

Fuzzy Logic Mppt Controller for a Standalone PV/Battery Hybrid Energy System

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ABSTRACT

This paper describes the development and implementation of a hybrid energy system combining photovoltaic (PV) panels and battery storage (BS). This choice stems from the imperative need to overcome challenges posed by solar energy's intermittency, load variability, and efficient battery management. The proposed hybrid system incorporates a photovoltaic (PV) generator employing a fuzzy logic controller (FLC) based maximum power point tracking (MPPT) technique. The harnessed solar energy is then used to power a variable load connected to a battery, all orchestrated by a PI controller in a buck-boost configuration. The objective of this system is to optimize the utilization of solar energy and enhance the overall performance of the hybrid energy system. This research contributes to the advancement of renewable energy technologies, enabling efficient utilization of solar energy and improving the overall performance and reliability of hybrid energy systems. The Matlab/Simulink results show that the suggested PI controller delivers a stable DC bus with reduced chatter under quick irradiation and load changes.

I. Introduction

The increasing demand for clean and sustainable energy sources, coupled with the need to address environmental concerns, has led to the development of hybrid energy systems that combine multiple renewable energy technologies[1]. One promising approach is the integration of photovoltaic (PV) panels and battery storage systems (BSS). The efficient management and control of power flow between these components are crucial for optimizing energy utilization and system performance[2].

PV panels are widely recognized as a clean and abundant source of energy, converting sunlight directly into electrical power. However, the power output of PV panels is highly dependent on environmental factors such as solar irradiance and temperature. To address this challenge, the fuzzy logic controller is employed for MPPT, ensuring that the PV system operates at its maximum power output by continuously adjusting its operating point

[3]. In the hybrid energy system, battery storage plays a critical role in capturing and storing excess energy generated by the PV panels for later use. The PI controllers in the buck-boost configuration regulate the power flow between the PV panels and the battery system, allowing for efficient energy conversion and management[1]. The PI controllers ensure optimal operating conditions, avoiding power losses and maximizing energy transfer[4].

The integration of PI controllers in the buck-boost configuration and a fuzzy logic controller for MPPT offers several advantages. It enables efficient utilization of solar energy, improves the stability and reliability of the hybrid energy system, and enhances overall energy conversion efficiency. The combination of these control strategies ensures optimal power management and maximizes the power output from the PV system[5]. This research aims to contribute to the advancement of hybrid energy systems by proposing an integrated solution that combines PV panels, battery storage, PI controllers in a buck-boost configuration, and a fuzzy logic controller for MPPT. The effectiveness and performance of the proposed system will be evaluated through experimental analysis, providing valuable insights into the feasibility and benefits of this hybrid energy system configuration.

In conclusion, the integration of PV panels and battery storage with PI controllers in a buck-boost configuration, along with a fuzzy logic controller for MPPT, offers a promising solution for efficient and reliable hybrid energy systems. This research aims to address the challenges associated with PV system power fluctuations, optimize energy utilization, and contribute to the advancement of sustainable energy technologies.

II. System Description

The hybrid energy system described in Fig 1 combines photovoltaic (PV) panels and battery storage, utilizing PI (Proportional-Integral) controllers in a buck-boost configuration and a fuzzy logic controller for maximum power point tracking (MPPT) in the PV system. The system aims to optimize energy utilization, enhance stability, and improve overall performance.

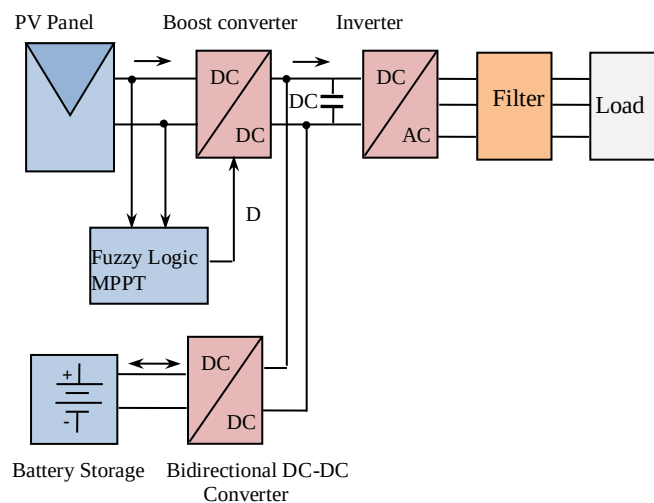


Figure 1. The hybrid energy system

The PV panels are responsible for converting sunlight into electrical energy. The generated power is then either consumed immediately or stored in the battery for later use. The PI controllers, implemented in the buck-boost configuration, ensure efficient power conversion and management between the PV panels and the battery system. They regulate the power flow, optimizing the charging and discharging processes, and maintaining optimal operating conditions.

To extract the maximum power from the PV panels, the fuzzy logic controller is employed for MPPT. This controller continuously adjusts the operating point of the PV system based on real-time environmental conditions

such as solar irradiance and temperature. By dynamically tracking the maximum power point, the fuzzy logic controller maximizes the energy extraction efficiency of the PV panels.

The battery storage plays a crucial role in the system. It captures and stores excess energy generated by the PV panels during periods of high generation or low demand. The stored energy can then be utilized during periods of low generation or high demand, ensuring a continuous and reliable power supply.

III. Modelling of Hybrid Energy System

This section goes over the modeling of HES components. This covers the solar PV array as well as the battery storage.

III.1. Modelling of PV module

A solar PV system directly turns solar energy into electricity. The single diode model, as illustrated in Fig 2, is the most basic PV model. [6][7]

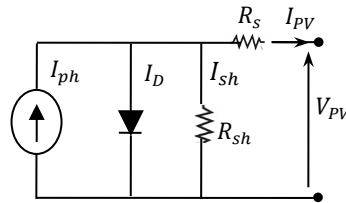


Figure 2. The Equivalent circuit of the PV cell.

The relationship between voltage (V_{PV}) and current (I_{PV}) in a single diode model with a given temperature and irradiance is stated in Eq. (1) [8], which holds true for a PV cell, a module, and an array.

$$I_{PV} = I_{ph} - I_D$$

$$= I_{ph} - I_0 \left\{ \exp \left[\frac{(V_{PV} + R_s I_{PV})}{a} \right] - 1 \right\} - (V_{PV} + R_s I_{PV}) / R_{sh} \quad (1)$$

where I_{ph} represents the produced photocurrent, I_0 represents the reverse saturation current, I_d represents the diode current, I_{sh} represents the shunt current, R_s represents the series resistance, R_{sh} represents the shunt resistance, and a represents the curve fitting parameter. The R_s and R_{sh} values have been overlooked. The current analysis disregards the influence of R_{sh} [6]. Eq. (1) is thus adjusted as follows.

$$I_{PV} = I_{ph} - I_0 \left\{ \exp \left[\frac{(V_{PV} + R_s I_{PV})}{a} \right] - 1 \right\} \quad (2)$$

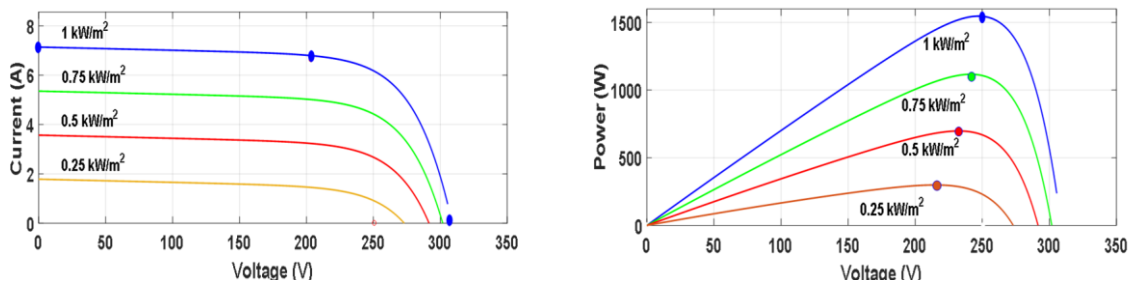


Figure 3. PV characteristic I(V) and P(V)

The manufacturer's equations stated in [2] assist in computing the values of I_{ph} , I_0 , a , and R_s at reference circumstances or standard test conditions (STC). Based on the equations presented in [2] these reference values

may then be used to calculate the actual values of I_{ph} , I_0 , a , and R_s for a given irradiance (G) and ambient temperature (T_a).

By analysing the (current-voltage) and (power-voltage) curves of PV systems, Fig. 3 elucidates the nonlinear nature of their operation by (1) and (2). The MPP is computed for various meteorological conditions by utilising these characteristic contours.

III.2. Modling of battery storage system

For the purpose of modelling the battery, the SOC model was utilised. This model approximates the state of charge (SOC) at moment $t + 1$ by utilising the SOC at instant t , which is supplied by [9].

$$SOC(t + 1) = SOC(t) \cdot \left(1 - \frac{\sigma \Delta t}{24}\right) + \left(\frac{I_{bat}(t) \cdot \Delta t \cdot \eta_{bat}}{C_{bat}}\right) \quad (3)$$

In the equation, σ represents self-discharge rate, I_{bat} represents charge/discharge current, η_{bat} represents battery efficiency, Δt represents time interval, and C_{bat} represents battery capacity in Ah. Fitting a curve for the voltage polynomial in terms of SOC gives the battery's floating charge.

$$V_{bat} = A(SOC)^3 + B(SOC)^2 + C(SOC) + D \quad (4)$$

The values of A , B , C , and D , which are functions of battery current, are obtained through the least squares method of fitting the equations to the battery performance data supplied by the manufacturer.

IV. The Methodology Proposed

IV.1. Design of an MPPT Controller Utilising Fuzzy Logic

As previously mentioned in Fig 3, the PV system operates in a non-linear fashion [10]. Developing a conventional controller to manage a non-linear system comprising various parameters (e.g., damping, regulation) is typically challenging. When modeling nonlinear systems, fuzzy logic emerges as the most suitable approach. Designing a Fuzzy Logic Controller (FLC) requires a number of inputs and specialized knowledge [11]. The FLC defines the fuzzy principles in accordance with the inputs. A fuzzy logic controller (FLC) consists of three primary components: the fuzzifier, which transforms the input values from their corresponding crisp values to fuzzy sets; the inference system, which maps and applies fuzzy rules derived from the fuzzy sets to produce outputs that are also in the form of fuzzy sets; and the defuzzifier, which converts fuzzy sets back to crisp values using various conversion theorems, such as the center of area and center of gravity (COG) [12],[13]. The FLC model is illustrated in Fig 4.

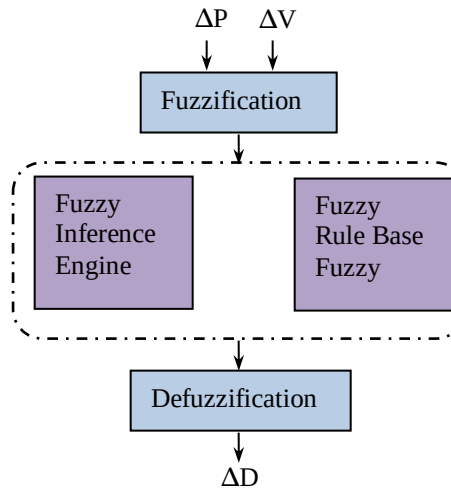


Figure 4. Fuzzy logic model

As previously mentioned, the FLC requires multiple inputs. Therefore, the initial step is to choose and establish the inputs [14]. Changes in PV array voltage (ΔV) and power (ΔP) are regarded as inputs in this study, whereas duty cycle (ΔD) changes are regarded as outputs of FLC. ΔP , ΔV , and ΔD are described as

$$\Delta P = [P(k) - P(k - 1)] \times Y_1 \quad (5)$$

$$\Delta V = [V(k) - V(k - 1)] \times Y_2 \quad (6)$$

$$D(k + 1) = [D \pm \Delta D] \times Y_3 \quad (7)$$

This study employs a variety of linguistic variables, the specifics of which are provided in Table I.

Table 1. Type linguistic variables of FLC

Change in Power (ΔP)		Change in voltage (ΔV)		Change in Duty cycle (ΔD)	
NB	Negative Big	NB	Negative Big	NB	Negative Big
NM	Negative Medium	NM	Negative Medium	NM	Negative Medium
NS	Negative Small	NS	Negative Small	NS	Negative Small
ZE	Zero	ZE	Zero	ZE	Zero
PS	Positive Small	PS	Positive Small	PS	Positive Small
PM	Positive Medium	PM	Positive Medium	PM	Positive Medium
PB	Positive Big	PB	Positive Big	PB	Positive Big

A multitude of Membership Functions (MFs) are documented in the literature; however, based on their past performance and expert opinion [15], trapezium methods have been determined to be the most effective. MFs for the input variables (ΔV and ΔP) are illustrated in Fig 5 and 6, whereas MFs for the output variable (ΔD) are depicted in Fig 7.

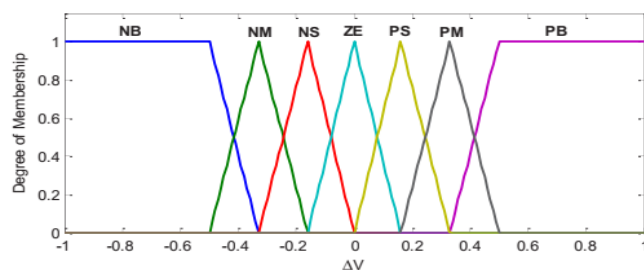


Figure 5. MF for input variable ΔV

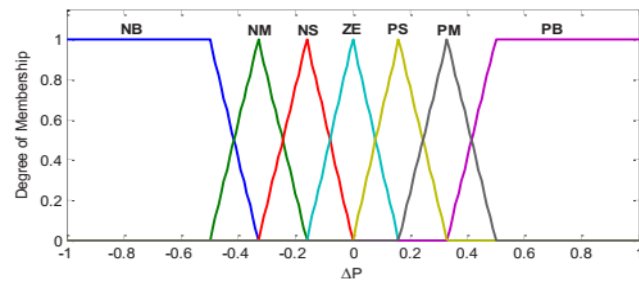


Figure 6. MF for input variable ΔP

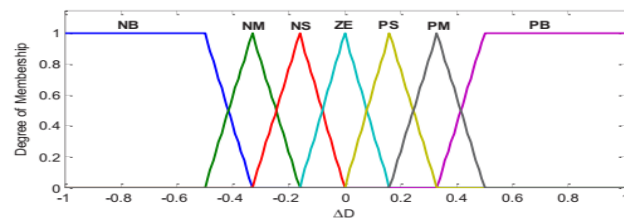


Figure 7. MF for output variable ΔD

Fuzzy principles are essential for the development of fuzzy logic controllers with enhanced performance. The relationship between input and output is readily comprehensible through the use of surface waveforms. The FLC's surface waveform is illustrated in Fig 8. In addition to being formulated on the basis of expert opinion, the rules are selected through an examination of error manipulations and system parameters. The IF-THEN condition that governs the proposed FLC is detailed in Tab II. FLC is designed utilizing the Mamdani model in this study.

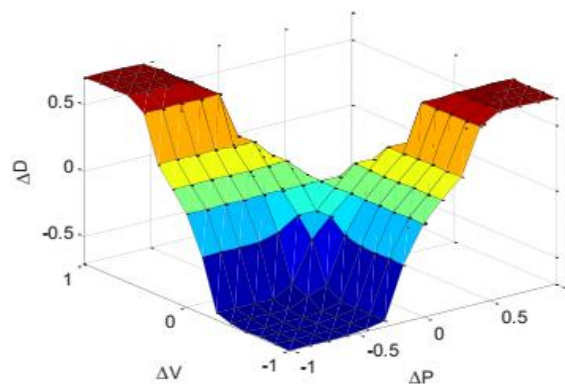


Figure 8. FLC Input-Output surface waveform

Table 2. Rule base of FLC

ΔP	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	ZE	PS	PM	PB
NM	NB	NM	NS	ZE	PS	PM	PM
NS	NS	NS	NS	ZE	PS	PS	PS
ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE
PS	PS	PS	PS	ZE	NS	NS	NM
PM	PM	PM	PS	ZE	NS	NM	NB
PB	PB	PM	PS	ZE	NM	NB	NB

In general, as the quantity of rules increases, so does the computational expense of the system. For optimal performance, a complex nonlinear system can only be modeled and controlled with a large number of principles.

This research thus employs 49 principles as opposed to the originally intended 25. It is believed that the power-voltage characteristics curve follows the optimal MPP. The FLC apparatus detects alterations in the input (ΔP & ΔV) and produces an output (ΔD) in response. The precise duty cycle produced by PMS and supplied to DC/DC boost converters in the form of a PWM signal is denoted by D . The output D is calculated mathematically utilizing Eq (8) [16][17].

$$D = \frac{\sum_{j=1}^k D_j \mu_A(D_j)}{\sum_{j=1}^k \mu_A(D_j)} \quad (8)$$

In the given context, D_j represents the j th input value and denotes the centre of max-min composition at the output MFs. $\mu_A(D_j)$ signifies the maximum of the j th membership function. Several studies propose a procedure in which the crisp value D is added to the preceding duty ratio value before its transmission to the MOSFET's gate. In contrast, the precise value D is transmitted directly to the IGBT's gate in this investigation; the FLC functions exceptionally well.

V. Strategy for battery control

To achieve the necessary power output, it is crucial to control the electric current produced by the battery. It's important to consider the limitations associated with the current charging and discharging processes, as well as the overall state of charge (SOC) boundaries. The following factors need to be evaluated based on the SOC [2].

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (9)$$

The abbreviations SOC_{max} and SOC_{min} represent the upper and lower limits of permitted storage capacities, respectively. The battery plays a vital intermediary role connecting the photovoltaic system and the load. Essentially, it functions in two discrete phases: the process of charging and discharging. The Buck-Boost Controller regulates the DC voltage through the utilisation of two switches, designated as Q_1 and Q_2 .

Voltage as desired and to ensure that the battery is charged or discharged in accordance with the PV system. The control principle is illustrated in detail in Fig 9.

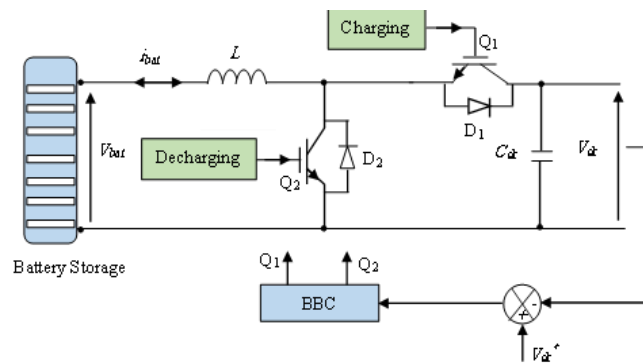


Figure 9. Bidirectional DC/DC converter control principle.

In general, when power is either lost or gained, the battery functions as either a burden or a source of power. Charges and discharges are regulated by the weather in accordance with predetermined thresholds. In the present analysis, initially, excess power is provided to the battery bank as a reaction to conditions of elevated power, prior to the bank surpassing its maximum storage capacity [18]. The control coordination between the PV and battery is illustrated in Fig. 10 through a flowchart. In this coordination, the battery maintains its minimum and maximum SOC limits at 0.2 and 0.6, respectively [2].

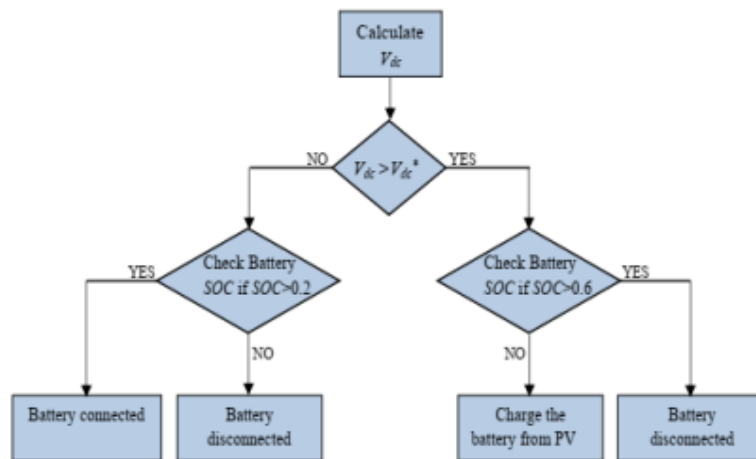


Figure 10. DC link voltage control algorithm

VI. PI controller

The control scheme of the PI controller for the bidirectional converter is illustrated in Fig 11 [19]. The bidirectional buck-boost converter is regulated by two cascaded PI controllers, which regulate the interior current while controlling the outer voltage. The error is generated by comparing the DC bus voltage reference V_{dc}^+ with the sensed DC bus voltage V_{dc} . The PI controller mitigates this error and generates the current reference I_{ref} . The current through this reference must be restricted to the utmost permissible levels for charging and discharging $[I_{batmax}; I_{batmin}]$ using the battery current regulation function. Current restrictions are contingent on battery ratings. By comparing the current reference with the actual battery current I_{bat} and fine-tuning the error once more, complementary pulses are generated to operate the switches $Q1$ and $Q2$.

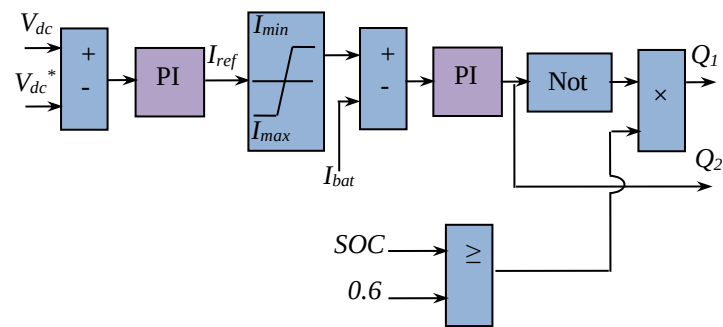


Figure 11. Cascaded PI controller for bidirectional converter.

VII. Simulation results and discussion

Matlab/Simulink implements the control loop with $T_s = 10^{-5}$ s sampling. Tabs 3 and 4 summarise PV and battery system parameters.

Table 3. PV Array parameters

Components	Ratings values
Module Type	Sanyo HIP-225HDE1
Number of Cells	60
Series module	06
Parallel module	06
V_{oc} , I_{sc} , V_{mmp} , I_{mmp}	41.79V, 7.13A, 33.9V, 6.63A
R_s , R_p , I_{sat} , I_{ph} , Q_d	00.204 Ω , 1830.7 Ω , 3.0815e-07A, 7.145A, 1.6

Table 4. Battery parameters

Components	Ratings values
Battery type	Lead-Acid
Nominal voltage	300 V
Capacity rating	6.5 Ah
Initial state of charge	60%

Fig 12 illustrates the change in the power load from 2000 W to 4000 W between 2 and 3 s. This is to determine the robustness of the controller.

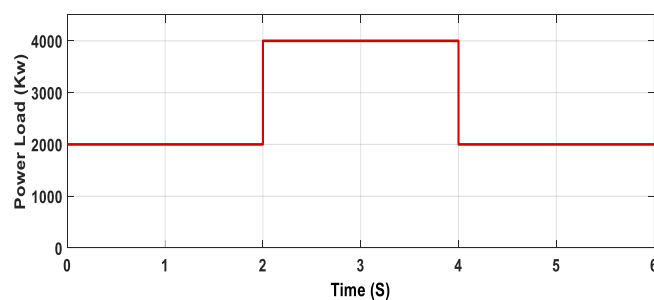


Figure 12. Power oad

Fig 14 shows that PV power production always reaches its maximum with varying irradiance (G), satisfying the first control target.

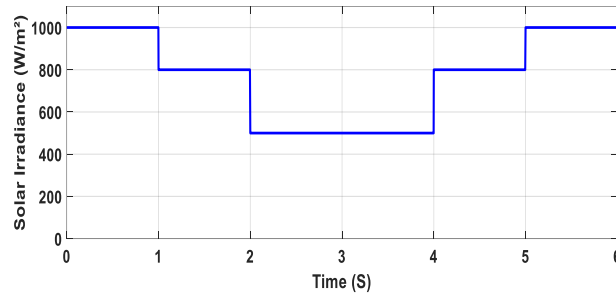


Figure 13. Irradiance variations

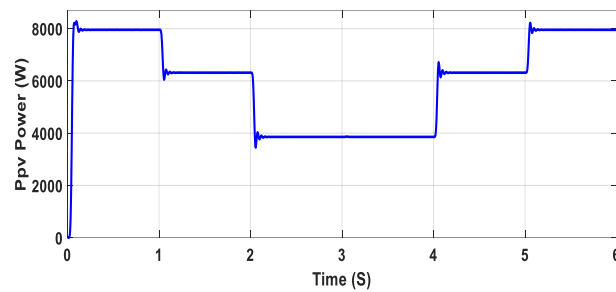


Figure 14. Variable of Maximum PV power output.

By sensing the PV module's current Fig. 15 and voltage Fig. 16, the MPPT FLC controller computes the duty ratio necessary to supply power to the boost converter.

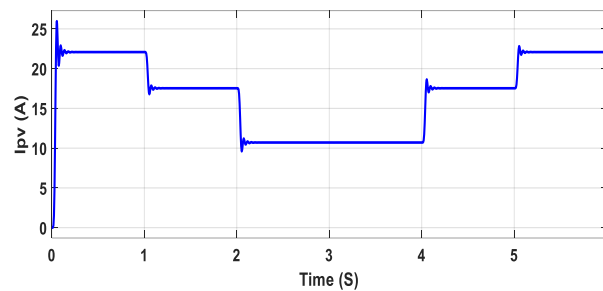


Figure 15. Output Current of PV array

As indicated in Tab 3, the maximal output power of the PV array at STC is 8000 W. From $t = 0$ s to $t = 1$ s, when solar irradiance is 1000 W/m², the PV output power is equivalent to its maximal value of 8000 W, as shown in Fig 14. Likewise, verification is possible for additional instants as well.

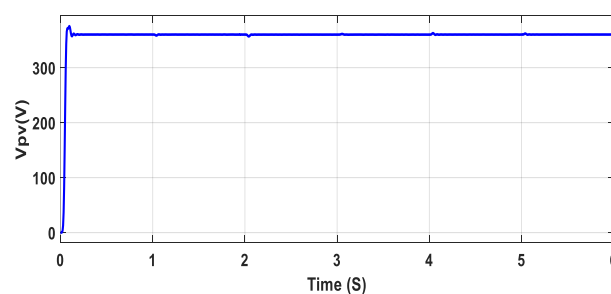


Figure 16. Output voltage of PV array.

The second objective is achieved when a constant DC link voltage V_{dc} is maintained through a current sharing mechanism between the PV array and battery bank in the presence of variable solar irradiance Fig. 17.

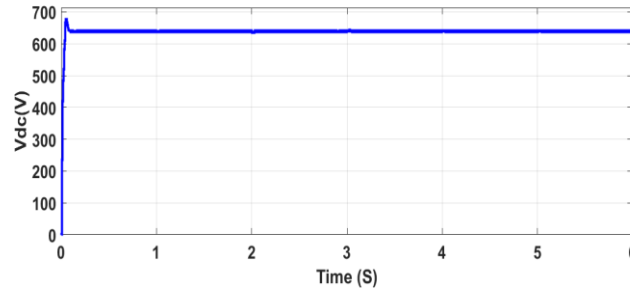


Figure 17. DC link voltage of PV/Battery system employing PI controllers

In order to evaluate the robustness of the proposed controller, a DC link fixed at 650 V was utilised to observe load and irradiance variations. The response of the PI controllers was a factor in this investigation. The DC link voltage, as illustrated in Figure 17, exhibits minimal variation despite the substantial time lag between PV and load adjustments that is recouped by the battery see Fig 18.

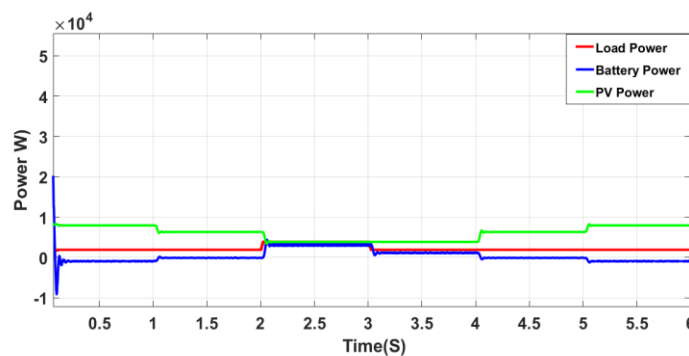


Figure 18. Curves of power distribution for photovoltaics, batteries, and load

Furthermore, as illustrated in Fig 18, the output of the BBC controller is highly satisfactory. This is because the battery bank power fluctuates (charges/discharges) in order to preserve the system's power balance amidst diverse irradiance and load circumstances. In practice, should the AC load power exceed the PV power generated, the BBC controller is configured to release the battery power into the AC load. Additionally, the controller can recharge the battery when the demand power is less than the generated PV power.

Fig 19 illustrates that the SOC begins at 60%, decreases during the transitional regime to 0.2 S, and then increases to 1 S during the charging period. The discharge is then limited to 4 S (in the case of a decreasing PV power and an increasing power demand). Ultimately, it is re-charged in the event that the PV power increases and the power consumption decreases.

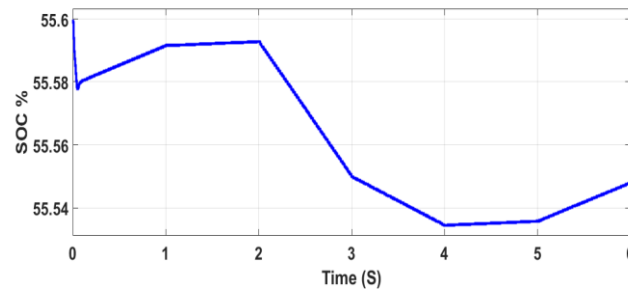


Figure 19. State of Charge SOC of the battery

Fig. 20 illustrates the current and voltage waveforms of the load's inverter when PI control is implemented.

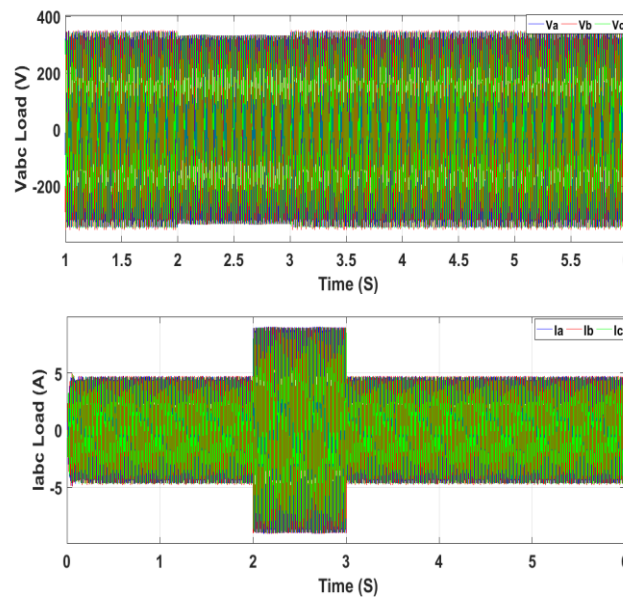


Figure 20. The output phase current and inverter voltage.

VIII. Conclusion

For optimal power receipt from a PV array regardless of the weather, a Fuzzy Logic Controller (FLC) MPPT controller is engineered. The system that emerges possesses the ability to precisely and swiftly monitor MPPs while avoiding steady-state oscillations.

This paper presents a study that examines the performance and robustness of PI controllers used to regulate the DC link voltage in a hybrid system consisting of a PV and battery system. Various variations in solar irradiance and electrical demand were evaluated.

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