International of Advanced Research and Multidisciplinary Journal Trends (IJARMT)
An International Open Access, Peer-Reviewed Refereed Journal
Impact Factor: 7.2 Website: https://ijarmt.com ISSN No.: 3048-9458

Modeling and Simulation of a PV-Based Boost Converter with Maximum Power Point Tracking

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ABSTRACT

This study presents the modeling and simulation of a hybrid renewable energy system integrating solar photovoltaic (PV), wind energy, and battery storage using MATLAB/Simulink. The system is designed with a common DC bus architecture, where the PV array operates under a Maximum Power Point Tracking (MPPT) controller, and the battery is connected through a bidirectional DC–DC converter for energy management. A DC–AC inverter with PWM control converts the DC power into three-phase AC, which is supplied to the load and utility grid through an LC filter.Simulation results demonstrate that the PV system achieves a stable DC voltage of approximately 375 V, while the inverter delivers a constant output power of about 5 kW. The three-phase voltage and current waveforms are balanced and sinusoidal, indicating efficient inverter performance with good power quality. The battery effectively supports the system during fluctuations, and the overall system maintains stability under varying wind speed conditions.The results confirm that the proposed hybrid system provides reliable, efficient, and continuous power supply, making it suitable for grid-connected and standalone renewable energy applications.

Keywords –Solar, MPPT, Wind, Diesel Engine, Battery, frequency control.

I. INTRODUCTION

The concept of microgrid is gaining lot of popularity worldwide due to their ability of working independently. The microgrid also allows the optimal utilization of available renewable energy sources (RES) in a coordinated way in order to feed remotely placed isolated locations where grid is not readily available. Thus, the microgrid is expected to work both in grid tied mode and off grid (islanded) mode. In grid tied mode[1][2] the grid voltage sets the reference for DG interfacing VSC's and chances of internal conflict among different VSC's are very rare. However, in islanded mode of operation, the different VSC's are needed to be controlled in such a way that the load demand must be shared by all interconnected VSC's in proportion to their individual rating. Therefore, the VSC's in microgrid may either be controlled in centralized manner with dedicated communication channel between them or they may be controlled individually with droop control which may require low bandwidth communication channel or no communication channel at all[3]. High penetrations of renewable energy like wind and solar challenge the conventional planning/design and operation of the electricity infrastructure due to the intermittent nature of the resources. To avoid system breakdown in the electricity infrastructure, generation and demand have to be in balance on second-scale. Furthermore, the renewable energy sources displace conventional generation which today is responsible for providing many of the power system services such as reserves, voltage control, frequency control, stability services, and black start restoration that are needed for stable and reliable operation of the electricity infrastructure. Trading of energy through electricity and gas interconnects to neighboring countries is widely used to balance the system and ensure stable and reliable operation. But the ability of neighboring energy systems to interact may be limited if the neighboring systems have similar characteristics like renewable energy penetration, and new interconnectors are often very difficult and take longtime to establish. The heating, cooling, gas, and transport infrastructures have certain intrinsic storage capability (e.g. due to the temperature of the hot water in the pipes, state-of-charge of the electric vehicle battery, or pressure of the gas in the system) and can Therefore provide some of the energy flexibility needed in the electricity infrastructure. Also, the demand side in the electricity system in itself has some ability if proper mechanisms (markets, communication etc.) are introduced. Utilizing this potential of integration of the infrastructures requires either direct coupling of the systems through energy conversion technologies or through couplings at the generation side and/or demand side[4][5]. A closer integration of the energy infrastructures will not only solve some of the challenges of integration of renewable sources at the technical level[6]. Closer integration and coordination of different energy infrastructures are a prerequisite for a cost-effective energy system with a high share of variable and somewhat difficult to predict renewable energy sources. The impending global energy crisis has opened up new opportunities for the automotive industry to meet the ever-increasing demand for cleaner and fuel-efficient vehicles. This has necessitated the development of drive trains that are either fully or partially electrified in the form of electric and plug-in integrated electric vehicles (EVs and HEVs), respectively, which are collectively addressed as plug-in EVs (PEVs). PEVs in general are equipped with larger on-board storage and power electronics for charging or discharging the battery, in comparison with HEVs. Semiconductor devices utilized (silicon, silicon carbide, or gallium nitride) are thoroughly reviewed. Since grid-connected systems do not need batteries, they are more cost-effective and require less maintenance and reinvestment than stand-alone systems. This concept together with the cost reduction, technology development, environmental awareness, and the right incentives and regulations has unleashed the power of the sun.[7][8].

Table 1 Literature Review Table: Renewable Energy & AI Integration

Author(s) / Year	Study Focus	Objectives	Methodology / Model Used	Key Findings	Strengths	Limitations / Research Gap
Islam et al. (2026)[9]	Renewable	To analyze structural,	Time-series models	Canada shows stable	Comparative international	Limited focus on social and

	energy transition (Canada vs Bangladesh)	institutional, and market factors influencing renewable energy transition	(ARIMA, ETS, Prophet) + policy evaluation	transition due to diversified energy & policies; Bangladesh faces challenges due to import dependency and institutional barriers	analysis; use of forecasting models	environmental justice aspects; lacks micro-level implementation analysis
Benhacene et al. (2025)[10]	Renewable energy and sustainable development (Saudi Arabia)	To assess impact of renewable energy sources on sustainability	PLS-SEM with 180 expert responses	Wind and hydropower significantly support sustainability; solar has high potential but less measurable impact	Empirical validation using SEM; multi-dimensional sustainability analysis	Geographic limitations; limited practical scalability discussion
Dol et al. (2024)[11]	Advances in renewable energy technologies	To explore recent developments in renewable energy and sustainability solutions	Literature review (multi-disciplinary)	Solar and wind dominate; emerging tech (tidal, hydrogen, VIV) and AI/ML improve efficiency and forecasting	Comprehensive overview; inclusion of AI integration	Lacks empirical validation; mostly conceptual
Cavus (2025)[12]	Smart grid and AI integrati	To examine modern power system	Review of grid technologies (SG, MG,	AI improves grid stability, voltage	Strong focus on AI-driven optimization;	Limited real-world case studies; lacks

	on in power systems	transformation with renewable integration	HVDC, AI-based optimization)	control, and energy management; supports smart infrastructure	future-oriented	cost-benefit analysis
Barrera-Singaña et al. (2025)[13]	Renewable energy planning & optimization	To develop integrated optimization approaches for renewable systems	Systematic review of 90 studies (deterministic, stochastic, AI models)	AI-enhanced optimization improves planning efficiency; identifies gaps in resilience and policy uncertainty	Large-scale review; strong methodological classification	Limited practical implementation insights; policy uncertainty remains

II. PROPOSED WORK

Large-scale introduction of fluctuating renewable energy implies that the key to successful integration is not to focus solely on the power system, but on the entire energy system and on energy systems integration. Successful integration of large fractions of fluctuating renewable calls for complex interactions between energy production, storage, distribution, and consumption. An integrated energy system with a high share of renewable energy will utilize, and be highly reliant on, digital technologyA novel integrated energy system is proposed for renewable sources.In the presented technique, the pitch angle controller is designed for wind turbine generator (WTG) system to smooth wind power output and diesel generator system to restore system Wind diesel hybrid systems (WDHS) are autonomous systems that use wind turbine generators with diesel generators to procure utmost contribution by the sporadic wind energy to the total power generated, while ensuring uninterruptible electric power of high quality . As a result the fuel consumption decreases and the overall operating cost reduces while also contributing to a green environment. In integrated micro-grid, PV system is usually controlled to operate in the maximum power point tracking (MPPT) mode. The battery energy storage system is operated in constant power charging or discharging mode. In order to provide the frequency support and prevent power fluctuation,. The pitch angle controller for WTG and the load frequency controller for diesel generator separately to improve the response speed and the robustness of micro-grid. This concept together with the cost reduction, technology development, environmental awareness, and the right incentives and regulations has unleashed the power of the sun. and all system result will be carried out by matlab simulation is proposed for isolated micro grids with renewable sources.In the presented technique, the pitch angle controller is designed for wind turbine generator (WTG) system to smooth wind power output. The proposed strategy is tested in a typical integrated micro-grid with both PV and wind turbine generator.

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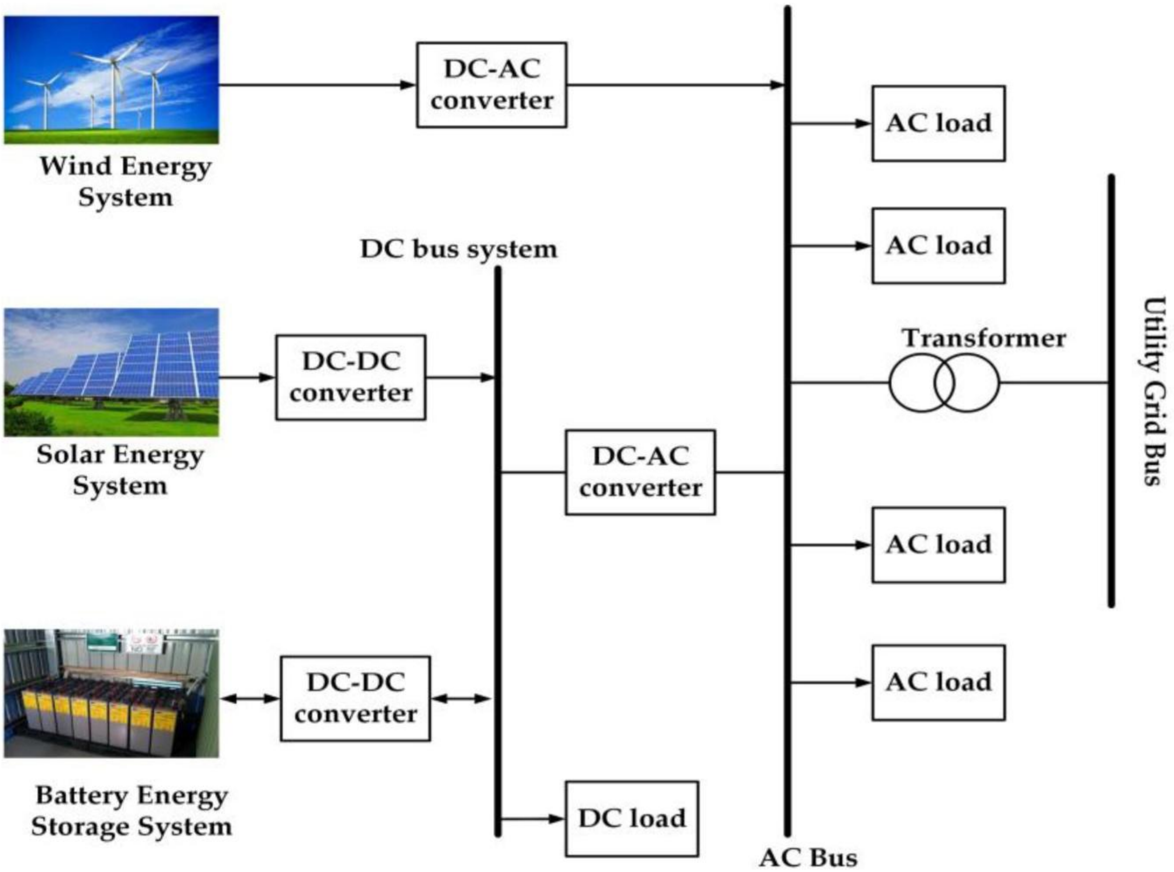

Fig. 1 Proposed Integrated Energy System

The figure 1 represents a hybrid renewable energy system that integrates wind energy, solar energy, and battery storage to supply power to both DC and AC loads, as well as to the utility grid. The system is structured around two main buses: a DC bus and an AC bus, which facilitate efficient power flow and energy management.

The wind energy system generates electrical power, which is typically converted into a suitable form using a DC–AC converter before being supplied to the AC bus. Similarly, the solar energy system (PV) produces DC power, which is regulated using a DC–DC converter to maintain proper voltage levels and is then fed into the DC bus. The battery energy storage system is also connected to the DC bus through a bidirectional DC–DC converter, allowing it to store excess energy when generation is high and supply power when generation is low.

The DC bus acts as a central node for DC power, supplying energy directly to DC loads and also feeding a DC–AC converter (inverter) that converts DC power into AC. This AC power is delivered to the AC bus, which distributes power to multiple AC loads. Additionally, the AC bus is connected to the utility grid through a transformer, enabling grid interaction such as exporting excess energy or importing power when needed.

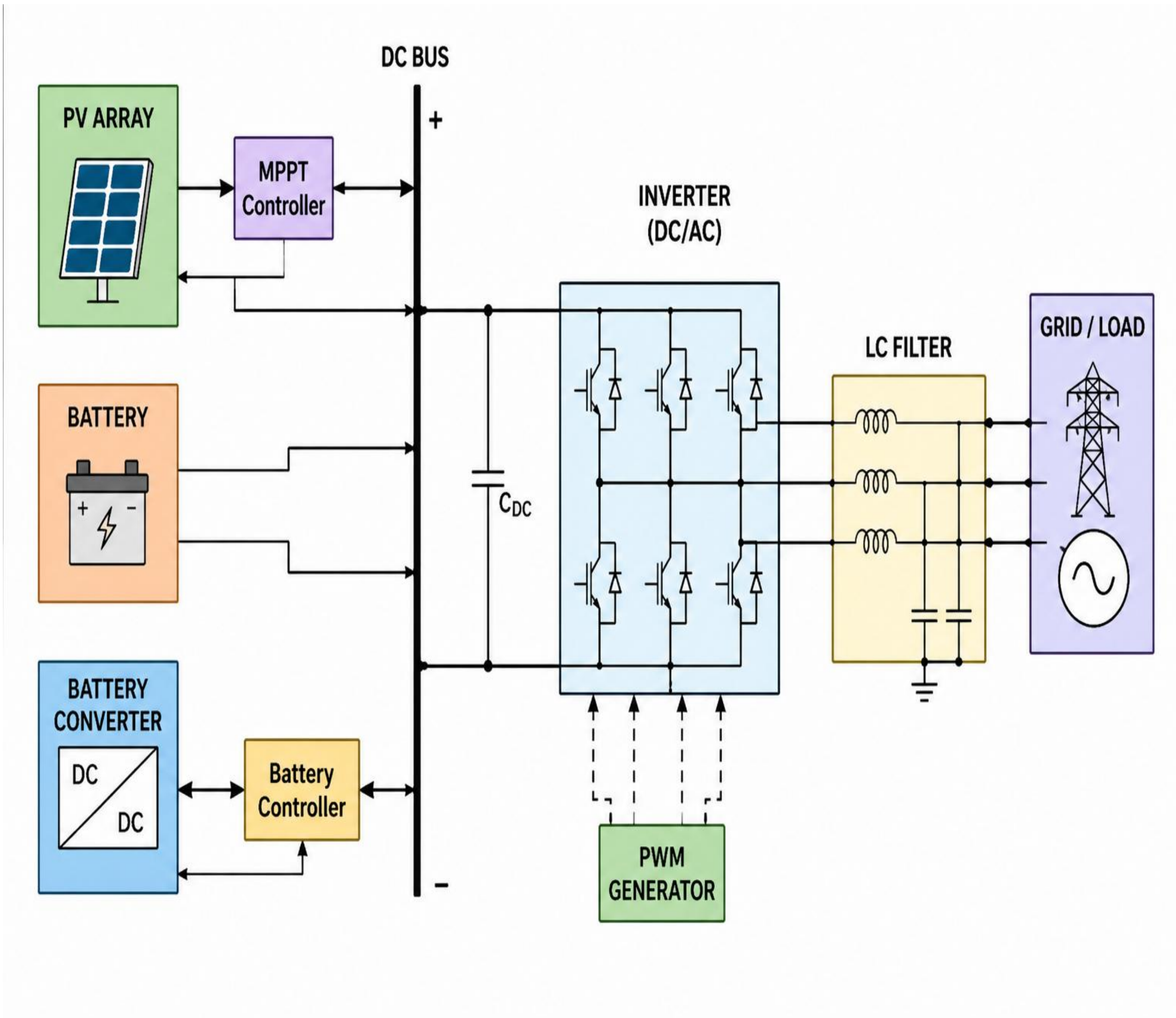

Fig.2 Simulink Model of Proposed System

Diagram 2 illustrates the working process of a hybrid renewable energy system that integrates a PV array and battery storage to supply power to a grid or load through power electronic converters and control systems. The process begins with the PV array, which generates DC power from solar energy. This output is fed into an MPPT (Maximum Power Point Tracking) controller, which continuously adjusts the operating point of the PV system to extract maximum available power under varying environmental conditions. The optimized DC power is then delivered to the DC bus, which acts as a central energy hub. Simultaneously, a battery system is connected to the DC bus through a bidirectional DC–DC converter. The battery controller manages charging and discharging operations depending on system requirements. When excess power is generated by the PV array, the battery stores energy; when PV output is insufficient, the battery supplies power to maintain system stability. The DC bus, supported by a capacitor (Cdc), stabilizes voltage and ensures smooth power transfer. From here, power is supplied to a DC–AC inverter, which converts DC into three-phase AC using switching devices controlled by a PWM (Pulse Width Modulation) generator. The PWM controller regulates switching patterns to produce a sinusoidal AC waveform.

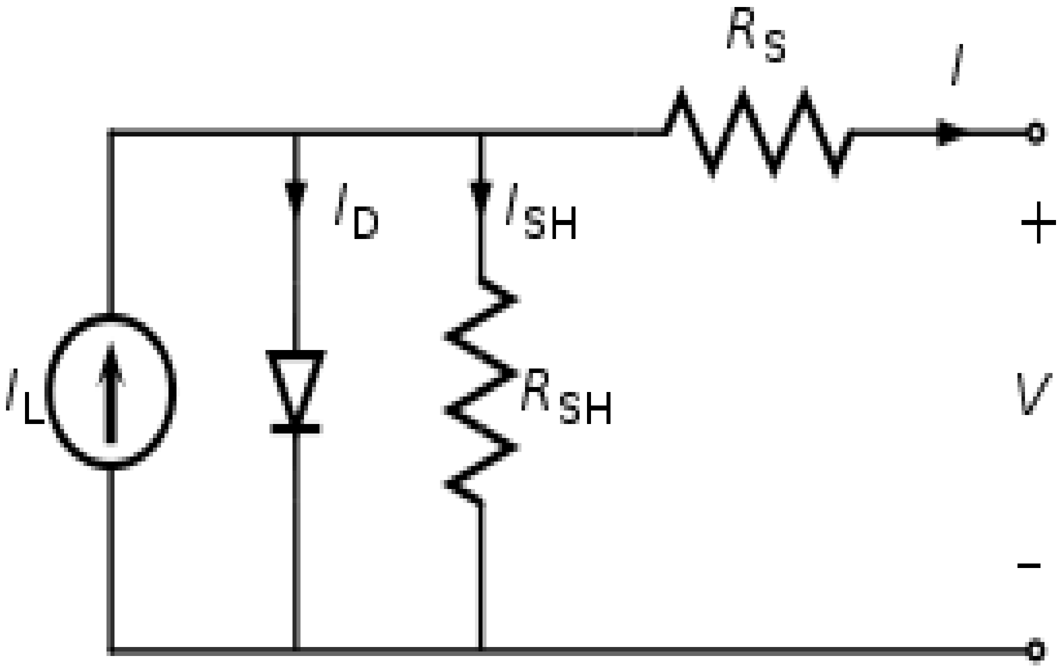

Fig 3 Single Diode Equivalent Circuit Models

Solar Panel: The solar micro grid system is designed to operate in two modes; Grid-Interactive and Islanded mode. In grid-interactive mode the battery system operates in parallel with the PV system. The PV system operates normally as a typical grid-tied solar PV system. During peak sun hours of the day the battery system is less active, but when the PV system is not utilizing the majority of the inverter capacity (i.e. at night) it is able to actively participate in fast response frequency regulation. The control system is designed to always prioritize the use of the inverter capacity for the solar PV generation first, and then the remainder is utilized for frequency regulation participation. In full sun the PV system will normally require approximately 325 kW of AC capacity, leaving 175 kW of inversion capacity available for participation in the frequency regulation market. When there is a grid outage the micro grid system senses the loss of grid and signals the isolation breaker to open and convert to Islanded mode. The system adjusts automatically from a grid-tied current source to an islanded voltage source in a few cycles

Where Is and Is2 are the diode saturation currents, Vt is the thermal voltage, N and N2 are the quality factors (diode emission coefficients) and Iph is the solar-generated current.

MPPT: In integrated micro-grid, PV system is usually controlled to operate in the maximum power point tracking (MPPT) mode. The battery energy storage system is operated in constant power charging or discharging mode. In order to provide the frequency support and prevent power fluctuation, the novel integrated micro-grid, PV, frequency control strategy is proposed in this section. The SM control is used to design the pitch angle controller for WTG and the load frequency controller for diesel generator separately to improve the response speed and the robustness of micro-grid. Furthermore, the adaptive SMLFC is redesigned based on the disturbance observer and adaptive law for improving the controller precision and reducing the SM chattering. The proposed .the frequency deviation with the rated power limit of diesel generator. However, it cannot cover large-scale wind power penetration which is over the power limit of diesel generator. If the generation of renewable energy sources is larger than the rated power of diesel generator, other method such as load shedding has to be used to maintain system stable operation when there is large wind speed drop.

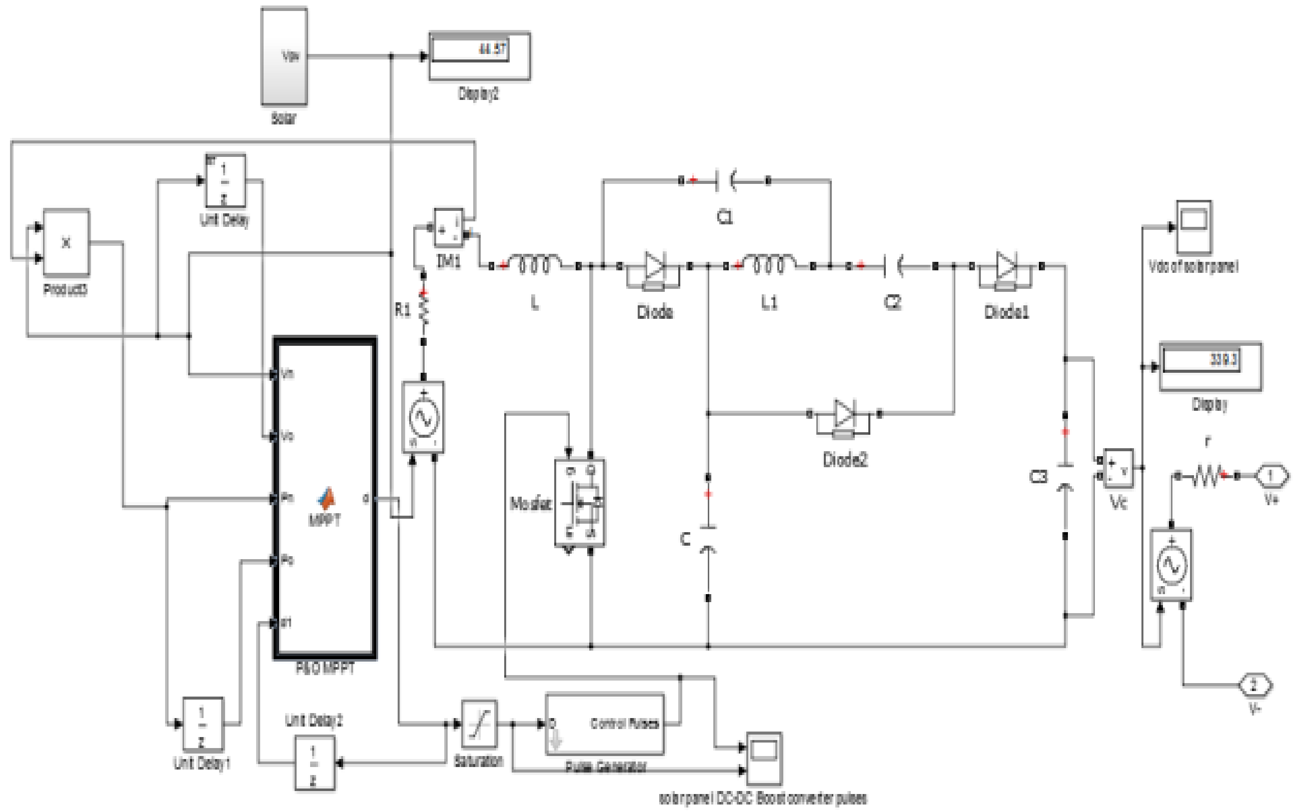

Fig.4.MPPT Model

The figure represents a DC–DC boost converter integrated with an MPPT (Maximum Power Point Tracking) control system for a solar photovoltaic (PV) application. The PV source provides input voltage, which is processed through an MPPT controller to extract maximum available power. The MPPT block receives voltage and current signals from the PV panel and generates an optimized duty cycle using a control algorithm. This duty cycle is then passed through a saturation and control signal block to produce appropriate switching pulses.

The power conversion stage consists of an inductor (L), switching device (MOSFET), diodes, and capacitors (C1, C2, C3), forming a boost converter topology. When the switch is turned ON, energy is stored in the inductor, and when it is turned OFF, the stored energy is transferred to the output through the diode, resulting in an increased output voltage. The capacitors help in filtering and maintaining a stable output voltage, while resistive elements represent load conditions.

Voltage measurement blocks are used to monitor both input and output voltages, with display units showing values such as the PV output and boosted voltage (approximately 300 V). The system ensures that the output voltage is higher than the input voltage while operating at the maximum power point of the PV system.

DC-DC Boost Converter a DC/AC converter is used as the interface between the AC grid system and solar to maintain good dc voltage regulation and ac current shaping. The topology of the three phase DC/AC converter allows bidirectional power flow between solar and AC grid system. In single phase bridge converter to achieve bidirectional power flow in renewable system a PWM strategy may be applied to accomplish voltage regulation in DC side and current shaping in AC side. Generally, BPWM and UPWM strategies are often utilized in a single phase AC/DC converter but now a simplified PWM strategy is proposed. This proposed simplified PWM only changes the switching status of active switch.

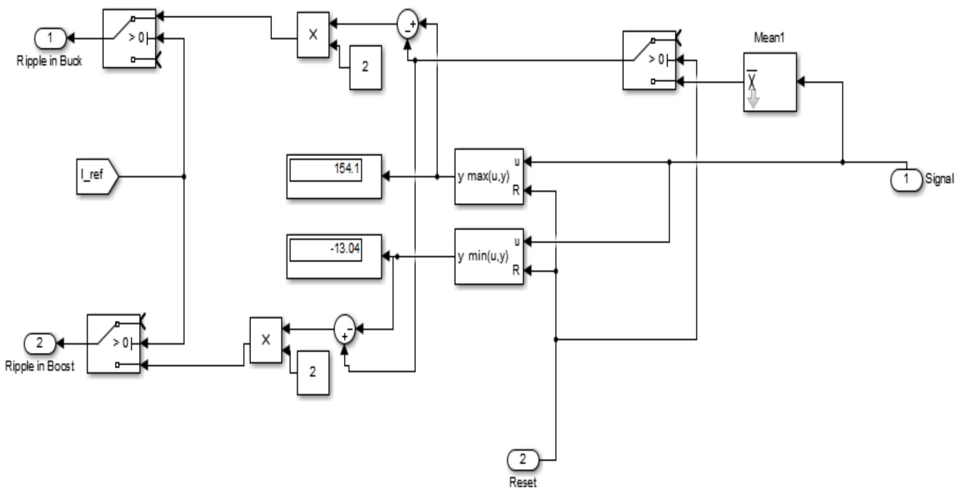

Fig.5 Buck Boost Sub System

IGBT: The Insulated Gate Bipolar Transistor (IGBT) The IGBT is a hybrid or also known as double mechanism device. Its control port resembles a MOSFET and its output or power port resembles a BJT. Therefore, an IGBT combines the fast switching of a MOSFET and the low power conduction loss of a BJT. Shows a circuit symbol that is used for an IGBT, which is slightly different from the MOSFET with similar terminal labels. The control terminal is labeled as gate (G) and the power terminals are labeled as collector (C) and emitter (E). The i-v characteristics of a real IGBT are shown, which shows that the device operates in quadrants I and III. The ideal characteristics of the device are shown. The device can block bidirectional voltage and conduct unidirectional current. An IGBT can change to the ON-state very fast but is slower than a MOSFET device. Discharging the gate capacitance completes control of the IGBT to the OFF-state. IGBT's are typically used for high power switching applications such as motor controls and for medium power PV and wind PE.

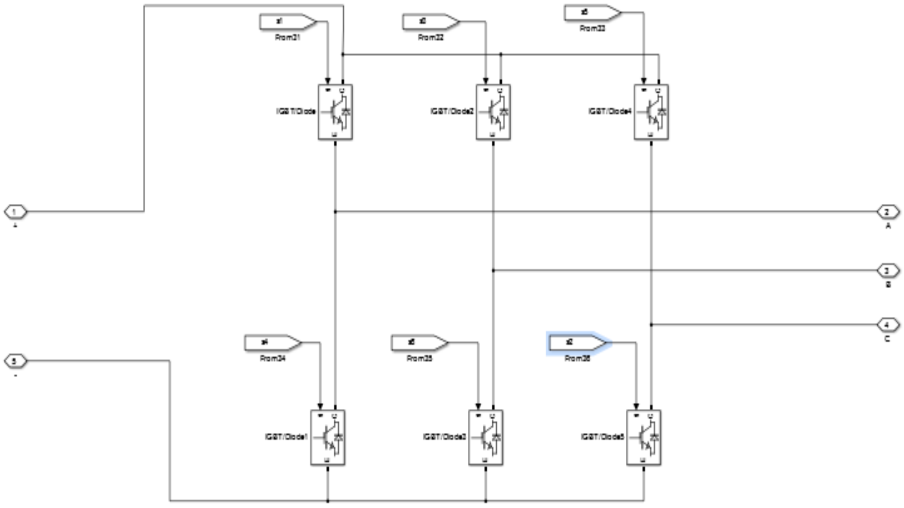

Fig.6 IGBT Circuit

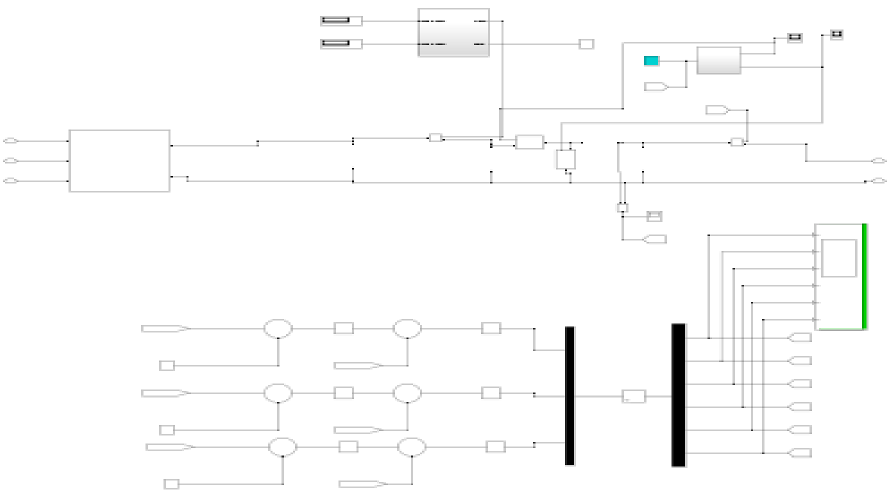

Fig.7 DC/DC bidirectional converter

The given Simulink diagram represents a three-phase power conversion and control system, most likely used in a grid-connected renewable energy or inverter-based application. On the left side, the model begins with an input source block that provides electrical signals—this could represent a DC supply such as a photovoltaic (PV) system or a controlled input signal. These signals pass through intermediate processing stages consisting of gain blocks, summation points, and control elements that regulate voltage and current. The central portion of the model includes interconnected control paths that perform signal conditioning and implement feedback mechanisms to ensure stable operation.

In the lower section, three parallel channels generate three-phase (R, Y, B) signals, each separated by 120 degrees, indicating balanced AC waveform generation. These signals are then routed through the system and connected to the DC link (represented by the vertical black bars), which acts as an energy transfer and stabilization point between the input and output stages. On the right side, the processed signals are distributed to multiple output lines, where measurement and monitoring blocks are used to observe system parameters such as voltage and current. These outputs are finally connected to a scope or display block (highlighted in green), allowing visualization of system performance. Overall, the model demonstrates a complete flow from input energy source through control and conversion to three-phase AC output with real-time monitoring.

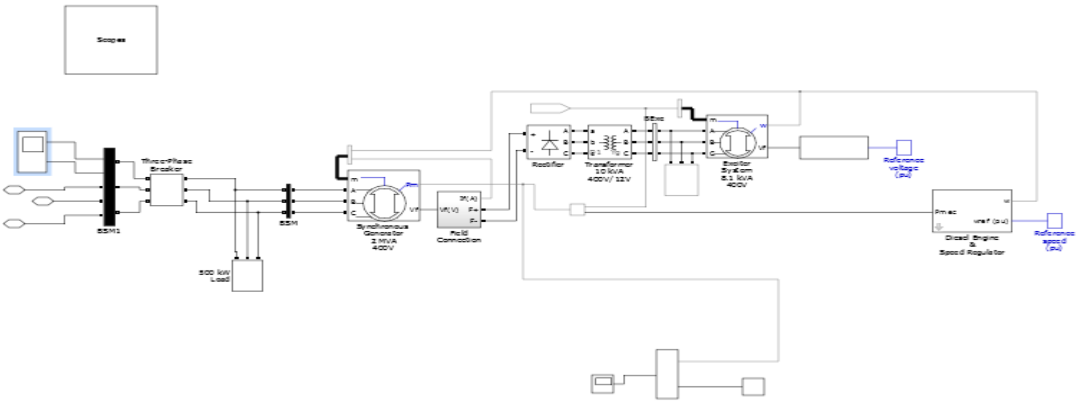

Fig.8 Diesel Generator

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. A governor can be defined as a mechanical or electromechanical device for automatically controlling the speed of an engine by relating the intake of fuel. The controller for the engine is a simple speed governor that keeps the turbine operating at its designed speed. The output of the speed governor is throttle signal that controls the fuel going into the engine After a literature review, four models has selected and analysis in order to show the most efficient model which presents a dynamic study of the DG and the more flexible to be used with several technologies. The models are implemented in Matlab/Simulink and the simulation results will not be presented here. Only models structure is presented and discuss by considering the interaction between Mechanical and electrical part of DG Implements a three-phase circuit breaker. When the external switching time mode is selected, a Simulink logical signal is used to control the breaker operation. Breaker resistance Ron (Ohm): 0.001Snubber resistance Rs (Ohm): 1e6 Implements a 3-phase synchronous machine modeled in the dq rotor reference frame. Stator windings are connected in wye to an internal neutral pointed 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. A governor can be defined as a mechanical or electromechanical device for automatically controlling the speed of an engine by relating the intake of fuel. Implements a three-phase or a five-phase permanent magnet synchronous machine. The stator windings are connected in wye to an internal neutral point. The three-phase machine can have sinusoidal or trapezoidal back EMF waveform. The rotor can be round or salient-pole for the sinusoidal machine, it is round when the machine is trapezoidal. Preset models are available for the Sinusoidal back EMF machine.

Battery: Implements a generic battery that model most popular battery types. Uncheck the "Use parameters based on Battery type and nominal values" parameter to edit the discharge characteristics. Nominal Voltage (V) Rated Capacity (Ah) Initial State-Of-Charge (%)67 **.**Battery is acts the continuous growth and evolve of vehicle electrification causes the electric power systems to confront new challenges, since the load profile changes

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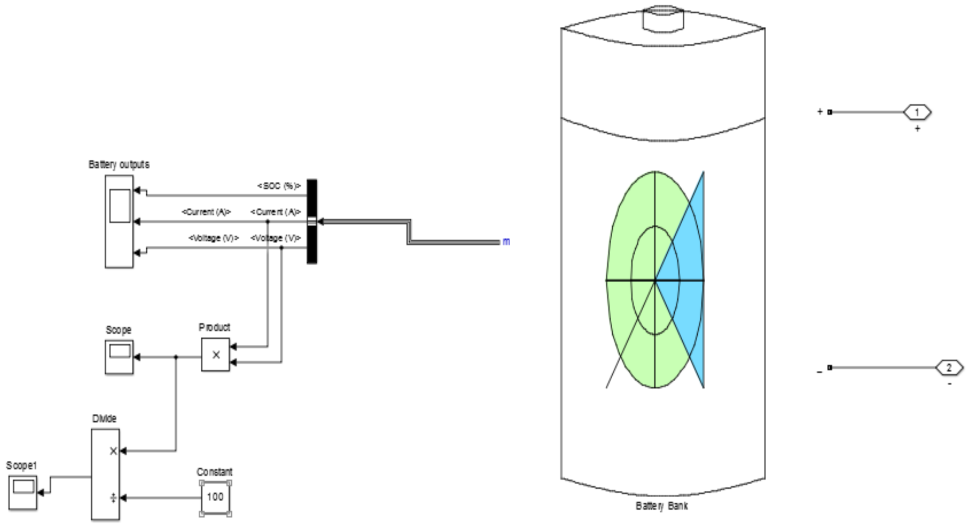

Fig.10 Battery Model

Wind Turbine :This block implements a variable pitch wind turbine model. The performance coefficient Cp of the turbine is the mechanical output power of the turbine divided by wind power and a function of wind speed, rotational speed, and pitch angle (beta). Cp reaches its maximum value at zero beta. Select the wind-turbine power characteristics display to plot the turbine characteristics at the specified pitch angle.

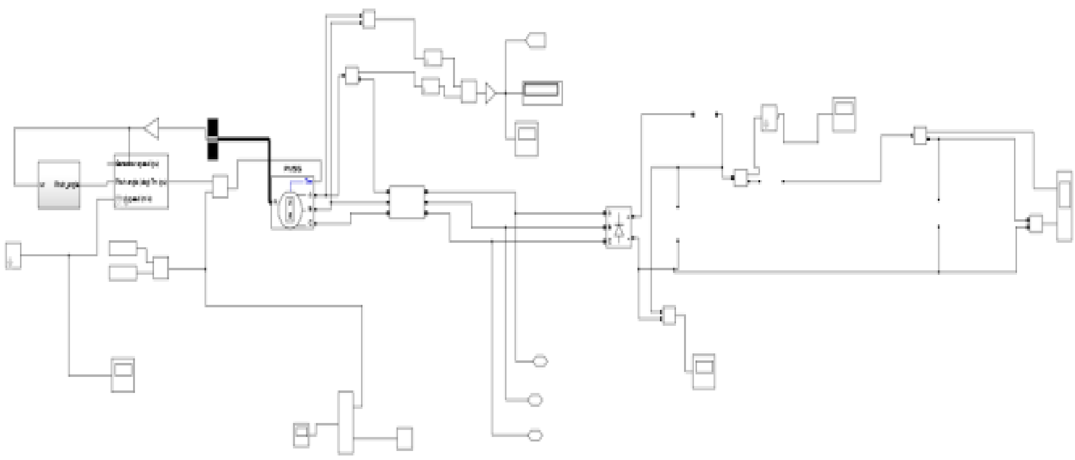

Fig.11 Wind Turbine Model

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III. SIMULATION AND RESULTS

The proposed hybrid PV–battery system was modeled and simulated using MATLAB/Simulink to evaluate its performance under different operating conditions. The system consists of a photovoltaic (PV) array integrated with a battery storage unit through a DC–DC converter and controlled using an MPPT algorithm to ensure maximum power extraction. The generated DC power is fed to a common DC bus and then converted into three-phase AC using a PWM-controlled inverter. An LC filter is employed at the inverter output to reduce harmonics and provide a smooth sinusoidal waveform to the grid/load.

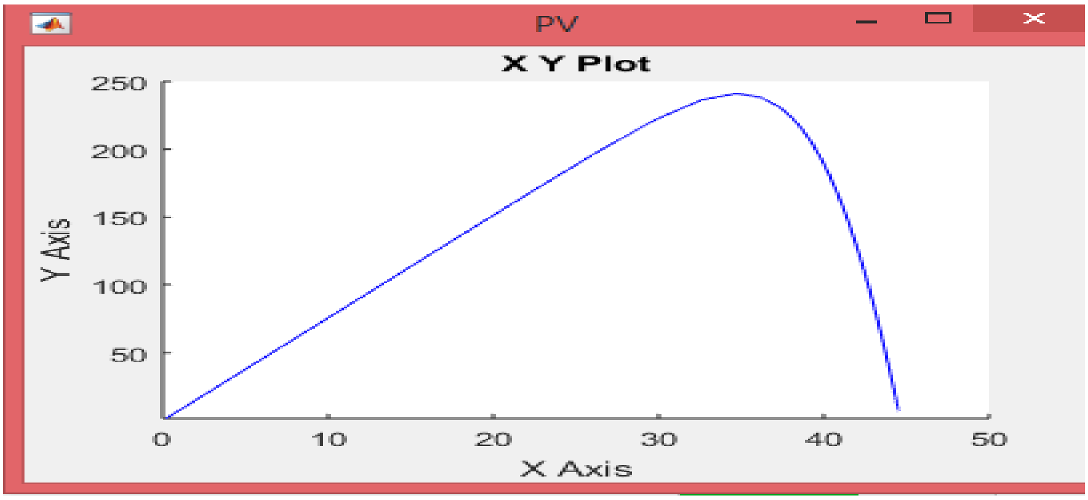

Fig. 12 PV Characteristics Waveform

In figure 12 show PV characteristics and there are X-Y coordinates voltage Vs current plotted. The maximum power is generated 230 Kw by the solar cell at point of the current-voltage characteristic where product of V and I is maximum shown in fig 12 Y Axis plotted 230Kw and x-axis point maximum 44I

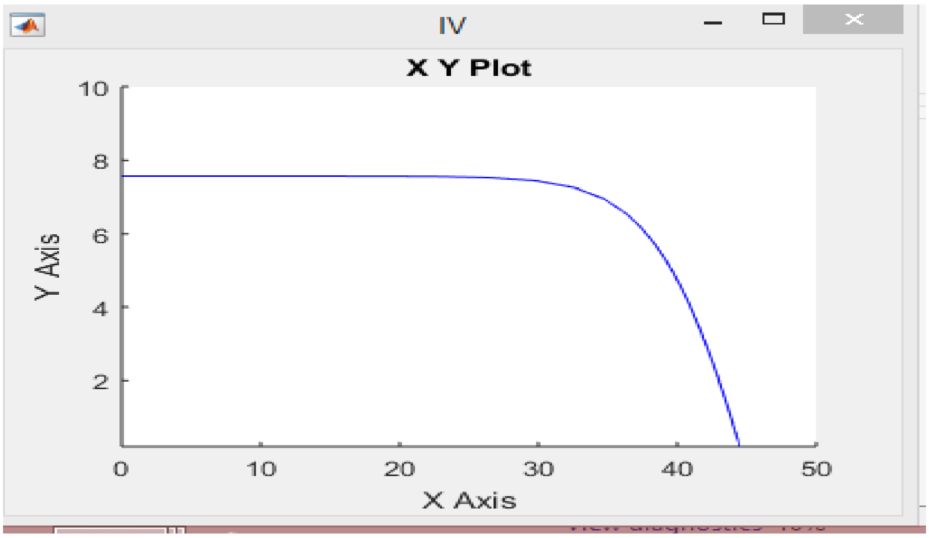

Fig. 13 PV Characteristics Waveform

This curve illustrates the relationship between current and voltage of the solar panel. The current remains high at low voltage and gradually decreases as voltage increases, showing the typical nonlinear behavior of a photovoltaic system and the maximum power point region.

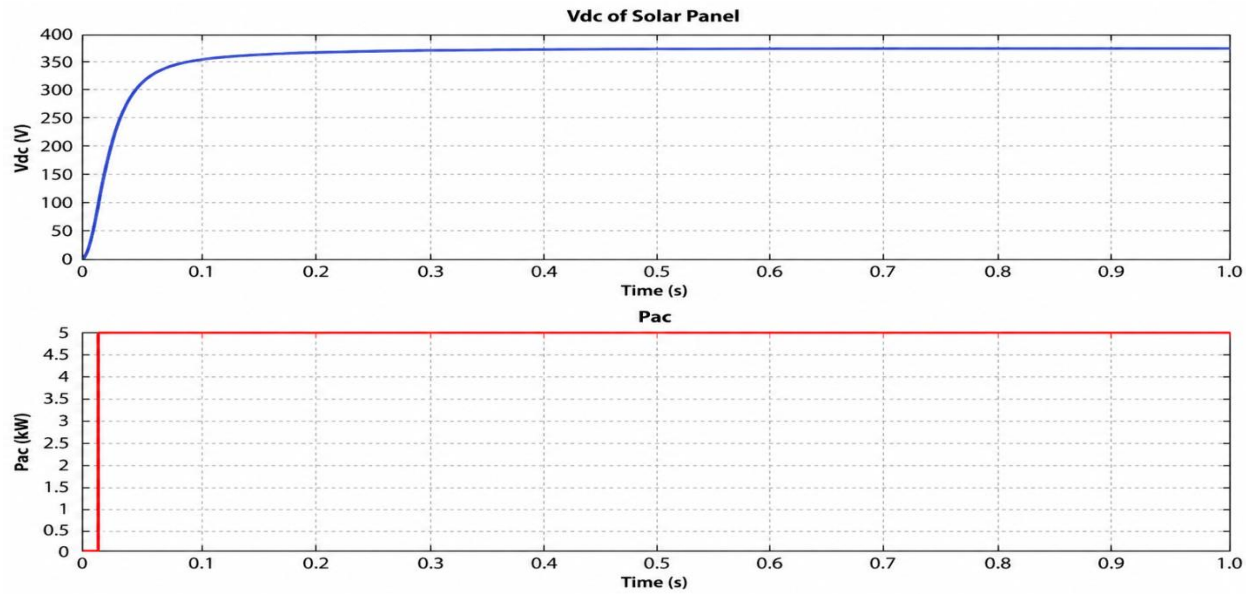

Fig.14 VDC from Solar Panel

Figure 14 shows the dynamic response of the solar PV system, specifically the DC voltage (Vdc) of the solar panel and the AC output power (Pac) over time.

In the upper graph (Vdc of Solar Panel), the DC voltage starts from zero and rises rapidly within a short duration (around 0–0.1 seconds). This sharp increase represents the startup behavior of the PV system, where the system quickly reaches its operating voltage. After this transient phase, the voltage stabilizes at approximately 370–380 V, indicating that the system has reached a steady-state condition. The smooth and stable curve confirms proper operation of the MPPT controller and DC–DC converter, which regulate the voltage efficiently. In the lower graph (Pac), the AC output power also rises almost instantly and settles at a constant value of around 5 kW. This indicates that the inverter is successfully converting DC power into AC and supplying a stable and continuous power output to the load or grid. The flat line after the initial step shows that there are no significant fluctuations, which reflects good system stability and effective control.

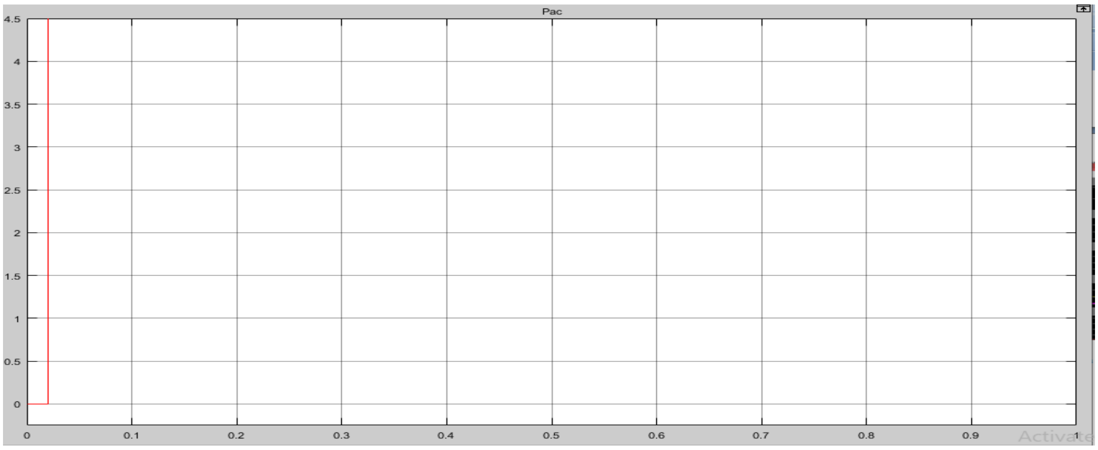

Figure 15 Wind Power

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Fig 15 showing the Wind power 4.5 P (W) from the wind turbine of the Mechanical power output (W): Generator base voltage (VA): 8.5e3: wind speed (m / s): Mechanical output power (W): increase or decrease input.

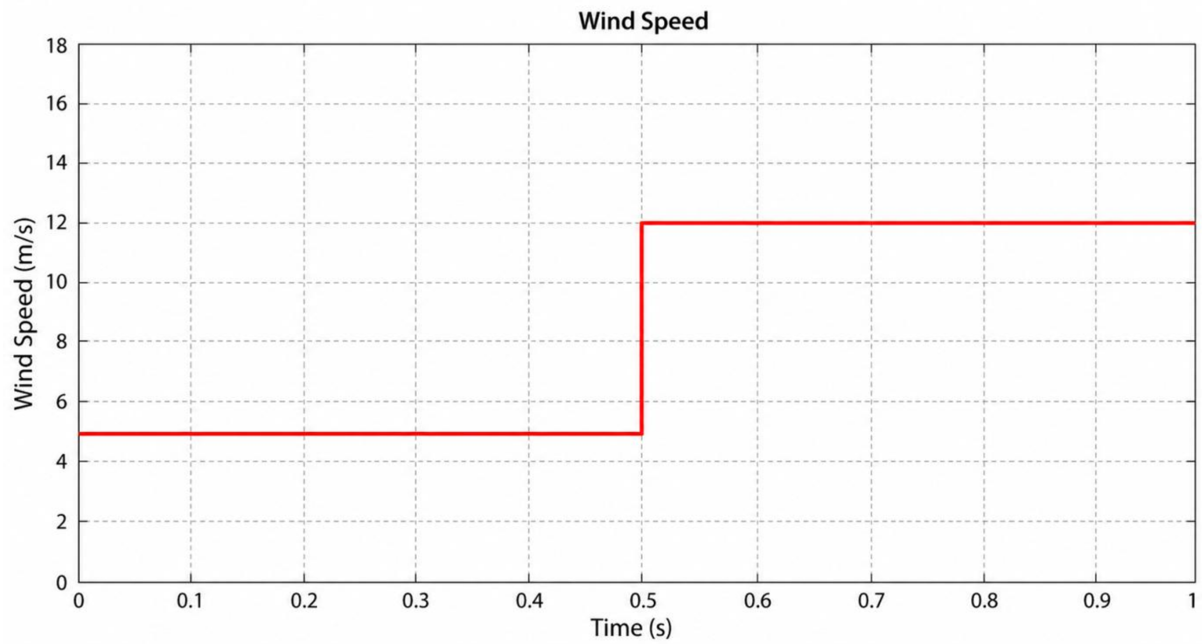

Figure 16 Wind speed

Figure 16 represents the variation in wind speed. Initially, the wind speed remains constant at around 5 m/s, then increases to approximately 12 m/s at 0.5 seconds and maintains this value. This demonstrates changing environmental conditions affecting wind power generation.

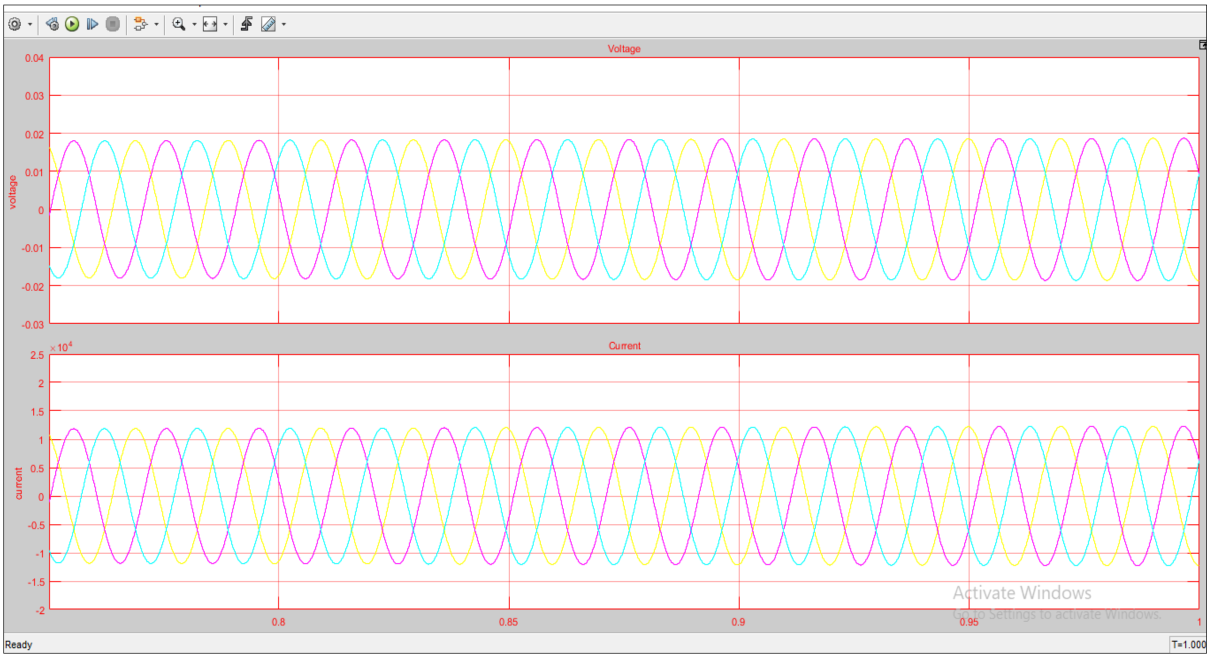

Figure 17 diesel Generator voltage and current

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Fig.17 shows three-phase sinusoidal voltage and current produced by the diesel generator. The smooth sinusoidal pattern indicates stable AC power generation and proper operation of the generator.

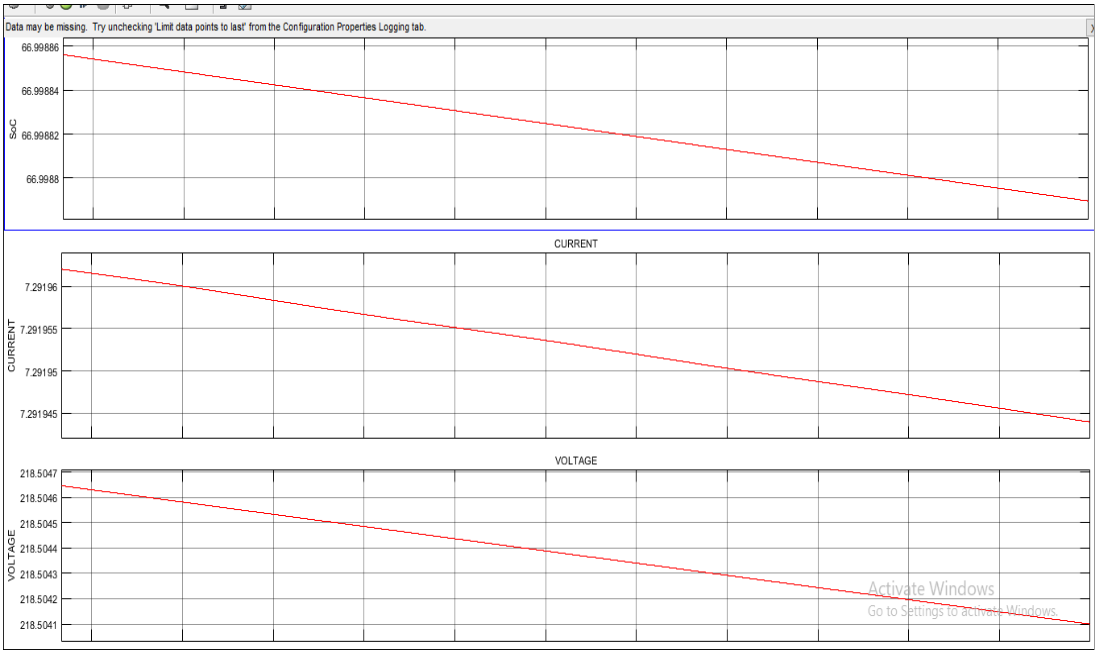

Figure 18 Charging Voltage and Current of Battery

Fig.18 shows the charging characteristics of the battery. The voltage and current gradually decrease over time as the battery reaches a higher state of charge, indicating controlled and efficient charging.

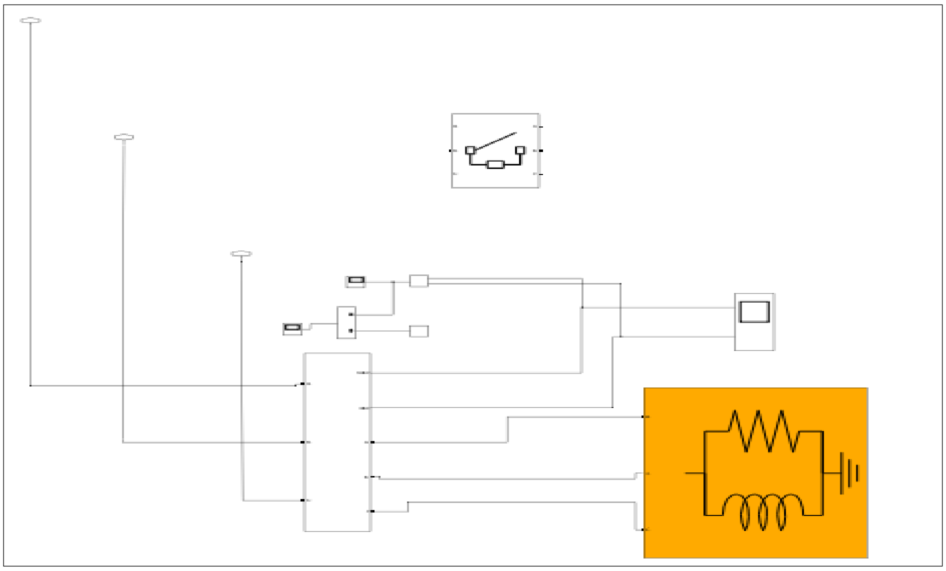

Fig. 19: Nonlinear Subsystem

Figure 19 represents the nonlinear subsystem used in the model. It captures the dynamic behavior of the system under nonlinear operating conditions such as varying loads and source fluctuations.

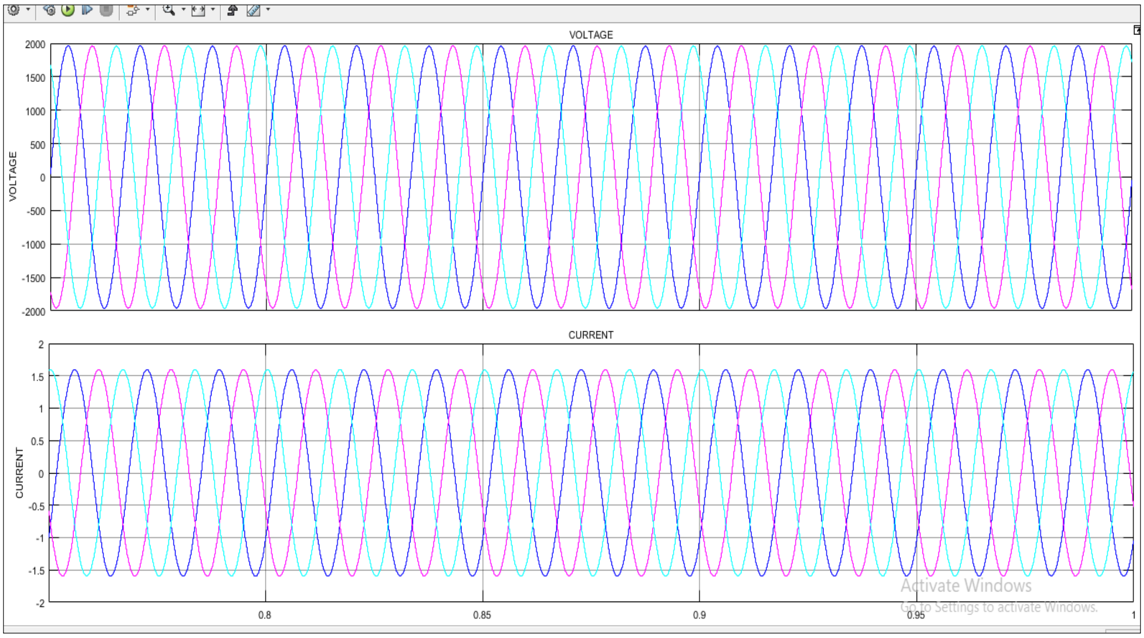

Fig.20 Nonlinear Voltage and Current

The waveform shows voltage and current under nonlinear conditions. The signals remain sinusoidal but may contain slight distortions, indicating the presence of nonlinear elements in the system.

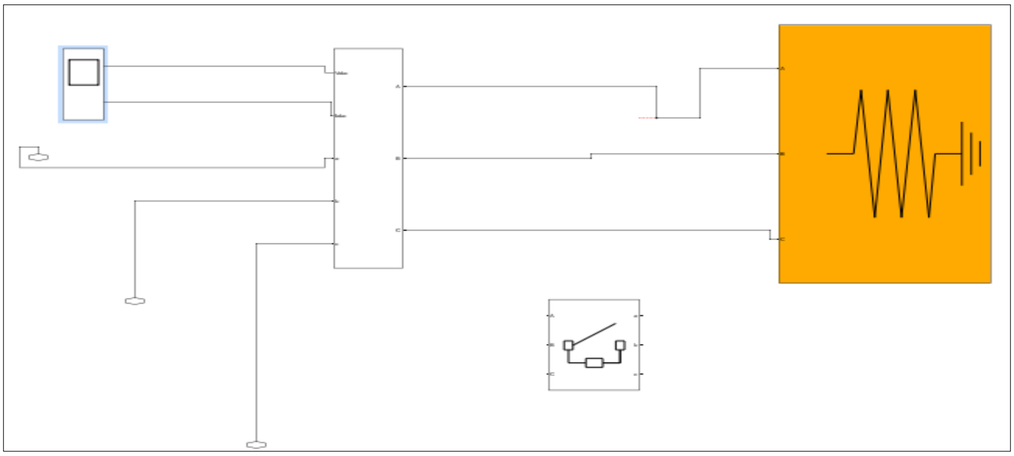

Fig.21 linear subsystem

Figure 21 shows the linear subsystem model used for simplified analysis. It helps in understanding system behavior under ideal and steady-state conditions.

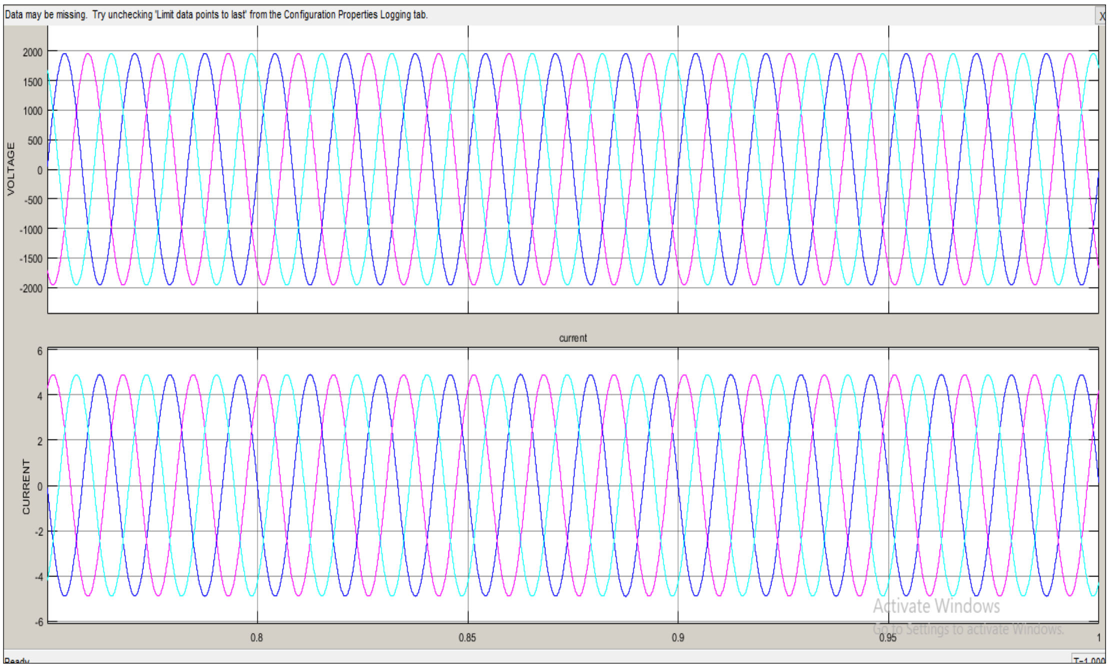

Fig.22 linear Voltage and Current

Fig.22 Shows waveform represents voltage and current under linear conditions. The signals are smooth and sinusoidal, indicating stable and ideal system performance without distortions.

Table: 2 Simulation result

Parameter	**Value / Range**
PV DC Voltage	0 → **375 V** (steady 370–380 V)
AC Output Power	**5 kW (constant)**
PV Current	**7.29 A → 7.291 A**
Battery SOC	**67% → 66.998%**
Three-Phase Voltage	**2000 V (peak)**
Three-Phase Current	± **1.5–2 A (peak)**
Grid Voltage	**230 V RMS (325 V peak)**
Grid Current	**1–1.5 A RMS**
Wind Speed	**5 m/s → 12 m/s** (at 0.5 sec)
DC Bus Voltage	**370–380 V (constant)**

IV. CONCLUSION

In this work, a hybrid renewable energy system combining solar PV, wind energy, and battery storage has been successfully modeled and simulated using MATLAB/Simulink. The system effectively integrates multiple energy sources through a DC bus architecture and ensures efficient power conversion using advanced control techniques such as MPPT and PWM-based inverter control.The simulation results confirm that the system achieves fast dynamic response and stable steady-state performance. The PV voltage stabilizes around 375 V, and the inverter delivers a consistent output power of approximately 5 kW. The three-phase voltage and current waveforms are balanced and sinusoidal, demonstrating good power quality and proper synchronization. The battery storage system plays a crucial role in maintaining system reliability by compensating for fluctuations in renewable energy sources.the proposed system enhances energy efficiency, ensures continuous power supply, and improves system stability. It is well-suited for modern renewable energy applications, including grid-connected systems and microgrids. Future work may focus on optimizing control strategies, reducing harmonic distortion, and implementing real-time hardware validation.

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