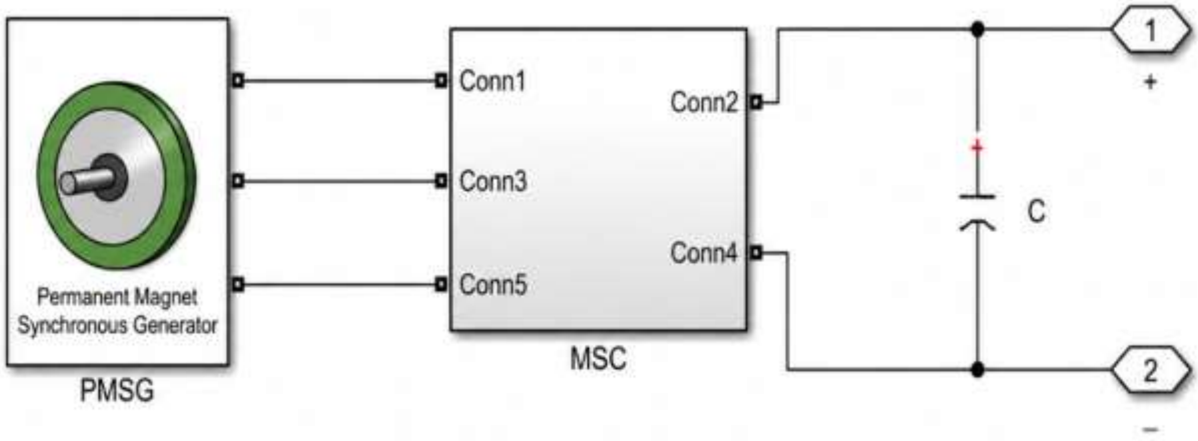

Fig.4 wind turbine system

DIESEL GENERATOR DG set (a unit of diesel engine and governor) is a device which converts fuel (diesel oil) energy into mechanical energy in diesel engine and subsequently converts mechanical energy into electrical energy in a governor.

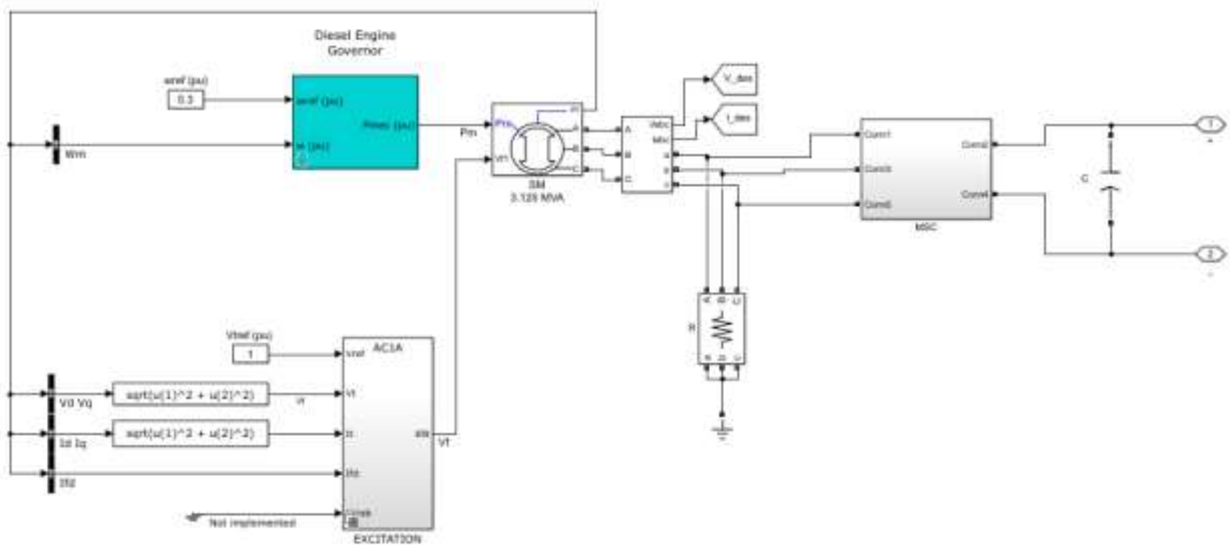

Fig.5 Diesel Generator system

BATTERY: A battery is a device consisting of one or more electrochemical cells with external connections provided to power electrical devices such as flashlights, mobile phones, and electric cars. When a battery is supplying electric power, its positive terminal is the cathode and its negative terminal is the anode. The terminal marked negative is the source of electrons that will flow through an external electric circuit to the positive terminal. When a battery is connected to an external electric load,

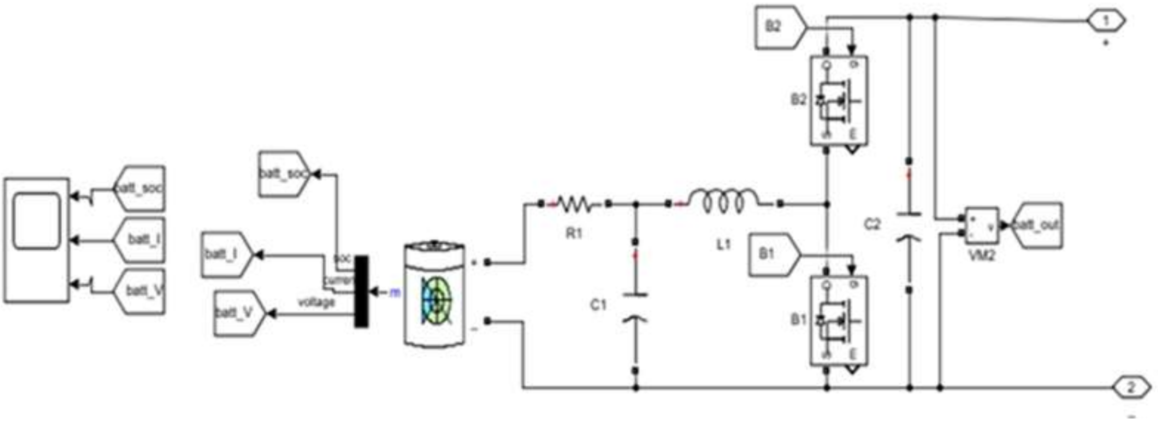

Fig.6 Battery Subsystem

SUPER CAPACITOR: Super capacitors (or super capacitors) differ from ordinary capacitors in two important ways: their plates actually have a larger area, and the distance between them is much smaller because the separator between them Conventional dielectrics works differently.

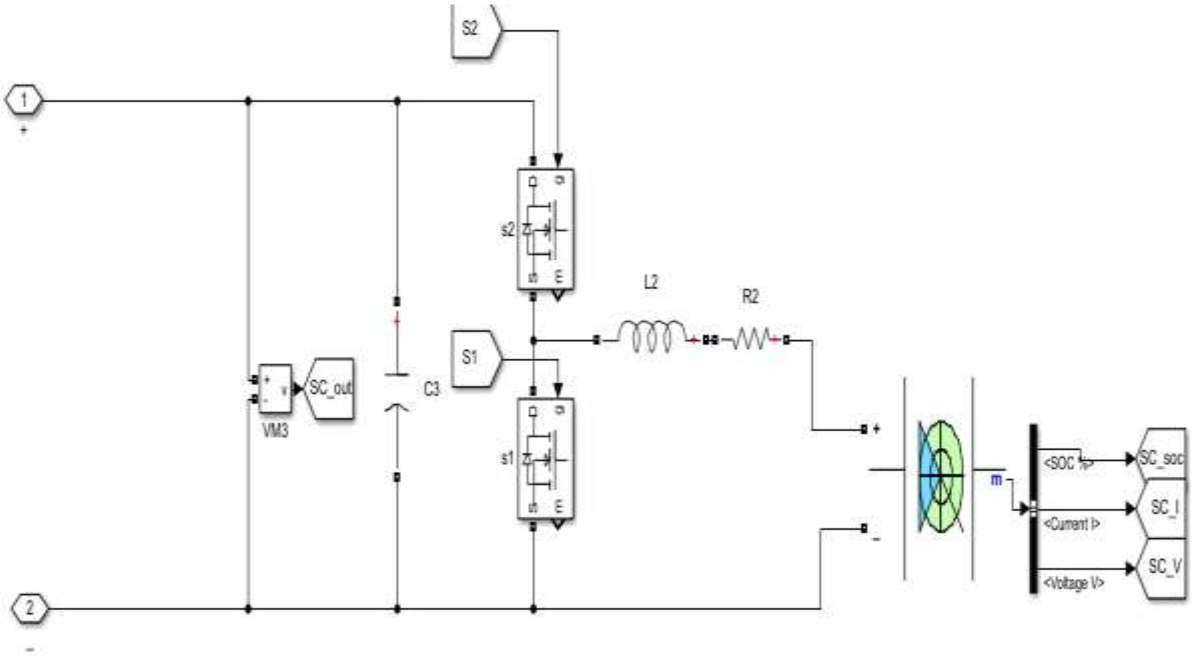

Fig.7 Super Capacitor

IV SIMULATION RESULT

The simulation of the proposed hybrid renewable energy system was carried out using MATLAB/Simulink. The model includes various components such as solar photovoltaic (PV), wind energy system, diesel generator, battery, and supercapacitor, along with power electronic converters like DC–DC converters, AC–DC rectifiers, and DC–AC inverters. Each component was designed and integrated to analyze system performance under different operating conditions. The control system was implemented to regulate power flow, maintain voltage stability, and ensure efficient energy management. The simulation results were obtained in the form of voltage, current, power, and state of charge (SOC) waveforms, which were used to evaluate the effectiveness, reliability, and stability of the proposed system.

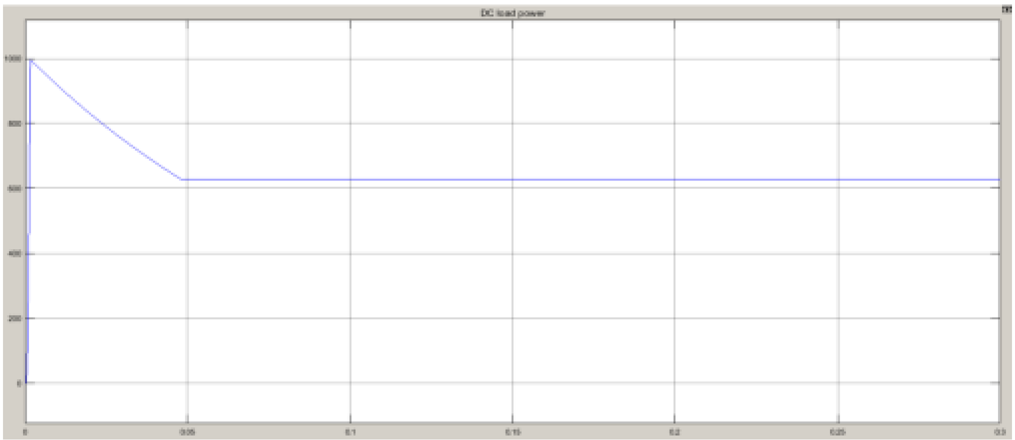

Fig.8 DC Load Power

Fig. 8 shows the DC load power, which initially varies slightly and then becomes stable, indicating a consistent power supply to the load.

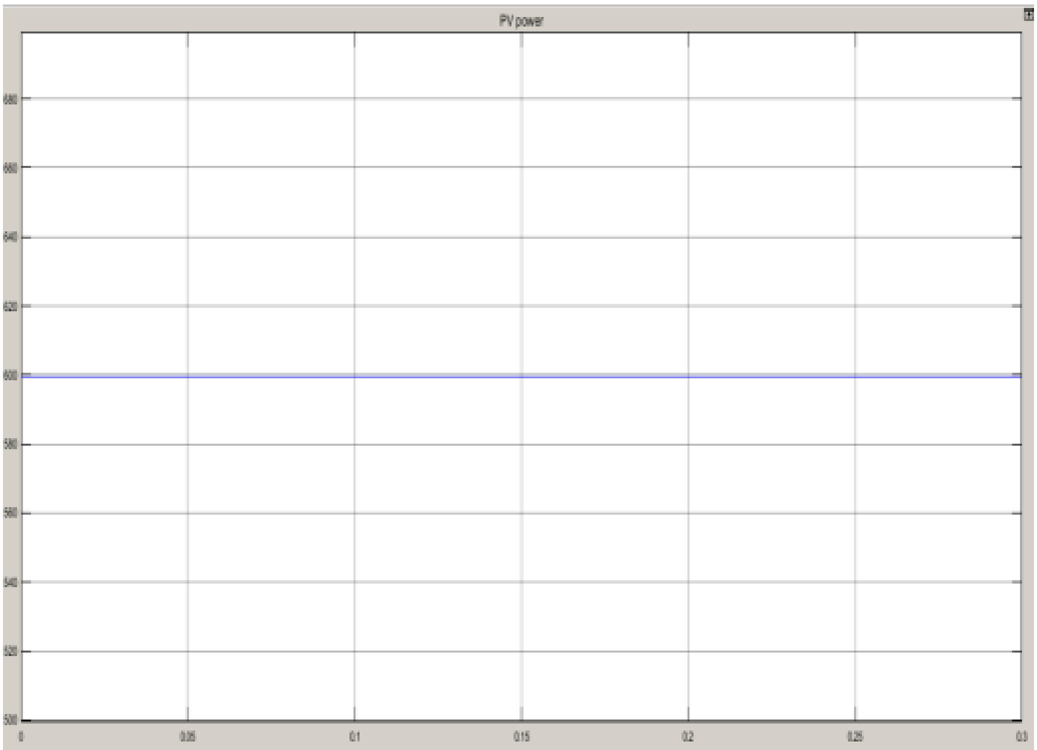

Fig .9 Solar (PV) Power

Fig. 9 represents the solar (PV) power output, where the system generates around 600 W and maintains stable performance using MPPT and a boost converter.

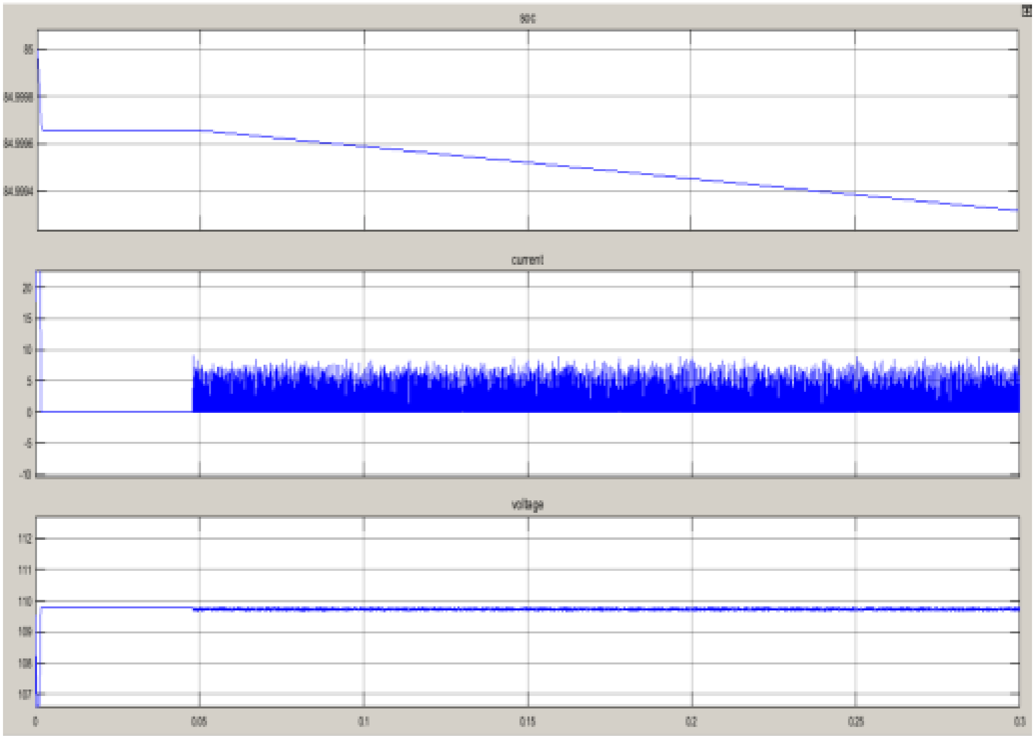

Fig. 10 Battery (SOC, Current, Voltage)

Fig. 10 illustrates the battery parameters such as SOC, current, and voltage, showing that the battery supports the system by charging and discharging as required.

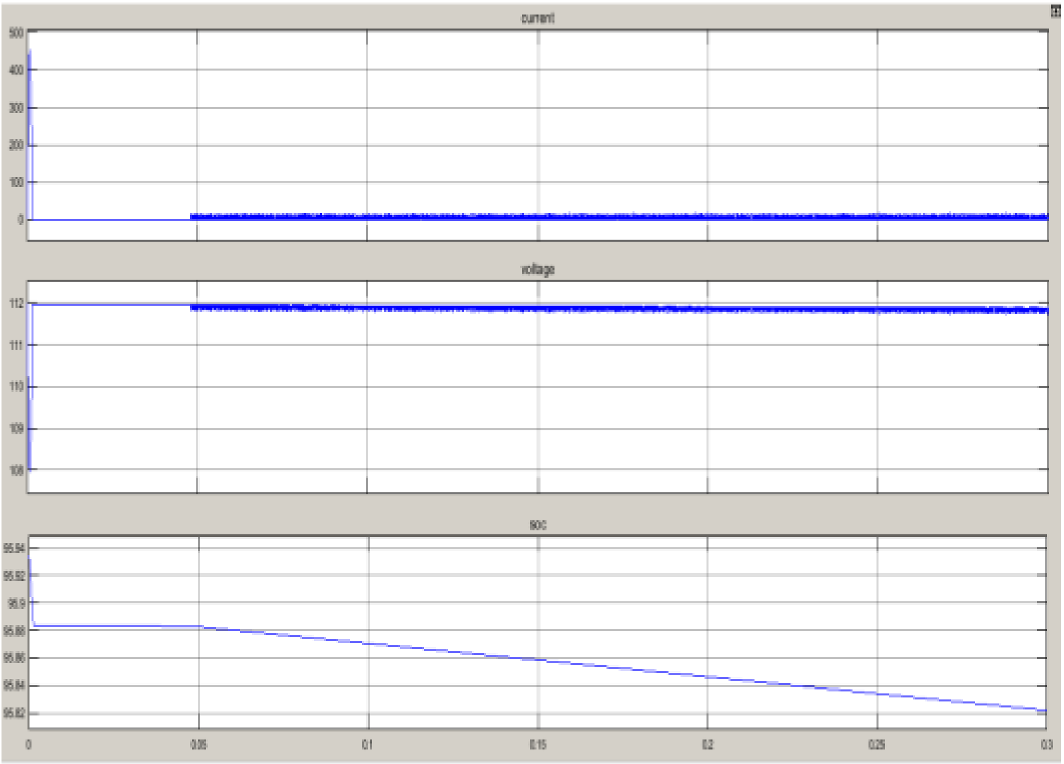

Fig 11 Super Capacitor (Current, Voltage, SOC)

Fig. 11 shows the super capacitor performance, which quickly responds to sudden load changes and helps in maintaining system stability

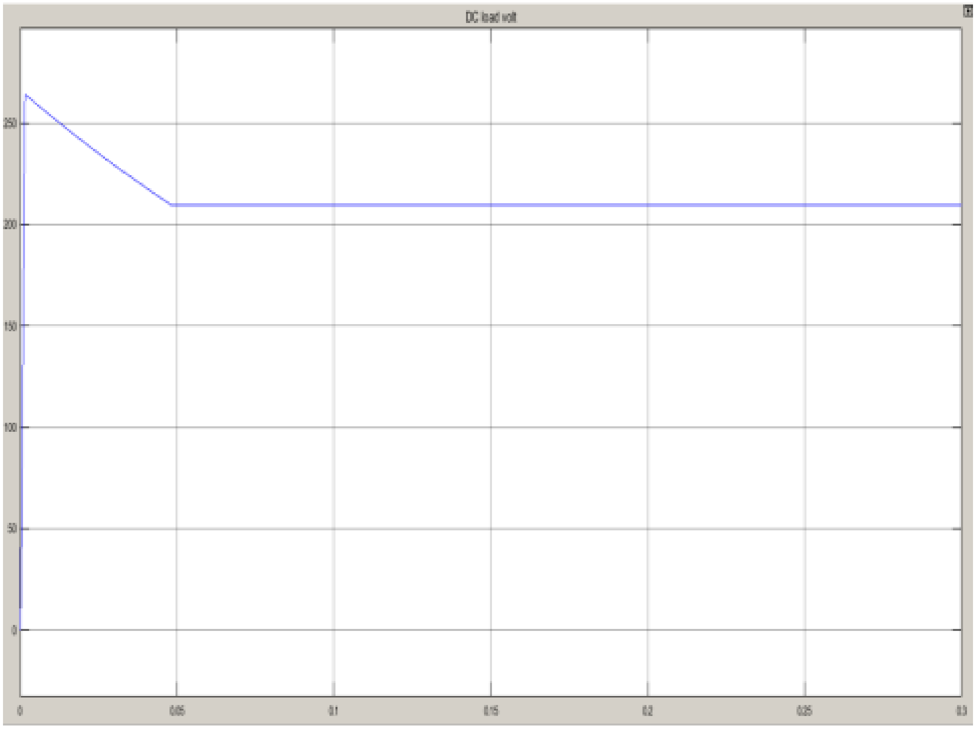

Fig 12 DC Load Voltage

Fig. 12 presents the DC load voltage, which remains constant over time, indicating proper voltage regulation.

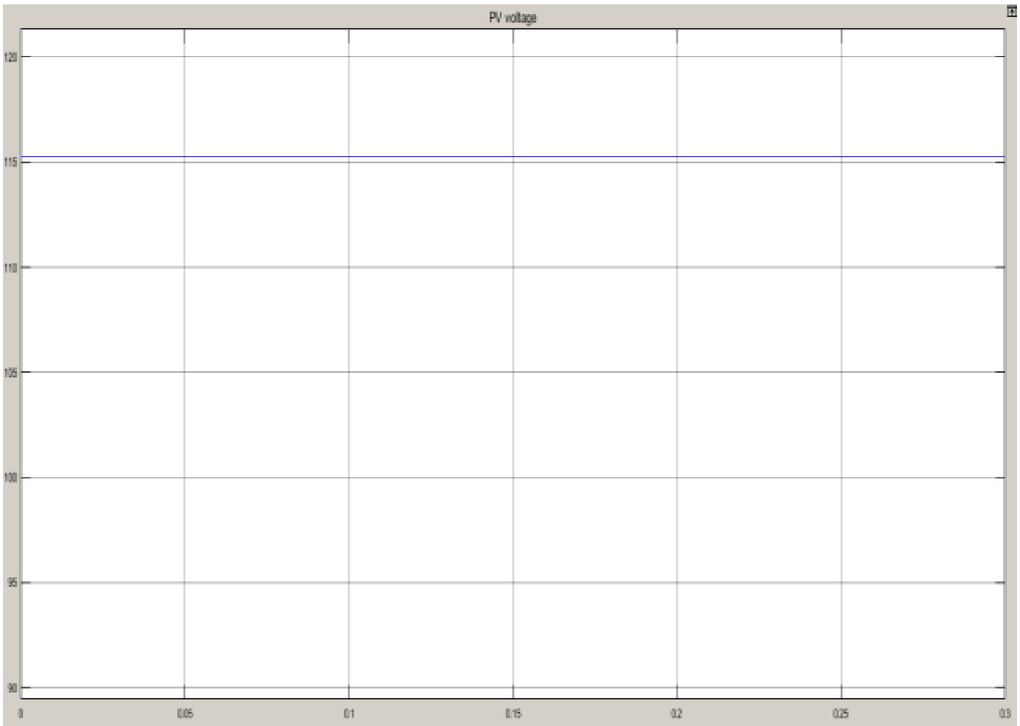

Fig.13 Solar(PV) Voltage

Fig. 13 shows the solar (PV) voltage, which is maintained at a stable level with the help of power converters.

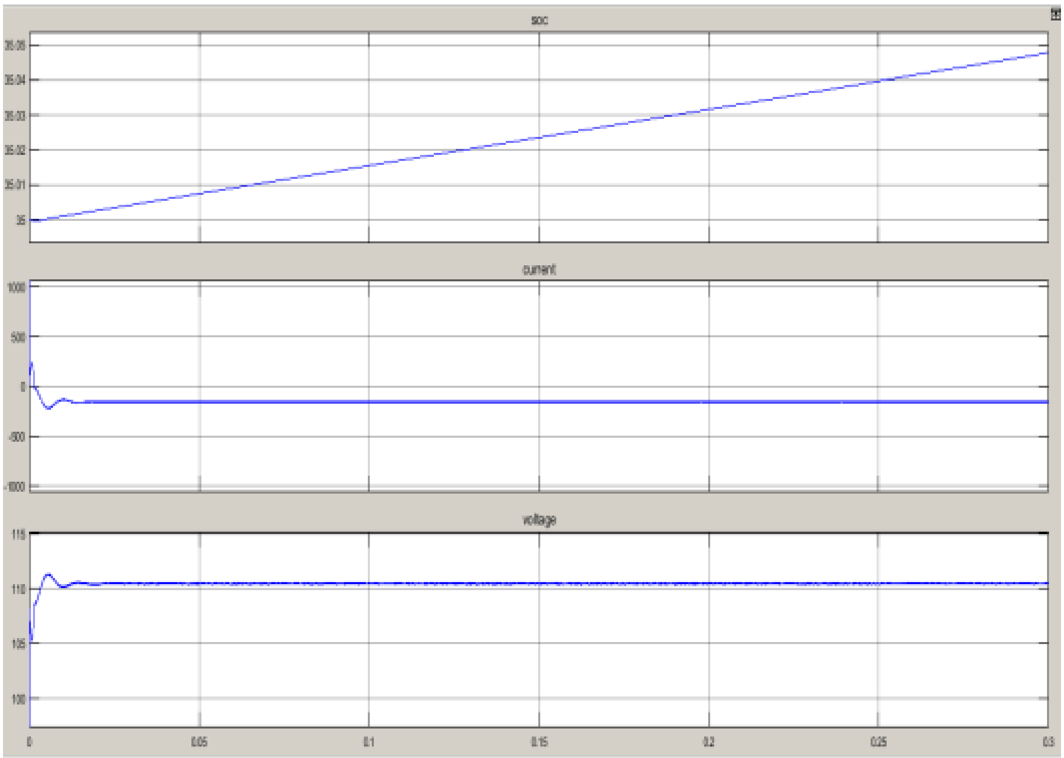

Fig. 14 Battery (Soc, Current, Voltage)

Fig. 14 shows the battery parameters (SOC, current, voltage), where the battery is discharged below the lower limit, indicating energy supply to the load.

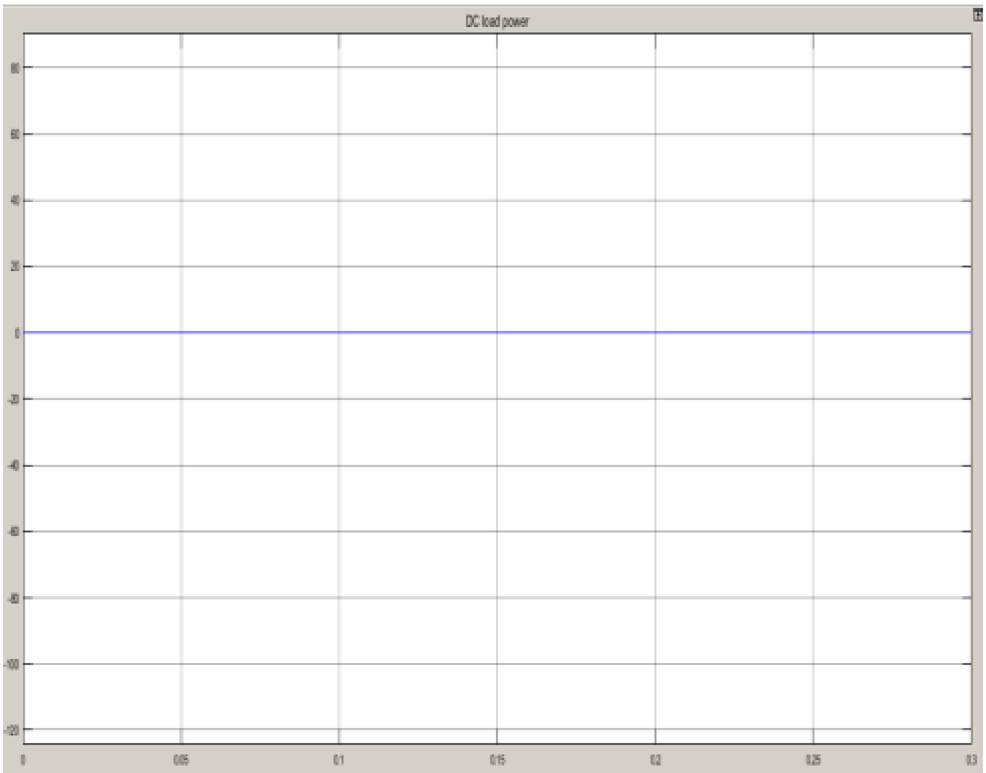

Fig 15 DC Load Power

Fig. 15 represents the DC load power, where the load is disconnected in load shedding mode to allow the available power to charge the battery.

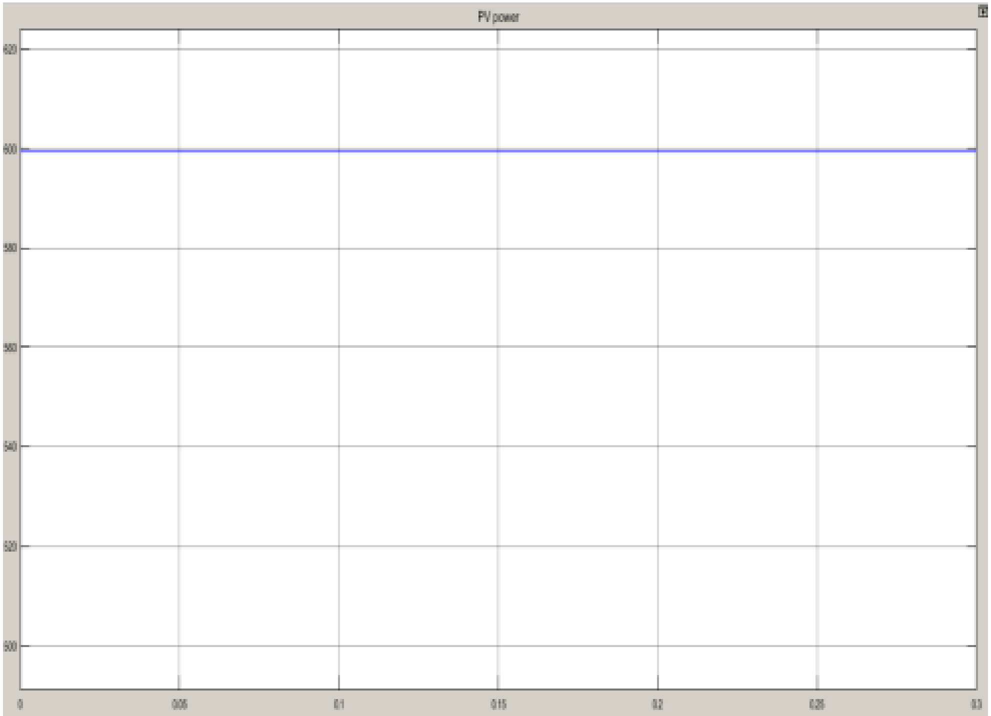

Fig .16 Solar (PV) Power

Fig. 16 (if included) shows the solar power behavior, indicating energy availability from the PV system for battery charging.

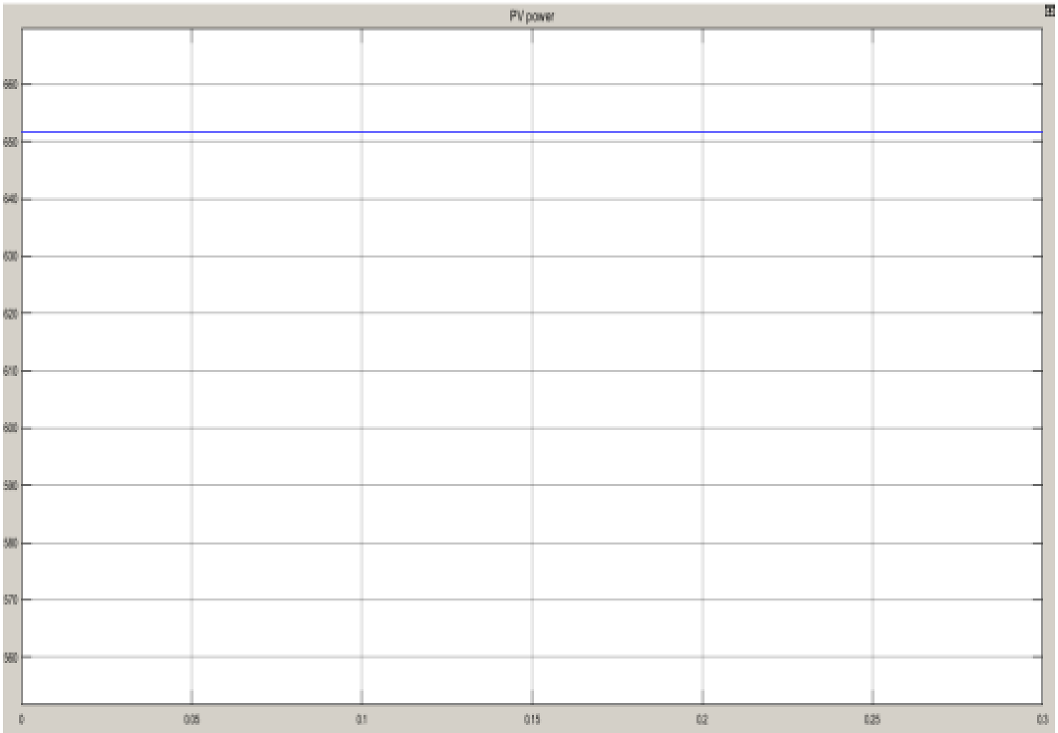

Fig 17 Solar (PV) Power

Fig. 17 shows the solar (PV) power output, where the generated power (around 652 W) is greater than the load demand (630 W), allowing excess energy to charge the battery.

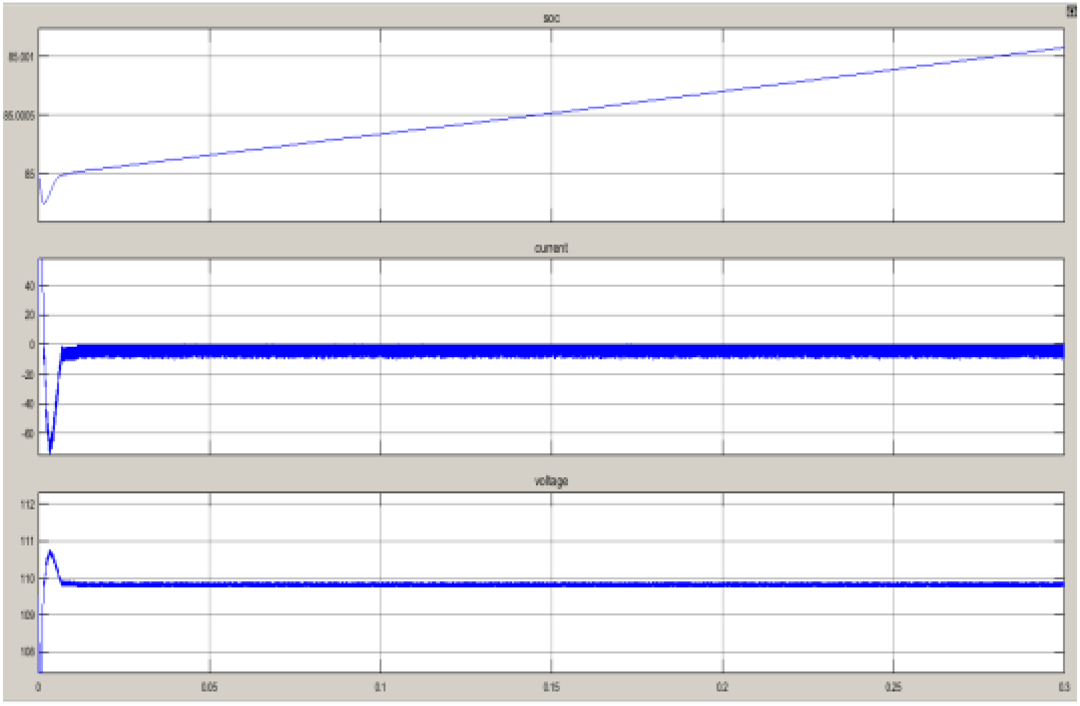

Fig 18 battery parameters

Fig. 18 illustrates the battery parameters, where the battery is charging and its SOC gradually increases, maintaining system balance.

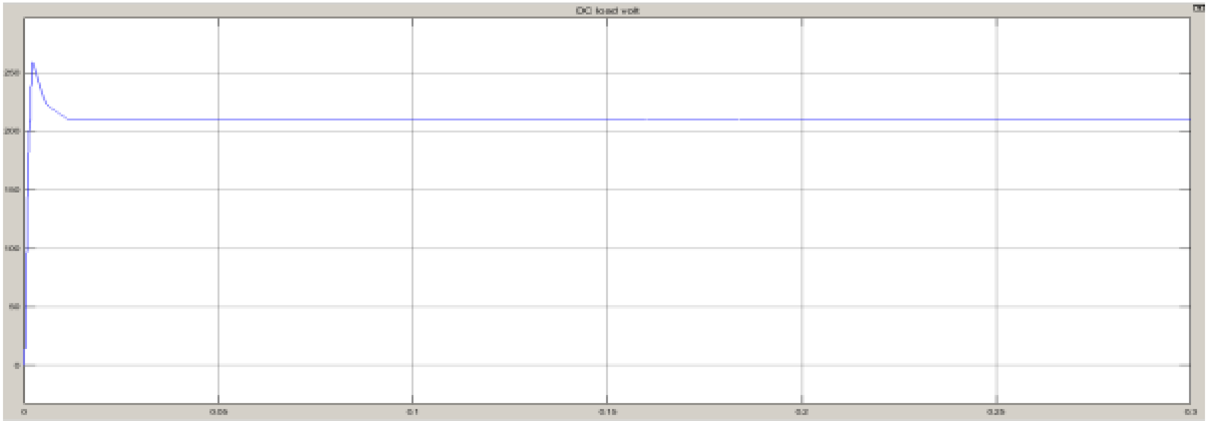

Fig 19 DC Load Voltage

Fig. 19 shows the DC load voltage, which remains constant at around 210 V, indicating stable voltage regulation.

Fig 20 MPPT output

Fig. 20 represents the MPPT output, where the system operates at maximum power point to optimize PV output and maintain DC bus voltage.

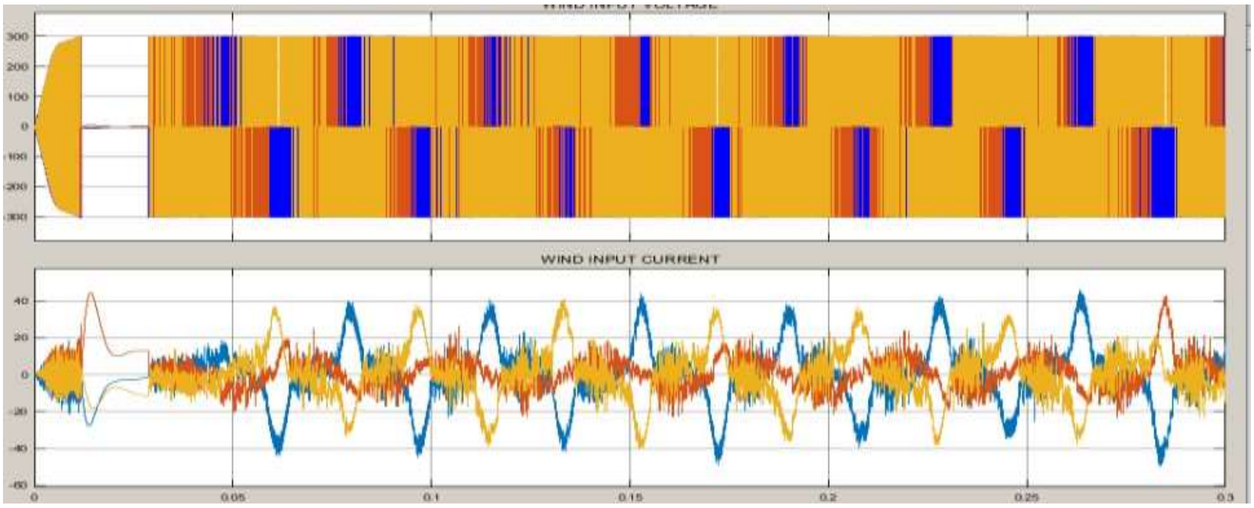

Fig. 21 wind output

Output from a wind turbine depends on the size of the turbine and the wind speed through the rotor. An onshore wind turbine with an average capacity of 2.5–3 MW can generate more than 6 million kWh of electricity per year, enough to power 1,500 ordinary EU homes.

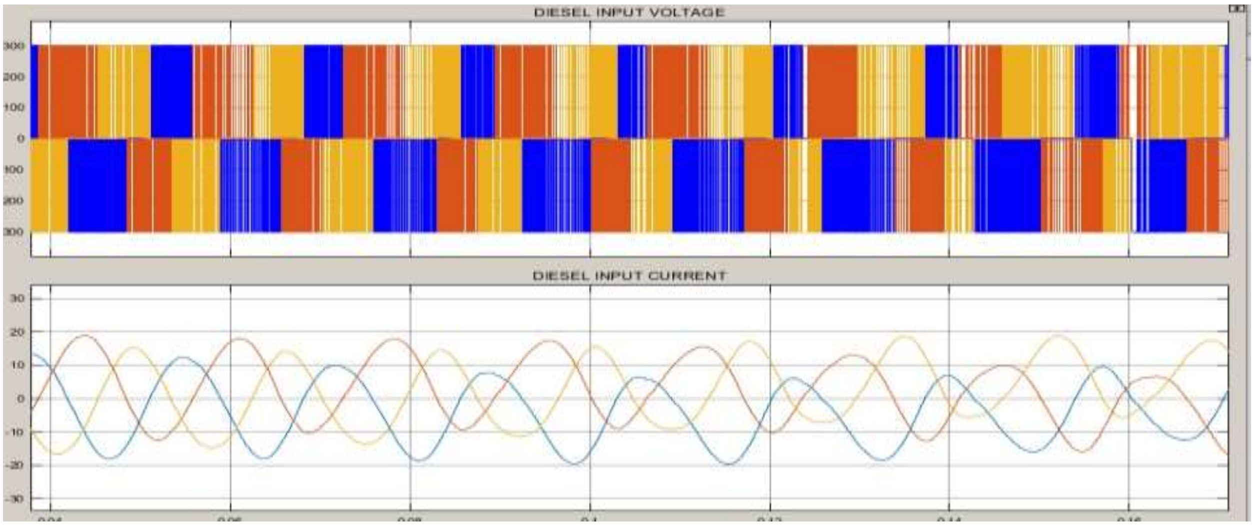

Fig.22 Diesel Input

The diesel input voltage waveform shows fluctuating pulses due to converter switching, while the diesel input current waveform is sinusoidal, indicating stable three-phase AC operation and reliable power supply from the generator.

Table 1: Numerical Values of Simulation Waveforms

Parameter	**Numerical Value**
DC Load Power	630 W
Solar (PV) Power	600 W
Battery Voltage	200–220 V
Battery Current	±5–10 A
Battery SOC	60–80 %
Supercapacitor Voltage	180–220 V
Supercapacitor Current	±10–20 A
DC Load Voltage	210 V
PV Voltage	200–220 V
Battery SOC	40–60 %
Battery Current	-5 to -10 A
DC Load Power	0 W
Solar Power	500–600 W
Solar Power	652 W
Battery SOC	70–90 %
Battery Current	+5 to +10 A
DC Load Voltage	210 V
MPPT Output Power	650 W
MPPT Voltage	210 V

V CONCLUSION

The proposed hybrid renewable energy system successfully integrates multiple renewable energy sources and storage technologies to provide a reliable and efficient power supply. The combination of solar, wind, and hydro sources ensures continuous energy generation, while the energy storage system consisting of battery, hydrogen storage, and supercapacitor enhances system flexibility and stability. The inclusion of an energy management system (EMS) plays a crucial role in optimizing power flow, maintaining energy balance, and improving overall system performance. The bidirectional interaction with the grid further increases system adaptability and efficiency. Additionally, the cooling system ensures safe and efficient operation of storage components. The overall results indicate that the proposed system is capable of delivering sustainable, stable, and efficient energy, making it suitable for modern power systems and smart grid applications.

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