

Enhancing the Performance of Integrated Solar Wind and Battery System with Grid using Fuzzy Based MPPT

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Abstract: There is worldwide interest in renewable energy, including solar and wind power, driven by the depletion of fossil fuel and global warming. An alternative source for energy presents availability, cost, and efficiency; however, their integration into hybrid systems becomes challenging due to the intermittent nature of power output. To tackle these matters, fuzzy based Maximum Power Point Tracking (MPPT) controller has been developed. Such an MPPT controller can smooth out weather disturbances for more reliable system operations under changing input or loads conditions. Additionally, a battery connected bi-directional converter makes for effective charging and discharging processes. The grid-connected system also acts as a backup source whenever the hybrid solar-wind system together with its battery fails to meet consumer load requirements. This integration improves overall output efficiency of solar-wind hybrid systems with batteries connected to the grid. In the proposed system there are two cases with the SOC of the Battery is 9% and 50% and maintaining the AC Load power 1000W from 0Sec to 2Sec and 2400W From the 2Sec in both conditions. The efficacy of this scheme is justified through detailed simulation results obtained from using MATLAB software tools which show remarkable performance enhancements in this regard.

Keywords: Solar Panel, Wind Turbine, PMSG, Incremental Conductance, Fuzzy Logic Controller, Bi-Directional Converter.

1. Introduction

This study offers an in-depth look at the proposed system backed by extensive MATLAB simulations. The simulation results show how well the fuzzy-based MPPT controller boosts the performance of the grid-connected solar-wind hybrid system with battery storage.

A bidirectional converter is additionally integrated with an MPPT controller to link with a battery storage system for energy flow regulation. In addition to this, the integration of the hybrid system with the power grid assures constant and consistent power delivery under any load demand, which renewable sources of energy and the battery alone cannot handle.

The empirical model for hybrid renewable energy systems based on solar and wind, it stresses the significance of hybrid systems in ensuring steadiness of energy supply through the complementary nature of the resources under consideration. The paper is more on empirical modeling but less on exploration of control strategies like MPPT or energy management within the grid-connected system [1]. A methodological approach will make the energy system capable of providing the load demands even with highly variable and uncertain renewable resources i.e. The optimal sizing of battery storage for a hybrid system in remote places. This introduces the great effect that battery

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storage has toward improving HRES reliability [2]. It discusses battery sizing but does not elaborate on MPPT as advanced control methods in detail for optimizing energy injected from PV, wind to the battery, and to the grid or diesel generator set [2]. The significant insights into the dynamic interactions between these renewable resources and their combined influence on overall power output. The work is particularly valuable for laying the groundwork for further explorations into hybrid system configurations [3]. However, the focus remains primarily on the modeling aspect, without incorporating advanced control strategies such as Maximum Power Point Tracking (MPPT) or addressing grid integration issues, which are critical for the practical deployment of such hybrid systems. A system integrating multiple renewables are mathematically modelled and battery storage is modeled dynamically and simulated [8]. Such an approach is important for resilient and reliable power system design especially in remote or off grid places without conventional power supply infrastructures. It turns out that better reliability can be achieved by integrating them together instead of using any single energy source alone [6]. It also provides potential optimization strategies to improve both efficiency and cost effectiveness of the hybrid system [4]. The study concentrates on standalone systems leaving out grid connected scenarios as well as the advantages that fuzzy control-based strategies can have on system performance optimization. Methods like Perturb and Observe (P&O), Incremental Conductance and others were commonly applied in MPPT. These techniques tend to have their own disadvantages like slow response times or sensitivity to environmental changes. As they can deal with uncertainties and nonlinearity which normally occurs in renewable resources, MPPT systems that rely on fuzzy logic were being promoted as possible alternatives [5][9]. Fuzzy logic controllers (FLCs) effectively manage intricate relationships among various renewable sources and system elements. FLCs employ linguistic variables and rules like human reasoning, thus making them appropriate for managing systems in which expert knowledge might be involved during the control strategy. the capabilities of handling non-linearity, managing uncertainties, integrating multiple energy sources, and adapting dynamically make solar-wind hybrid renewable energy systems well-suited for FLCs

[7]. In comparison with traditional control techniques [8-10], FLCs are particularly suitable for hybrid renewable energy systems which have a complex and variable nature mainly focusing on the optimization and system performance [11].

The remaining paper is organized as follows. Section 2 presents the methodology, Section 3 about proposed algorithm implementation process, Section 4 about the results and comparisons and lastly the conclusions are presented in Section 5.

2. Methodology

The methodology describes how to improve the efficiency of an integrated solar-wind hybrid system with battery storage and grid connection using fuzzy based MPPT approach. It encompasses such processes as system modeling, fuzzy logic controller design and system integration. The block diagram in Fig. 1 shows the overall performance.

2.1 Incremental conductance based fuzzy MPPT

The combination of Incremental Conductance (*IncCond*) method with the fuzzy logic control (FLC) gives rise to an incremental conductance-based fuzzy MPPT (Inc-Fuzzy MPPT). This hybrid technique combines the advantages of both systems to boost performance characteristics of photovoltaic (PV) and hybrid renewable energy systems. A complete account on Inc-Fuzzy MPPT technique is provided in this section, its operational and design considerations making it a better solution in maximizing production from hybrid renewable energy systems.

2.2 Incremental conductance (*IncCond*) method

The *IncCond* method is based on the relationship between the derivative of power (P) with respect to voltage (V). At the MPP, the derivative of power with respect to voltage is zero, expressed as (1)

$$\frac{dP}{dV} = 0 \quad (1)$$

Given $P = V \cdot I$, the derivative becomes (2)

$$\frac{dP}{dV} = I + V \cdot \frac{dI}{dV} = 0 \quad (2)$$

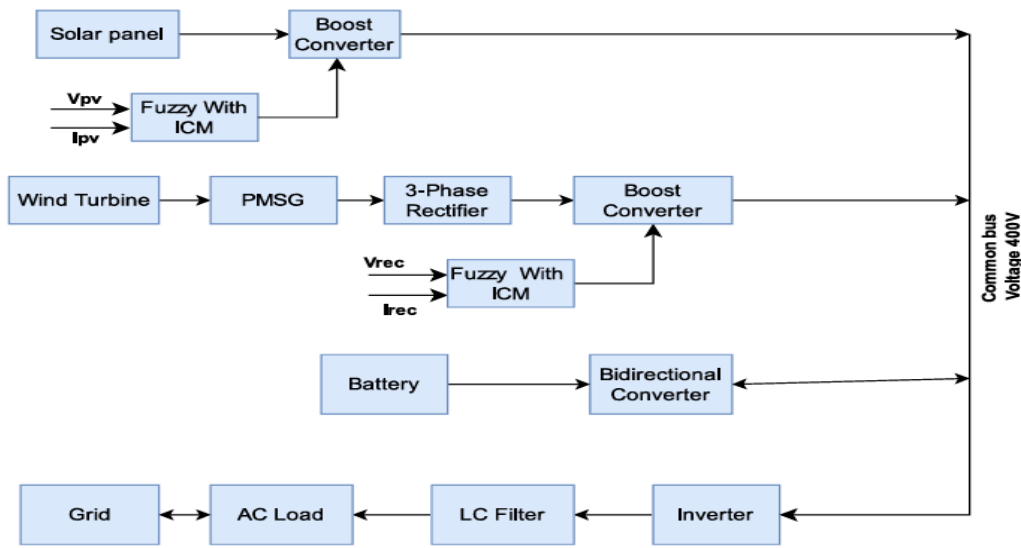


Fig.1: Block diagram for integrated solar wind hybrid and battery with grid along with fuzzy based MPPT

At the MPP

$$\frac{dI}{dV} = -\frac{I}{V} \quad (3)$$

With this method, the IncCond technique measures the gradual variations in current (ΔI) as well as voltage (ΔV) accordingly it calculates the incremental conductance ($\frac{\Delta I}{\Delta V}$) and compares it with instantaneous conductance ($-I/V$). Therefore, we can know whether operating point is at its left or right side or at true MPP from the equations (3).

2.3 Fuzzy Logic Control (FLC)

Due to nonlinearities and process variations this type of controller is required in fine-tuning mechanism. Usually, it contains the following three parts: Fuzzification, Inference engine and Defuzzification.

Fuzzification: It transforms the crisp input variables (dS , dD) into fuzzy sets using predefined membership functions. These are the Input Variables:

Error (E): incremental conductance - Instantaneous conductance.

Change in Error (ΔE): How fast the error is changing

Inference Engine - Evaluate the fuzzy variables arrived from information feeds to apply a set of Fuzzy Rules on process. The linguistic variables used are NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), PB

(Positive big) which is shown in Table. 1. These rules are written in the form IF-THEN. E.g.:

IF ($E = 0$) AND ($\Delta E = 0$), THEN $\Delta D = 0$

IF E is Positive Small AND ΔE is Positive Small THEN (ΔD Negativity Small)

Defuzzification: The number calculated from the data collected by defuzzied methods like centroid or weighted average involves a crisp kind of representation. This side instructs the appropriate duty cycle of DC-DC converter.

Table. 1: 7x7 fuzzy rule base

Variable	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

3. Algorithm implementation

The steps involved in implementing the Inc-Fuzzy MPPT algorithm are as follows:

- i. **Initialization:** First, the system parameters are set as power line zone readings in a time t_0 with voltage and current knowledge knowing that these measurements can be translated into 5

fuzzy sets classes which represent error statuses producing these observations.

- ii. **Sampling:** Take the current (I) and voltage of PV array at some sampling interval. Calculate the power (P).
 - iii. **Increment Calculation:** Measure increments of current (ΔI) and voltage (ΔV).
 - iv. **Conductance Calculation:** Compute the incremental conductance ($\Delta I/\Delta V$) and instantaneously conductance ($-I/V$)
 - v. **Error Calculation:** Determine Error (E) (4) and change in error (ΔE).
- $$\text{Error } (E) = \frac{P(K) - P(K-1)}{V(K) - V(K-1)} \quad (4)$$
- Change in Error (ΔE) = $E(k) - E(K-1)$
- vi. **Fuzzification:** Fuzzified E and ΔE
 - vii. **Inference:** Applying fuzzy rules shown in Table. 1, for finding fuzzy output corresponding to the change in duty cycle (ΔD)
 - viii. **Defuzzification:** Make a crisp value for ΔD from fuzzy output.
 - ix. **Voltage Adjustment:** Make DC-DC converter duty cycle adjustment according to de-fuzzified output so that corresponding change in PV arrays and rectifier of wind turbine voltage can occur.
 - x. **Iteration:** Continuously sampling and adjustment process should be done to trace MPP under varying environmental conditions.

The Incremental Conductance-Based Fuzzy MPPT has a balanced alternative that combines the accuracy of IncCond with fuzzy logic's adaptability.

3.1 Voltage controller for bi-directional converter

The load voltage is regulated by using PI Controller. The load voltage is compared with the Reference voltage and the Error signal is given as an input to the PI Controller as shown in Fig. 2.

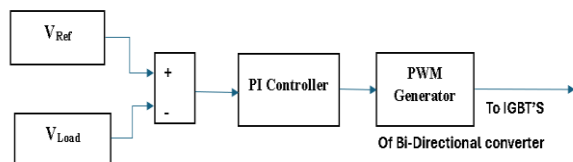


Fig. 2: Controller for Bi-Directional Converter

PI controller Minimizes the error, and the output of the PI Controller is given to the PWM generator. The Pulses output from the PWM generator is given to the IGBT Gates of the Bi-Directional Converter.

3.2 Inverter control

In a hybrid solar-wind system, the inverter plays a critical role in converting the DC power generated by solar panels and wind turbines into AC power suitable for grid integration or local use as shown in Fig. 3. The inverter is meant to ensure good conversion of power, stable and efficient operations and reliable interaction with the grid. These objectives can be attained through relevant techniques such as Parks transformation and current PI (Proportional-Integral) controller. dq0 Transformation (Parks Transformation): Converts the stationary $\alpha\beta$ frame into a rotating reference frame aligned with the grid or inverter frequency (5).

$$\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \\ I_0 \end{bmatrix} \quad (5)$$

Where θ is the angle of the rotating frame.

This reduces the three-phase system to a two-dimensional space, which makes it more controllable. It separates the control of active (d-axis) and reactive (q-axis) power, allowing a more straight forward and precise controlling process. The error between the desired current and the actual current is minimized by the PI controller to control the current in the dq0 reference frame (6).

$$I_{control}(t) = K_p \cdot e(t) + K_i \int e(t) dt \quad (6)$$

Where $e(t)$ is the error between the reference current and the actual current, K_p is the proportional gain and K_i is the integral gain. During this, K_p serves as the determinant of the controller's responsiveness. This means that it can rise to speed at a higher (K_p) but may also result in instability if it is too high. To eliminate any steady-state errors, K_i must be applied here. Proper tuning will help avoid excessive overshoot and oscillations. Applying Parks transformation helps convert three-phase AC currents into dq0 coordinates. To do this, the PI controller is used within the transformed space while regulating current through it.

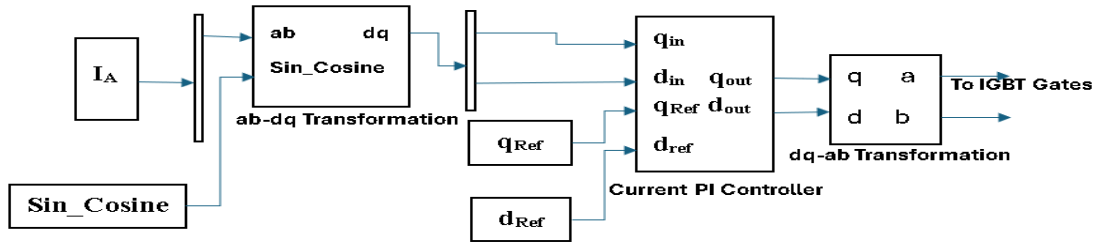


Fig. 3: Current PI controller for inverter

Then, we go back to the three-phase system for actual inverter operation from controlled $dq0$ signals (Inverse park’s transformation). The inverter efficiently manages power from solar panels and wind turbines together with battery storage and grid interaction. Continuously monitor system performance to ensure stability and efficiency. The parameters used for the test system, bidirectional converter and LC filter are presented in Table. 2, Table. 3 and Table. 4 respectively.

Table. 2: Parameters used Solar and Wind energy systems

Parameter	Rating
Inductance	0.1164Ω
Capacitance	$4.825 \times 10^{-5} \Omega$
Resistance	80 Ω
Duty Ratio	0.375

Table. 3: Parameters used Bi- Directional converter

Parameter	Rating
Inductance	0.1164Ω
Capacitance	$4.825 \times 10^{-5} \Omega$
Resistance	80 Ω
Duty Ratio	0.4

Table. 4: Parameters used for LC Filter

Parameter	Rating
Inductance	$6.6 \times 10^{-3} \Omega$
Inductance	$0.72 \times 10^{-3} \Omega$
Capacitance	$6.9 \times 10^{-6} \Omega$

4. Results and discussion

This work shows the performance enhancement of integrated solar wind hybrid and battery with grid using fuzzy based MPPT. The INC based fuzzy is used for extraction of maximum power for both solar panel and wind turbine. The SOC of the battery plays the major role for supplying the power to the AC Load with the changes in the Load.

- $I_{pv} < 0.5$ & $SOC < 10$ - Grid supplies Power to load
- $I_{pv} > 0.5$ & $SOC > 10$ - Hybrid system supplies power to load

The Above two conditions are very important in deciding that the power to be supplied to the Load which change with the time.

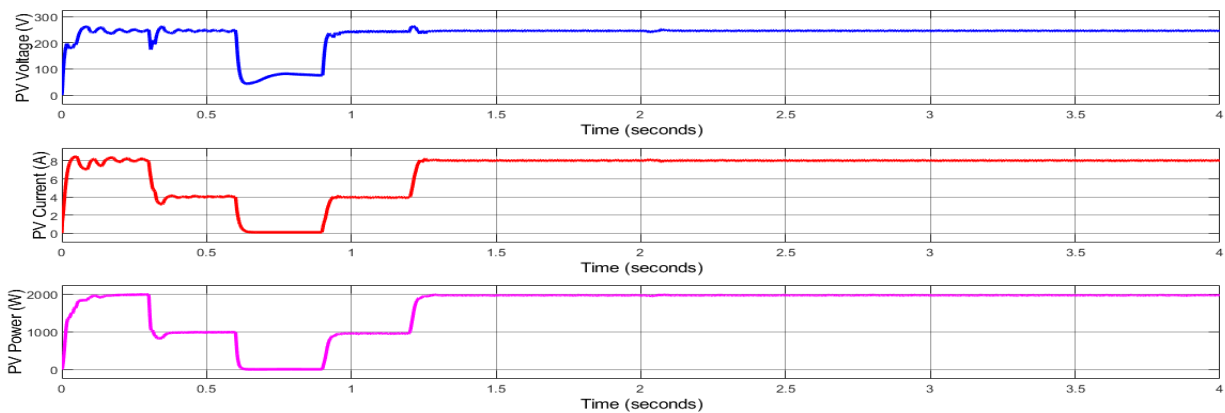


Fig. 4: Performance of PV voltage, PV Current and PV Power in different irradiance values

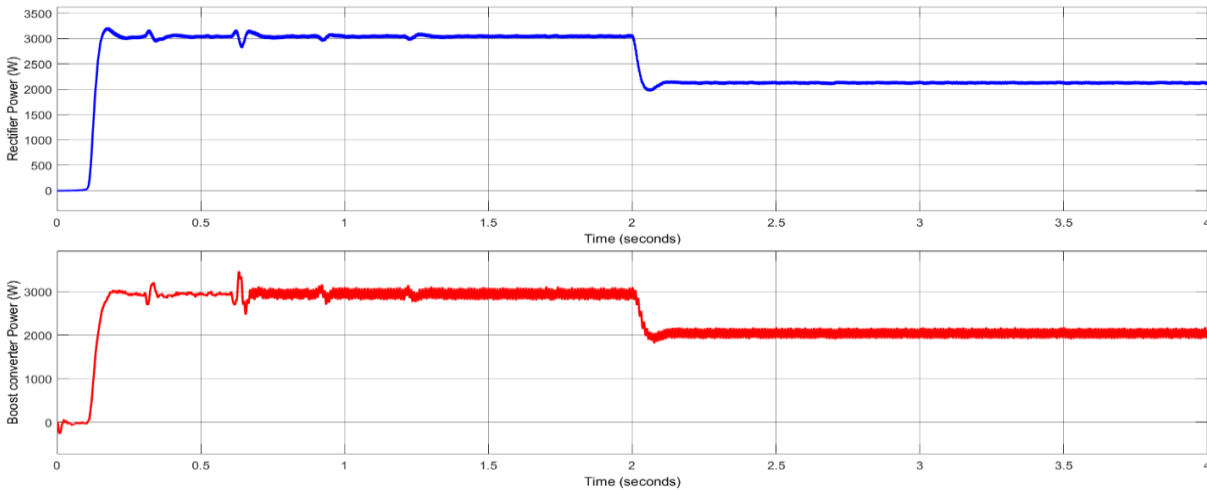


Fig. 5: Rectifier power and Boost converter power for different wind speeds

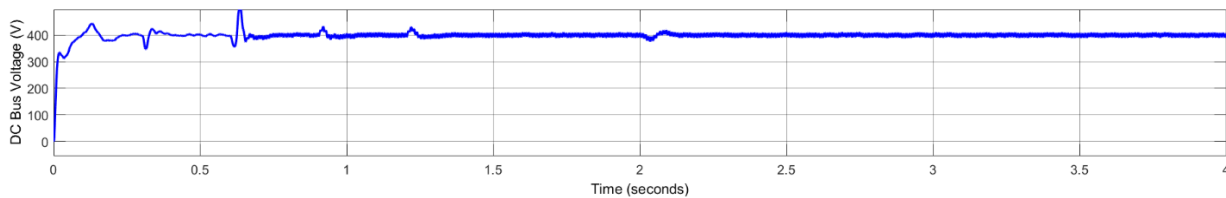


Fig. 6: Common bus voltage

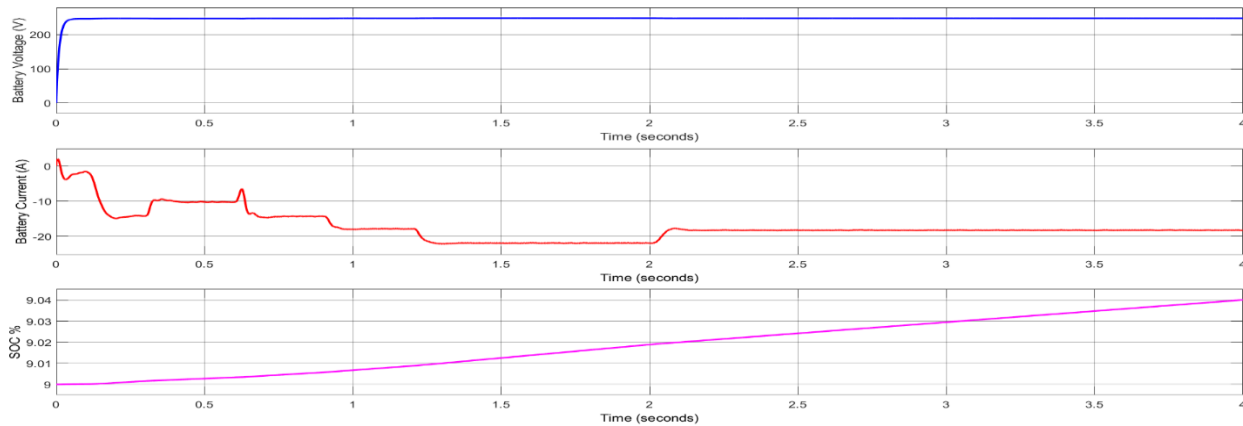


Fig. 7: Performance of Battery when SOC of the Battery is 9%

The PV irradiance is varied from 0sec to 2sec, where the 0sec to 0.3sec the irradiance is $1000W/m^2$ and the output power from PV is 2000W, the irradiance is decreased to $500W/m^2$ from 0.3sec to 0.6sec and the output power is decreased to 1000W again the irradiance is reduced to $100W/m^2$ from 0.6sec to 0.9sec and the output power is becoming almost 0W and from the 0.9sec to 1.2sec the irradiance is increased to $500W/m^2$ and the PV power is increased to 1000W and from the 1.2sec the irradiance is increased to $1000W/m^2$

maintaining the PV power is 2000W which is shown in Fig. 4. Different wind speeds are given to the turbine i.e 12m/s and 10.8m/s .when the wind speed is 12m/s then the rectifier output power is 3000W and after 2Sec the wind speed is decreased to 10.8m/s and the rectifier output power is also reduced to 2000W similarly the boost converter power also decreases as in Fig. 5. The common bus voltage is maintained at 400V DC. The boost converter output from every source like the PV, Wind and Battery is 400V shown in Fig. 6.

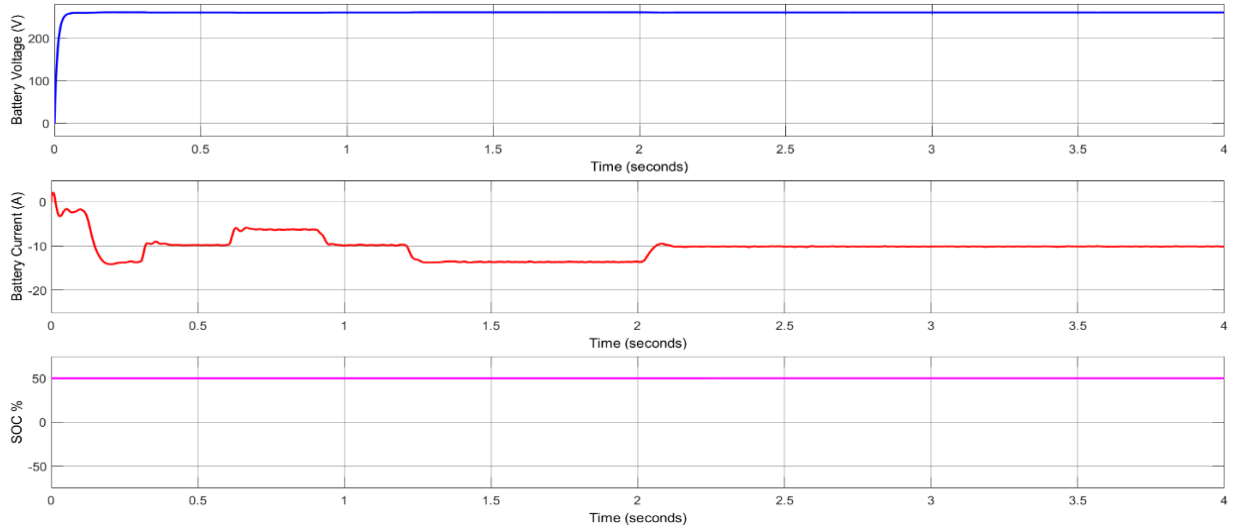


Fig. 8: Performance of battery when SOC of the battery is 50%

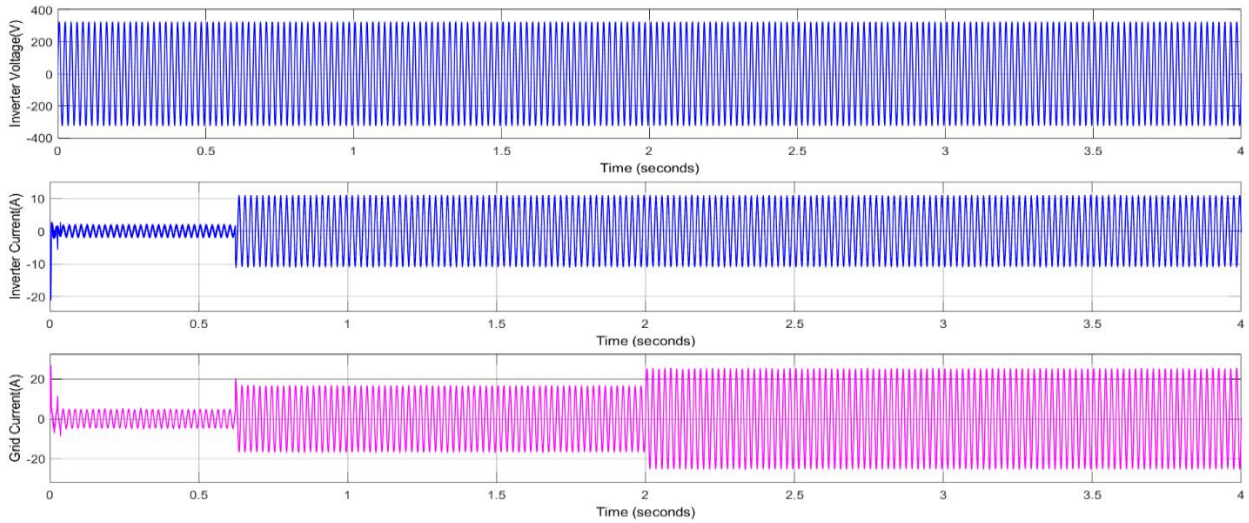


Fig. 9: Performance of Inverter voltage, Inverter current and Grid current when the SOC of the battery is 9%

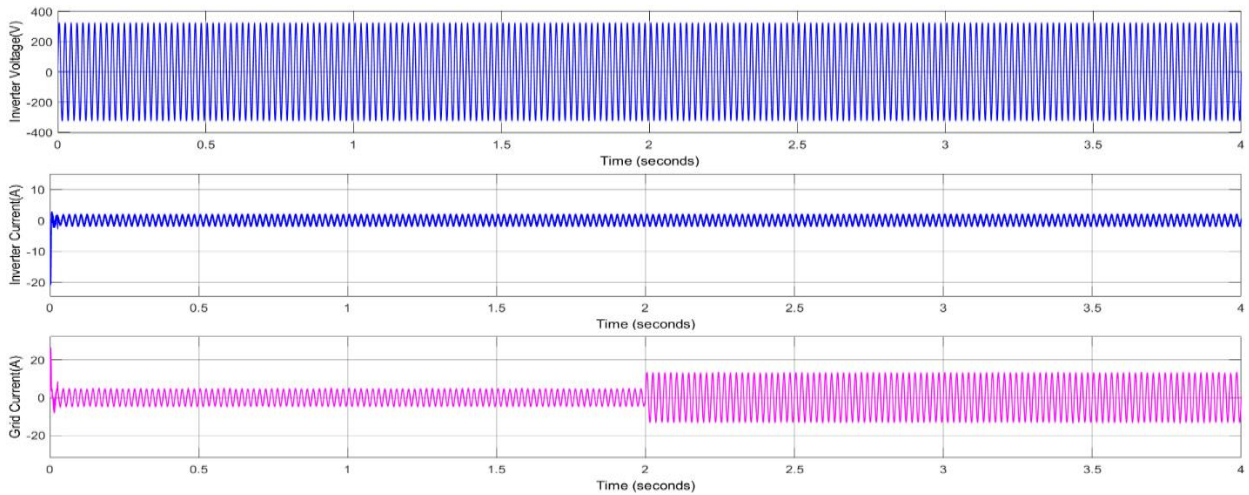


Fig. 10: Performance of Inverter voltage, Inverter current and Grid current when the SOC of the cattery is 50%

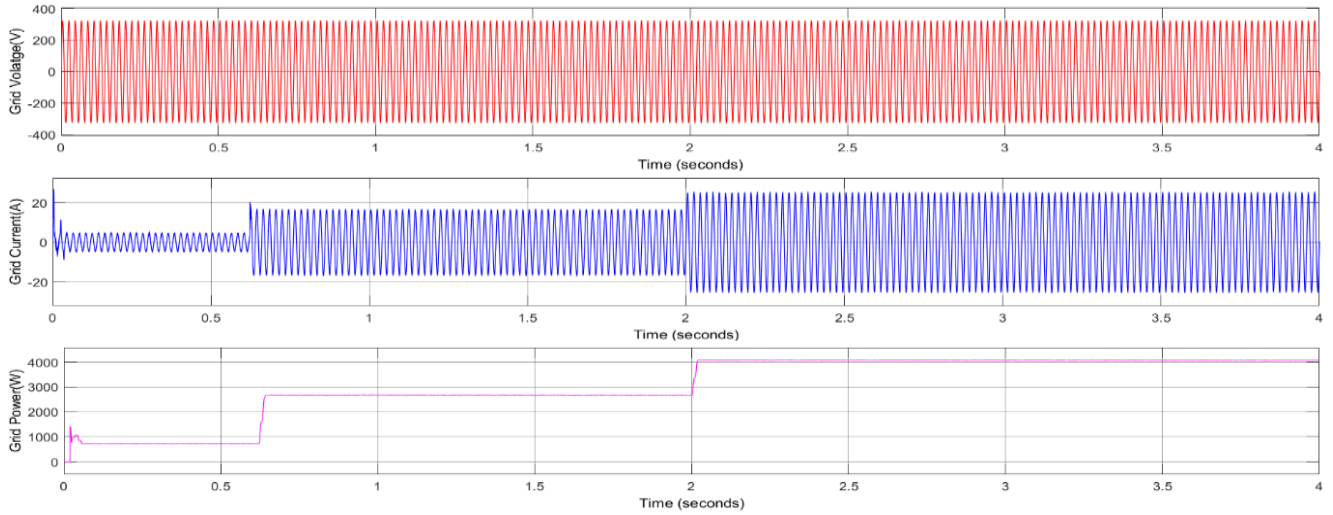


Fig. 11: Performance of Grid voltage, Grid current and Grid power when the SOC of the battery is 9%

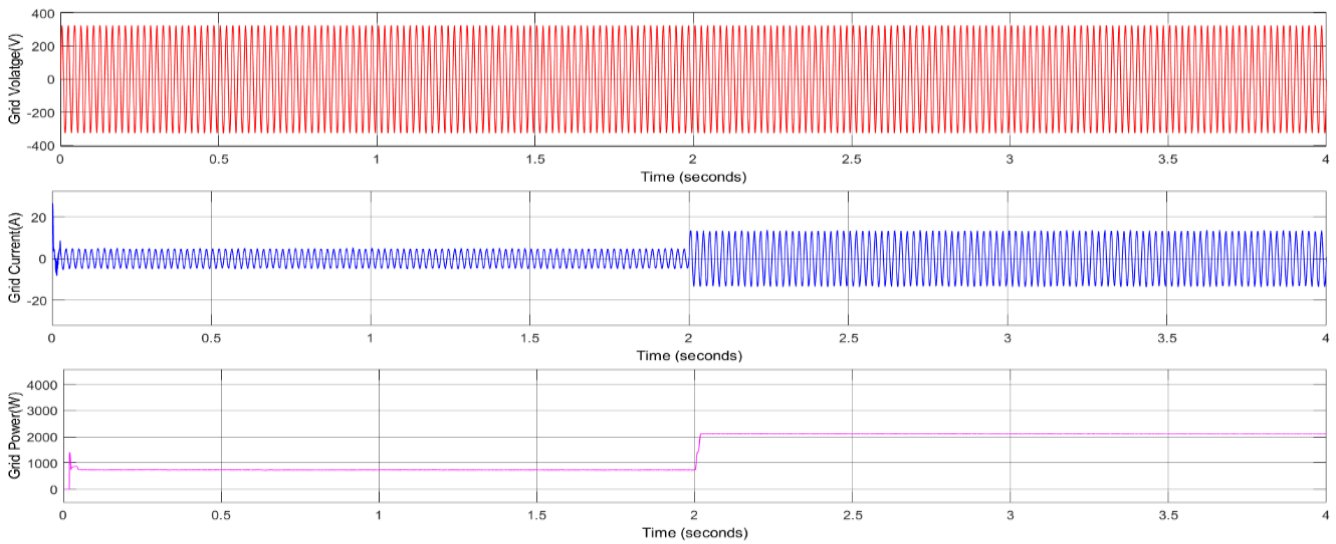


Fig. 12: Performance of Grid voltage, Grid current and Grid power when the SOC of the battery is 50%

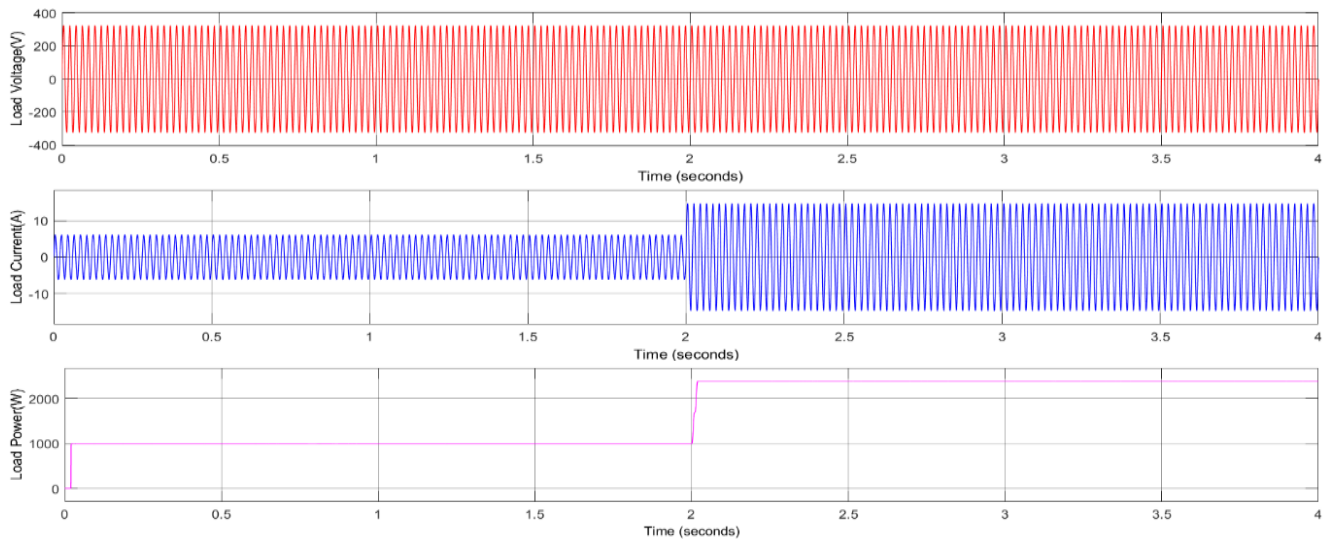


Fig. 13: Performance of Load voltage, Load current and load power

- In case-1 the SOC of the battery is maintained at 9% i.e. the discharged condition of the battery, that satisfies the condition-1 given to the inverter for the Load balancing between the grid and Hybrid system. Here in this the battery current is increased to -17A from -22A after 2 sec because the Hybrid system is maintaining constant voltage shown in Fig. 7.
- In case-2 the SOC of the battery is maintained at 50% i.e. the charging condition of the battery, that satisfies the condition -2. Here in this the battery current is increased to -10A from -14A after 2sec shown in Fig. 8.
- In case-1 the hybrid system is supplying power to load from 0sec to 0.6sec i.e. peak 2A. After 0.6 sec the PV Power almost becomes zero which satisfies the condition-1 of the inverter. After 0.6 sec the grid supplies the power to the load. When the grid is supplying the power to load the inverter peak current is 10A shown in Fig. 9.
- In case-2 the hybrid system is supplying power to the load with peak 2A of inverter current which Satisfies the condition-2 of the inverter shown in Fig. 10.
- In Case -1 the grid is supplying the power to the load as well as charging the battery. Initially the grid power is 700W from the 0sec to 0.6 sec. The grid power is increased to 2600 from 0.6 sec to 2sec because the power from the PV system is almost becoming Zero to feed the load as well as the battery charging. After 2sec the grid power is increased to 4100W because the Load is increased to 2400W, and Battery is still in discharged condition after the 2 sec also shown in Fig. 11.
- In Case-2 the grid receives the power of 700W from the 0sec to 2sec. After 2sec the power received is increased to 2200W which satisfies the condition-2 Given to the Inverter shown in Fig. 12.
- Fig. 13 shows the load is maintained 1000W from 0Sec to 2Sec and after 2Sec the Load is Increased from 1000W to 2400W and maintain constant from 2Sec. Even the Load is changing the stable and steady power is supplied by either grid or Availability of hybrid energy sources based on the conditions applied to the Inverter.

The comparison of the results obtained in the two cases is presented in Table. 5.

Table. 5: Differences between case-1 and case-2

Case-1	Case-2
The SOC of the battery is 9% i.e discharged condition and also the PV current is less than 0.5A at 0.6Sec then the power is not available in the hybrid system to supply AC Load, whereas the Grid is supplying the power to the load in this condition after 0.6sec and maintain the inverter current of 2A. Maintaining the load power of 1000W from 0Sec to 2Sec and 2400W from 2Sec	The SOC of the battery is 50% i.e charging condition and now hybrid system will supply power to AC Load, and excess power from hybrid system is fed to the grid and maintain the inverter current of 10A. Maintaining the load power of 1000W from 0Sec to 2Sec and 2400W from 2Sec

5. Conclusion

Integration of solar and wind energy systems with battery storage and grid assistance improves the overall efficiency and reliability of the renewable energy system. This is further enhanced by using a fuzzy logic-based MPPT system. Thus, the fuzzy-based MPPT technique can track MPPs arising due to several environmental conditions in faster and accurate ways. This adaptive approach might cope with the non-linearities and uncertainties of hybrid renewable systems and overcome the conventional MPPT algorithms drawbacks. This INC based Fuzzy helped to maintain the common bus Voltage 400V even though there are a change in the Irradiance and the Wind speed. The Two conditions used in inverter control helps to maintain the stable electrical power supply to the Load even changes in the Irradiation and wind speed as mentioned

Conflict of interest

The authors declared 'No conflict of interest'.

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