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MODELLING AND PERFORMANCE ANALYSIS OF HYBRID ENERGY SYSTEM USING FUZZY LOGIC FOR DOMESTIC APPLIANCES

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Abstract: Power Generation Systems use green energy sources such as Solar Energy Systems (SES), Wind Energy Systems (WES), and Fossil Fuels to address conversion efficiency challenges. To improve efficiency, DC-DC converters like SEPIC, Buck-Boost, and CUK are used, with SEPIC being the most effective in Hybrid Systems, addressing issues in Buck-Boost converters. An MPPT controller maximizes power extraction and Fuzzy Logic enhances MPPT performance by adapting to rapid input changes. The Hybrid System integrates Solar PV and Wind Energy Conversion Systems using Fuzzy Logic-based SEPIC converters to regulate the output and ensure a stable DC supply. The Simulink model developed demonstrates a Fuzzy Logic- based MPPT controller applied to a SEPIC converter connected to a PV and Wind Energy Conversion System. In this model, real-time voltage and current measurements are used to calculate power, and the Fuzzy Controller adjusts the duty cycle to keep the system operating at the Maximum Power Point. The model was tested under different irradiance conditions to verify stable tracking. This paper focuses on designing and analyzing a Fuzzy Logic-based solar-wind hybrid system with Battery backup to support AC and DC Loads, ensuring an Uninterrupted Power Supply. A Wind Energy Source with a PMSG and rectifier can be added to the same DC bus using the same Fuzzy Logic MPPT method. Overall, the Simulink model demonstrated improved power tracking and supported the integration of hybrid PV-Wind systems.

***Index Terms* - Hybrid Energy System, Fuzzy Logic, MPPT, SEPIC Converter, Renewable Energy, Battery Storage.**

I. INTRODUCTION

The rising global energy consumption, coupled with escalating environmental issues, has driven the accelerated integration of renewable energy technologies across the world. Among these, solar photovoltaic (PV) systems and wind energy systems have become leading alternatives for clean and sustainable electricity generation [26]. However, the variable and unpredictable nature of these energy sources presents challenges in maintaining a consistent power output. To overcome this, hybrid renewable energy systems (HRES), which synergize solar and wind energy, have been developed to enhance power reliability, minimize storage dependency, and boost overall system efficiency [25].

An essential component of HRES is the Maximum Power Point Tracking (MPPT) controller, which ensures optimal extraction of energy from the renewable inputs. Conventional MPPT strategies such as Perturb and Observe (P&O) and Incremental Conductance (INC) often face limitations under swiftly changing environmental conditions [8]. In contrast, fuzzy logic-based MPPT algorithms have exhibited better adaptability to system uncertainties and non-linear dynamics of renewable sources [12]. Furthermore, DC-DC converters play a pivotal role in stabilizing voltage levels and facilitating efficient power management within hybrid systems. Among the various converter topologies, the Single-Ended Primary Inductor Converter (SEPIC) is preferred for its ability to regulate voltage in both buck and boost modes while ensuring continuous input current flow [3]. The application of fuzzy logic controllers (FLC) with SEPIC converters has shown notable improvements in system robustness and dynamic response [13].

This research presents a detailed study of a fuzzy logic-controlled hybrid energy system integrating solar PV, wind turbines, and battery storage, tailored for domestic energy applications. The primary objective is to maximize energy harvesting from the available resources while maintaining a consistent and reliable power supply to both AC and DC loads.

II. SYSTEM CONFIGURATION LAYOUT

Figure 1 shows a Hybrid Energy System that integrates both solar and wind energy sources to ensure a reliable and continuous power supply. The photovoltaic (PV) array converts sunlight into DC electricity, which is then regulated by a SEPIC converter controlled using Fuzzy Logic to extract maximum power [2]. Simultaneously, a wind turbine driven by variable wind speeds powers a Permanent Magnet Synchronous Generator (PMSG), producing AC power that is rectified and processed through another SEPIC converter with Fuzzy Logic control. Both sources are fed into a common DC bus, which acts as the central power line. A battery bank connected via a bidirectional converter stores excess energy and supplies power when required, thereby maintaining system stability [1]. The system caters to both AC and DC loads, where the DC bus output is converted into AC using a PWM inverter for variable AC loads, and a DC-DC buck converter supplies power to the DC loads. This hybrid setup ensures efficient energy utilization, storage, and distribution for diverse load requirements [2].

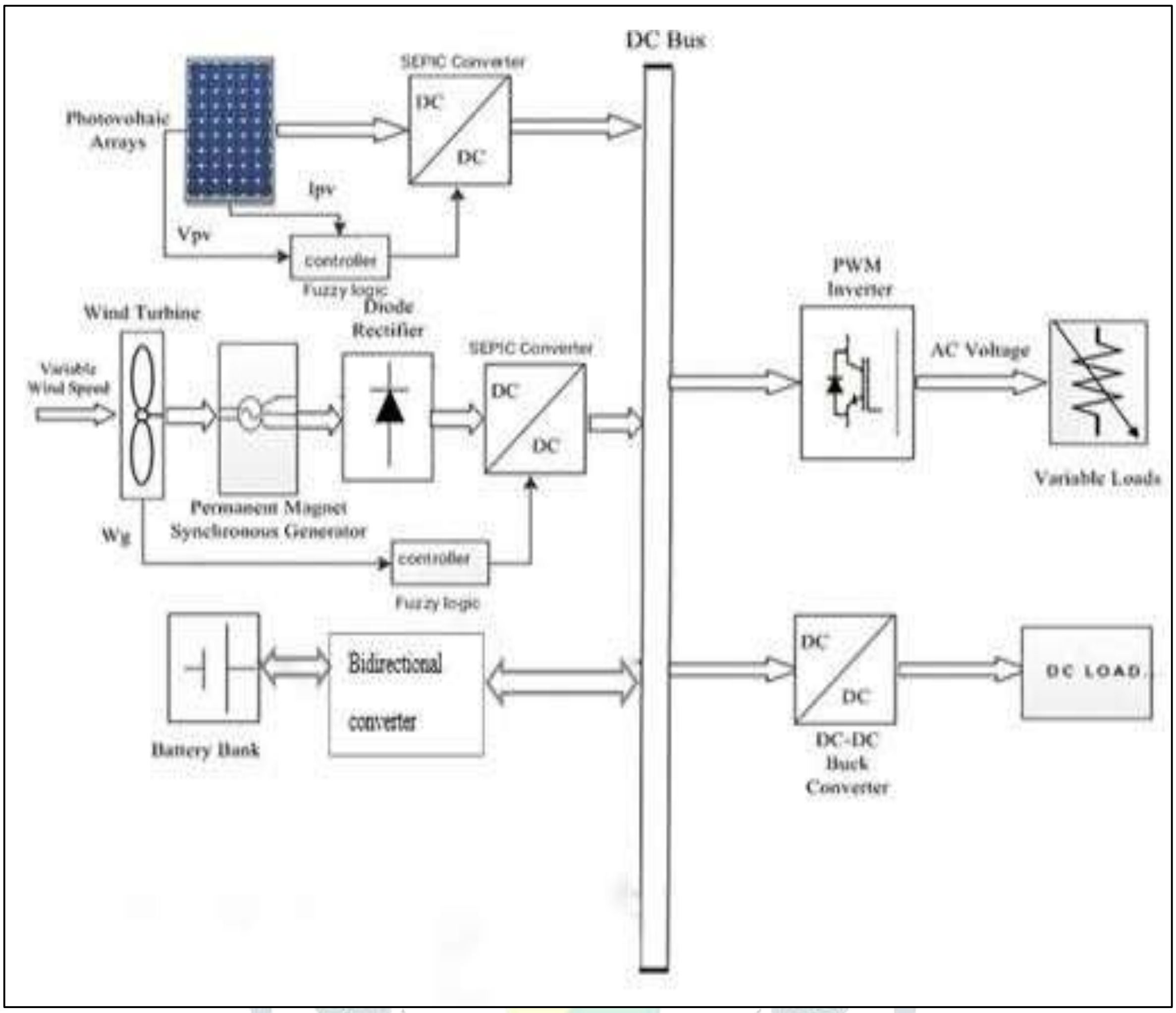


Fig.1 Block Diagram of a Hybrid Energy System

a) ***Design of the SEPIC***

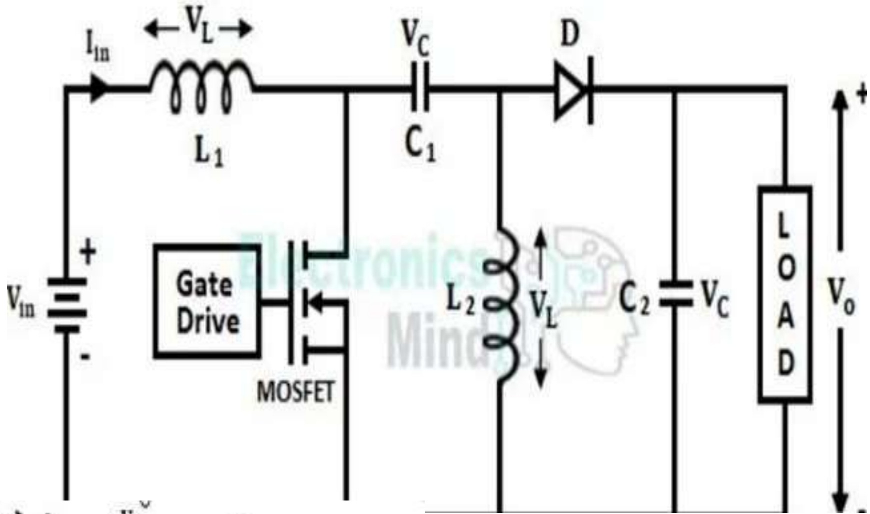
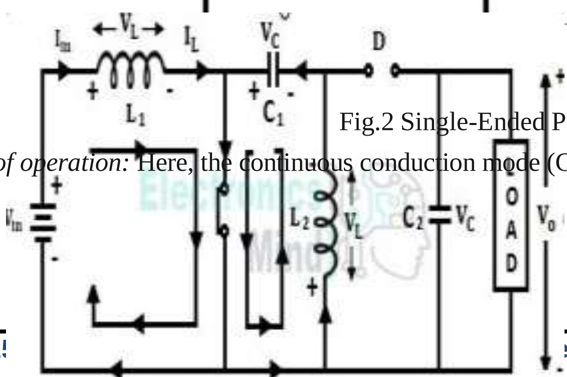
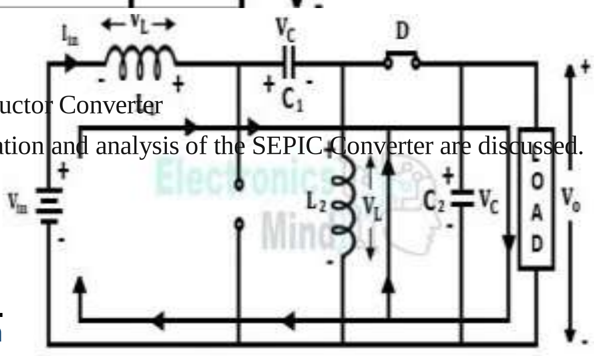


Fig.2 Single-Ended Primary-Inductor Converter

Modes of operation: Here, the continuous conduction mode (CCM) operation and analysis of the SEPIC Converter are discussed.





(a) (b)

Fig.3 SEPIC Converter modes of operation (a)when switch D is on, (b)when switch D is off

Mode 1: (0<t<DT) Figure 3 (a) illustrates that when the gate pulse is applied to the MOSFET, it turns ON, allowing the source current to flow through the inductor, MOSFET, and return to the input source. This causes the current through the inductor to rise, indicating that it is being energized from the input supply [4]. This is the stage where the instantaneous voltage of the inductor is similar to that of the input voltage. [11]. Simultaneously, the capacitor begins to discharge, transferring its stored energy to the inductor through the conducting MOSFET path [22].

Mode 2: (DT<t<T) Figure 3 (b) illustrates that once the MOSFET is switched OFF by removing the gate signal, the inductor resists the sudden interruption of current owing to its inherent property, following Lenz's Law [4]. As a result, the polarity of the capacitor reverses, and it begins to discharge by transferring its stored energy back to the capacitor, which was previously depleted during the MOSFET ON period [11]. This process is recharged by the reverse flow of the current. Simultaneously, the inductor, which had been energized earlier, also starts discharging in the opposite direction [22]. This reverse current causes the diode to become forward-biased, allowing the energy from the source to be delivered to the load [4]. When the MOSFET turns ON again, the cycle repeats, and the inductor charges from the source and the capacitor [4]. The SEPIC converter operates in either Continuous or Discontinuous Conduction Mode based on whether the inductor current falls to zero [11]. Figure 4 illustrates the current and voltage waveforms behavior [23].

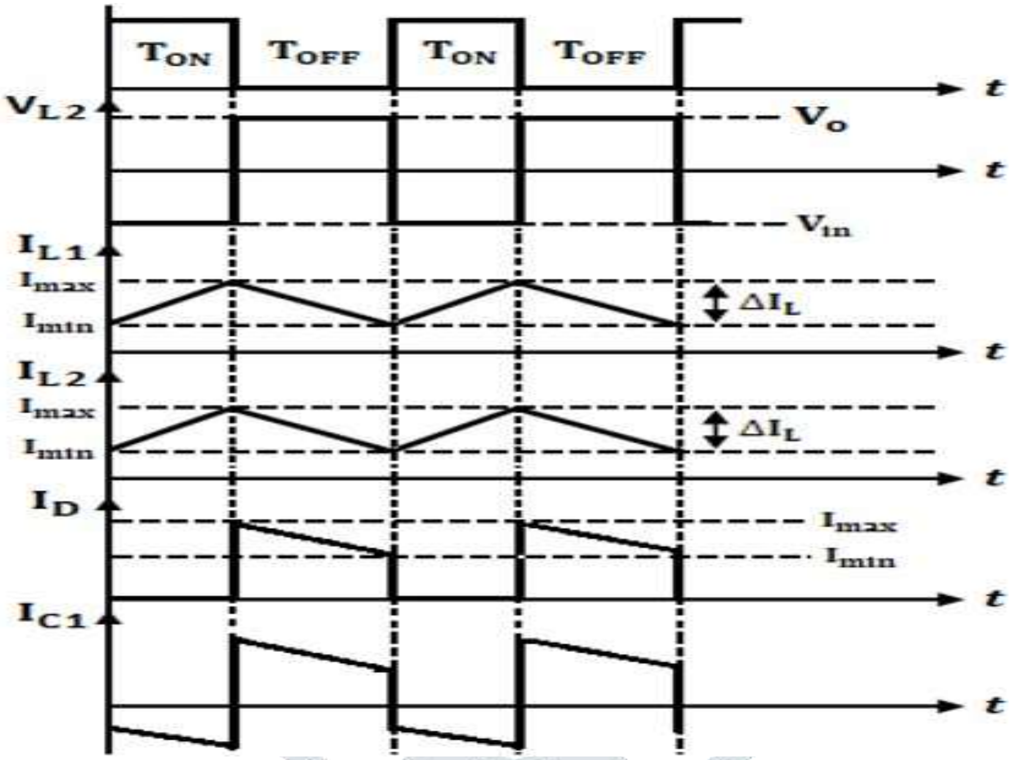


Fig.4 Voltage & Current Waveform of SEPIC Converter

b) ***Hybrid Fuzzy Logic-Based MPPT Controller:***

Flowchart of Fuzzy logic-based MPPT Controller illustrated in Figure 5. Fuzzy logic operates using two key inputs, the instantaneous error, derived through changes in power and voltage, and the change in error between sample periods**.** These inputs are passed through a fuzzification stage, where they are converted to linguistic variables. The fuzzy inference engine, using a predefined rule base, processes these variables to determine the necessary adjustment in the duty cycle. This adjustment is then defuzzified and applied to the SEPIC converter to maintain its operation at the maximum power point. The simulation model shown for the PV system in MATLAB/Simulink captures this process effectively, where the Fuzzy MPPT controller interacts with sensors measuring voltage and current and dynamically adjusts the SEPIC converter switching [1].

To extend the system for wind energy, a permanent magnet synchronous generator (PMSG) driven by a wind turbine was connected to a diode rectifier, which converted the variable AC output into DC. This output is then fed into another SEPIC converter, which is also controlled by a Fuzzy Logic MPPT controller. Both the PV and wind systems are integrated via a common DC bus, which supplies regulated power to the DC and AC loads via a PWM inverter. The Fuzzy Logic controller demonstrates superior tracking efficiency compared to conventional MPPT algorithms, such as Perturb and Observe (P&O) and Incremental Conductance, particularly under fluctuating weather conditions such as sudden irradiance or wind speed changes [2].

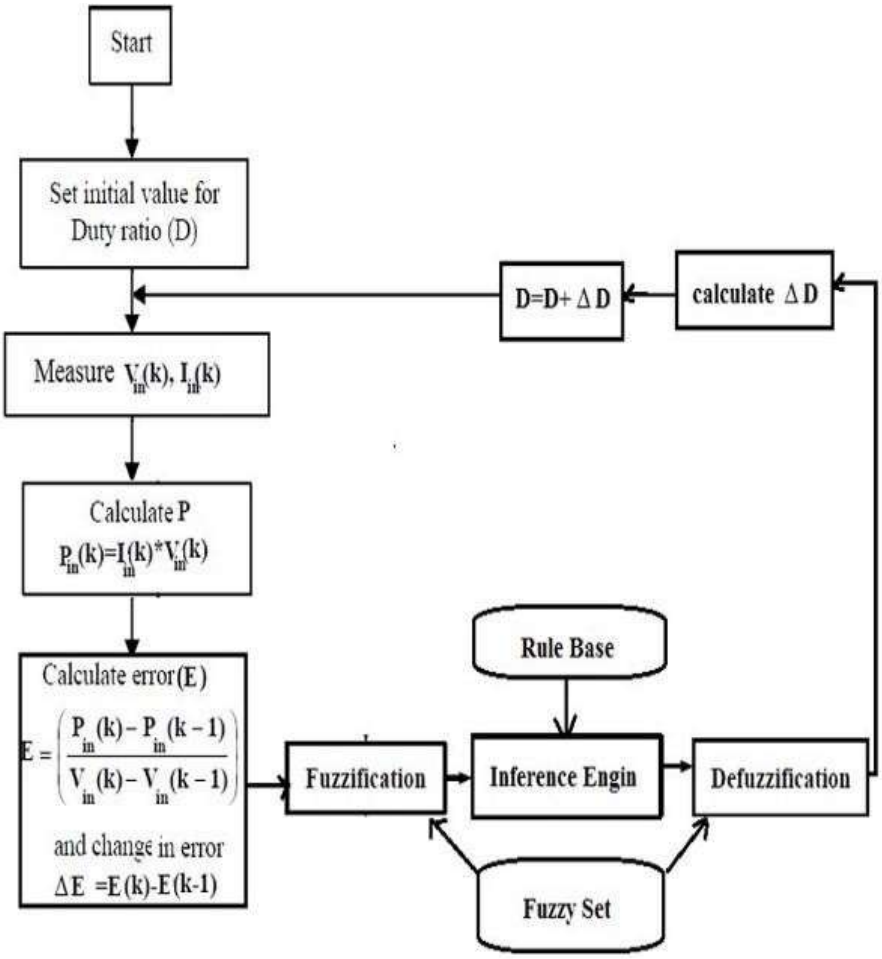


Fig.5 Flowchart for Fuzzy Logic-Based MPPT Controller

This enhances the system's adaptability and ensures better stability in hybrid configurations, as shown in the block diagram of the Hybrid Energy System in Figure 1.

III. MATHEMATICAL MODELLING

The PV Cell model uses its output,

$$I_{PV} = I_{PV} - I_O \left[exp\left(\frac{q(V_{PV} + I_{PV}R_S)}{nkT}\right) - 1\right] - \frac{V_{PV} + I_{PV}R_S}{R_S} \quad (1)$$

The Wind Turbine is modelled as,

$$P_W = \frac{1}{2}\rho A v^3 C_P \quad (2)$$

The SEPIC Converter is modelled as,

$$V_{Out} = \frac{D}{1-D} V_{in} \qquad (3)$$

Where duty cycle D is given by,

$$D = \frac{V_{out}}{V_{out}+V_{in}} \qquad (4)$$

Inductor Currents of SEPIC Converter are,

$$I_{L1} = I_{in}$$

$$I_{L2} = I_{out} - I_{c1}$$

When the switch is ON, it stores energy from the input and obtains energy from the coupling capacitor. When the switch is OFF, the energy is discharged to the load and output capacitor.

Component design Equations,

$$L_1 = L_2 = \frac{V_{in}D}{f_s \Delta I_L}, \quad C_1 = \frac{I_{out}D}{f_s \Delta V_{c1}}, \quad C_2 = \frac{I_{out}D}{f_s \Delta V_{out}}$$

The Fuzzy MPPT uses:

Input error,

$$E(k) = \frac{dp}{dv}$$

Change in error,

$$CE(K) = E(K) - E(K-1) \qquad (5)$$

These inputs are fuzzified into linguistic variables (e.g., NB, NM, Z, PM, and PB). The rule base uses IF-THEN rules to determine the duty cycle change (ΔD). Defuzzification (e.g., the centroid method) produces a crisp control signal.

Updated duty cycle,

$$D_{new} = D_{old} + \Delta D$$

The Fuzzy MPPT adjusts the SEPIC converter switching. The converter regulates the power flow from the source (PV or wind) to the load, maintaining a stable output even if the input conditions vary.

IV. DETAILS OF CASE STUDY

The proposed Hybrid Energy System combines photovoltaic (PV) and wind power sources with a battery storage unit to ensure an uninterrupted supply to both AC and DC domestic loads. The PV module generates a variable DC voltage depending on the irradiance levels, typically ranging from 118 V to 330 V. The output of this is fed to a Single Ended Primary Inductor Converter (SEPIC), which is used to regulate the DC voltage to a fixed level, making it compatible with the DC link and loads downstream of it. The SEPIC is preferred because of its ability to step up or step down the voltage without inverting the polarity, making it highly suitable for renewable systems with fluctuating inputs [3]. The wind subsystem employs a Permanent Magnet Synchronous Generator (PMSG), which is mechanically driven by a wind turbine. The three-phase AC output from the PMSG is rectified using a diode bridge and then processed by another SEPIC converter, similar to the PV side, to bring the voltage to the desired DC-link level [2]. This uniform DC interface allows for the easy integration of both sources and enhances system stability.

To maximize energy extraction from both sources, a fuzzy logic-based Maximum Power Point Tracking (MPPT) controller is implemented. The fuzzy logic controller takes the change in power (ΔP) and change in voltage (ΔV) as inputs and generates a suitable duty cycle signal to regulate the SEPIC converter switches. This method enables faster and more adaptive tracking of the Maximum Power Point (MPP) compared to conventional methods such as Incremental Conductance (INC) or Perturb and Observe (P&O) [3]. The AC output from the PMSG is rectified using a diode bridge and then processed by another SEPIC converter, similar to the PV side, to bring the voltage to the desired DC link level [2]. This uniform DC interface allows easy integration of both sources and enhances system stability.

To maximize energy extraction from both sources, a Fuzzy Logic-Based MPPT (Maximum Power Point Tracking) controller is implemented. The fuzzy logic controller takes change in power (ΔP) and change in voltage (ΔV) as inputs and generates a suitable duty cycle signal to regulate the SEPIC converter switches. This method enables faster and more adaptive tracking of the Maximum Power Point (MPP) compared to conventional methods like Incremental Conductance (INC) or Perturb and Observe (P&O) [3].

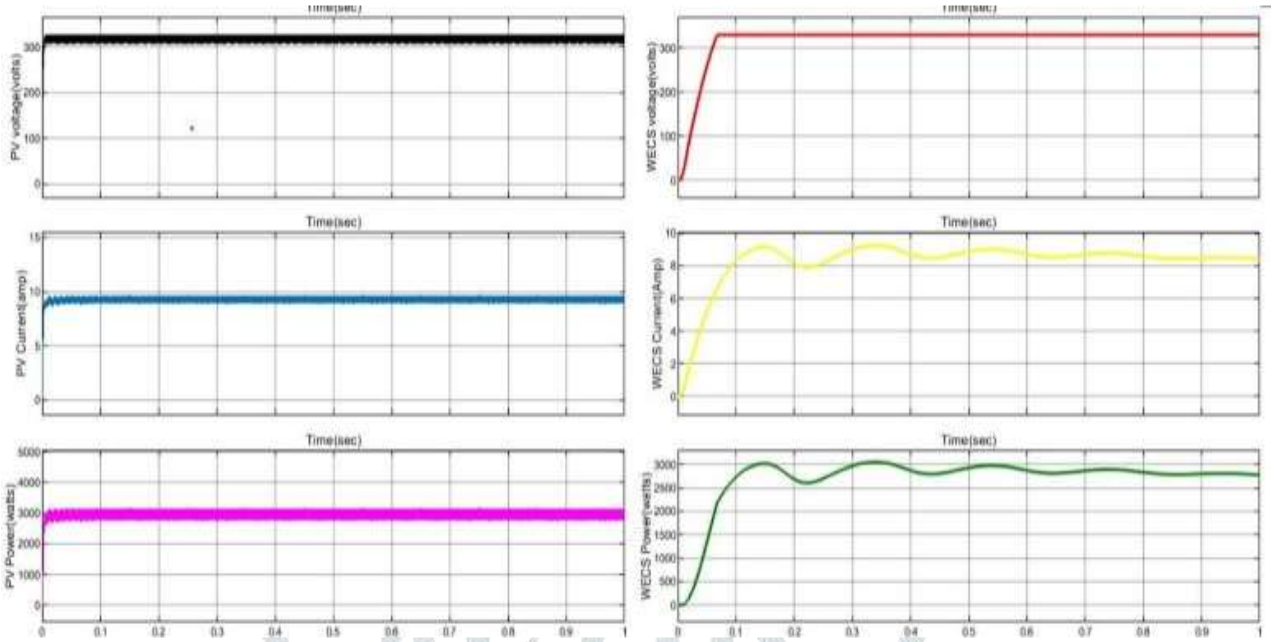
Table. Hybrid Energy Conversion System Specifications

Parameters	**Value**	**Units**
PV Panel Specifications		
Rated Power	3000	Watts
Open Circuit Voltage	135.96	Volts
Short Circuit Current	9.24	Amps
Voltage at Maximum Power Point	112.1	Volts
Current at Maximum Power Point	8.89	Amps
Wind Turbine Specifications		
Rated Power	3000	Watts
Radius	1.5	mtr
Wind speed	9	m/sec
Air Density	1.225	Kg/m^2
SEPIC Converter Specifications for PV System		
Rated Capacity	3000	Watts
L1 & L2	154.6	μHenry
C1	146	μFarad
C2	22.2	μFarad

Switching Frequency	50	KHz
Vin	80	Volts
Output Voltage	330	Volts
Output Current	8	Amps
SEPIC Converter Specifications for WECS		
Rated Capacity	3000	Watts
L1 & L2	307	μHenry
C1	134	μFarad
C2	23.3	μFarad
Switching Frequency	50	KHz
Vin	118	Volts
Output Voltage	330	Volts
Output Current	9.09	Amps
Battery Specifications		
Nominal Voltage	48	Volts
Series-connected batteries	4	-

State of Charge	50	Percentage
Rated capacity	150	Amp/hr

V. RESULTS AND DISCUSSION



(a) (b)

Fig.7 Simulation Results of (a) Solar Energy Conversion System & (b) Wind Energy Conversion System

The simulation results clearly validate the effective coordination of the proposed Hybrid Energy System, which integrates PV, wind, and battery units. The photovoltaic (PV) array maintained a stable output voltage of approximately 330 V and delivered a current close to 9.5 A, resulting in an average power output of approximately 3.1 kW. Simultaneously, the wind energy conversion system (WECS) using a permanent magnet synchronous generator (PMSG) achieved a steady voltage of 330 V, and its output current stabilized at approximately 8 A, producing approximately 2.6 - 3.0 kW of power.
These results confirm that the fuzzy logic-based MPPT controller responds quickly to changes in the input and successfully tracks the maximum power point for both sources, as shown in Fig. 7.
The battery system, connected via a bidirectional buck-boost converter, maintained a constant voltage of 75 V. The battery current remained very low, indicating minimal discharge, whereas the state of charge (SOC) declined only slightly from 49.9999% to

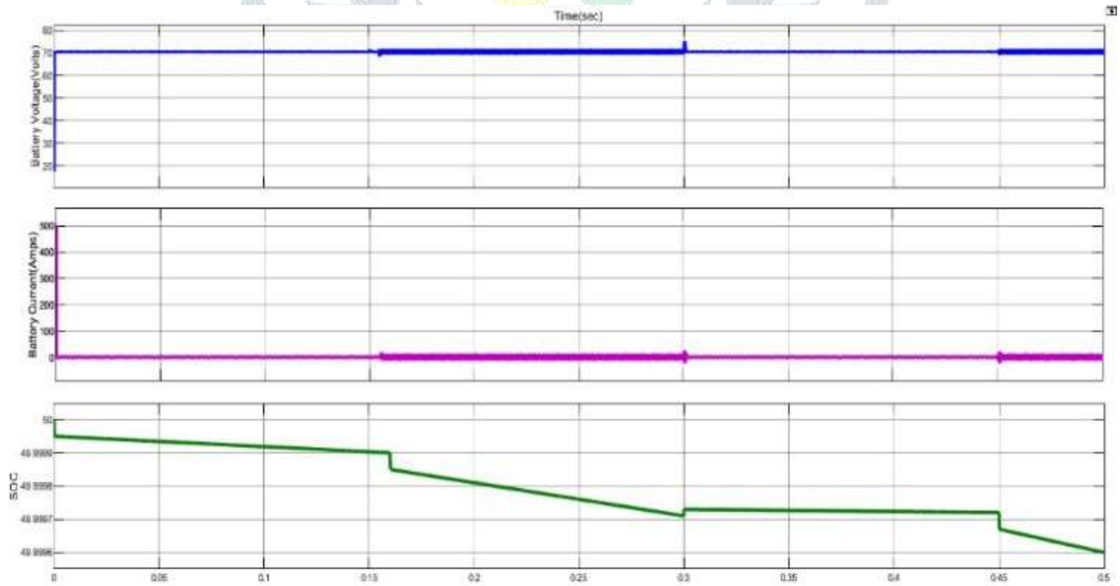
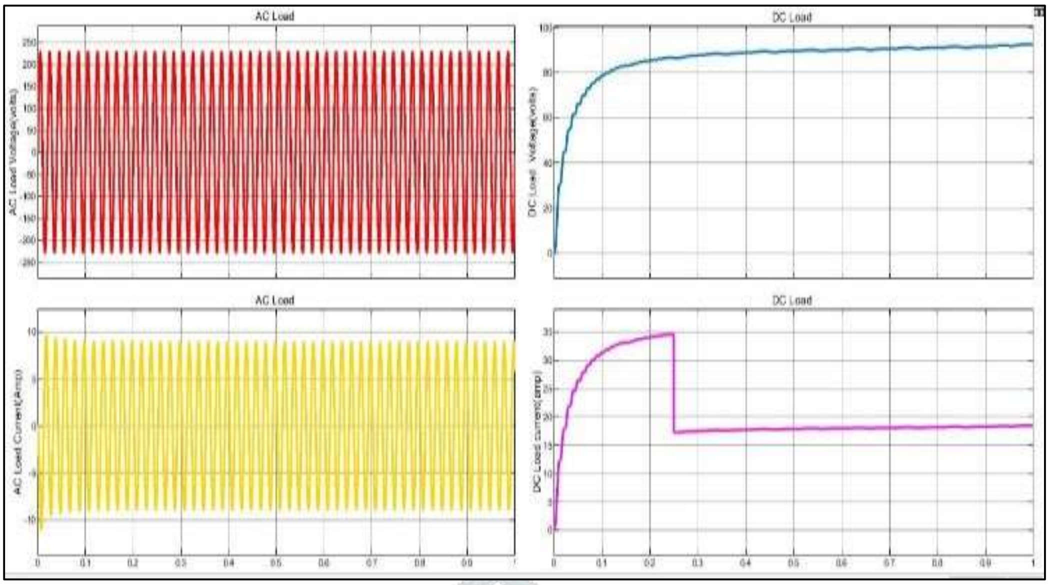


Fig.8. Waveform of Battery Voltage (Volts), Current (Amps), State of Charge (%) Vs Time (Sec)

49.9996%. This behaviour confirms that the battery is primarily in standby mode, supplying power only when the combined renewable sources are insufficient. On the load side, the AC output voltage reached ±230 V (sinusoidal waveform), and the AC current stabilized at approximately ±9 A, demonstrating the inverter's ability to support household AC appliances.
Additionally, the DC load receives a regulated output of 90 V, with an initial current surge to 35 A and Stabilization around 25 A, demonstrating smooth voltage regulation for sensitive DC devices, as shown in Fig. 7.
Overall, the simulation verified that the system delivered efficient energy conversion, rapid MPPT performance, and a reliable supply to both AC and DC loads. The model demonstrated improved voltage stability, proper load sharing, and reduced battery

cycling, all of which are aligned with the objectives as showed in the Fig.9.



(a) (b)

Fig.9. Output Waveform (a) AC Load Voltage (Volts), Current(Amps) & (b) DC Load Voltage (Volts), Current(Amps)

VI. CONCLUSION:

The proposed Hybrid Energy System, which combines PV, wind, and battery energy, successfully delivers stable power for domestic loads. The simulation results show that the PV subsystem generates 330 V, 9.5 A (≈3.1 kW), and the wind system contributes 330 V, 8 A (≈2.6–3.0 kW) through SEPIC converters. The Fuzzy Logic MPPT controller enables fast and efficient tracking while maintaining a consistent output. AC loads receive a pure ±230 V supply with 9 A current, whereas DC loads operate at 90 V, stabilizing at approximately 25 A. The battery voltage remained at 75 V with a minimal SOC drop, confirming balanced energy management. Overall, the system achieves an efficient Hybrid Operation with smart control and reliable load support.

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