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DESIGN OF AN EFFICIENT POWER MANAGEMENT SYSTEM FOR SOLAR-POWERED UAVs: A SYSTEMATIC APPROACH

***[1]Ter, K. P., [1]Yakubu, M. S., [2]Momoh, M. O., [1]Abbe, G. E., [2]Agov, T. E. and [3]Alioke, O. C.**

[1]Aerospace Engineering Department, Air Force Institute of Technology, Kaduna State, Nigeria
[2]Mechatronics Engineering Department, Air Force Institute of Technology, Kaduna State, Nigeria
[3]Computer Engineering Department, Ahmadu Bello University, Zaria, Kaduna State, Nigeria

*Corresponding authors' email: Kumaterpeter@gmail.com

ABSTRACT

As the demand for sustainable and efficient energy sources increases, integrating solar power into UAV operations presents a viable solution. Conventional MPPT controllers for solar-powered UAVs suffer from slow response times and inefficiencies under dynamic environmental conditions. This study proposes an enhanced power management system integrating FLC with MPPT for superior energy efficiency. The proposed power management design is achieved with the implementation of the Perturb and Observe (P and O) algorithm coupled with a Proportional-Integral (PI) controller to achieve Maximum Power Point Tracking (MPPT). The P&O algorithm was chosen for its simplicity and widespread adoption in MPPT applications, while PI control ensures stable convergence to the MPP. The integration of FLC further improves adaptability in fluctuating irradiance conditions. This approach ensures that the UAV operates at optimal power output levels under varying environmental conditions, specifically temperature solar irradiance. Additionally, a Fuzzy Logic Control (FLC) mechanism is employed to dynamically adjust the power output based on real-time data, ensuring optimal performance and stability. The results gotten from the simulations show that the FLC and the PI based on P & O algorithm returned a settling time of 0.01 seconds and 0.45 seconds respectively. The result showed that the fuzzy logic controller achieved a settling time 97% faster than the PI based on P & O algorithm. This research contributes to the development of more sustainable UAV technologies, paving the way for broader applications in various fields, including environmental monitoring and disaster response.

Keywords: Power Management, Fuzzy Logic Control, UAV, Solar, MPPT, PID

INTRODUCTION

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have witnessed an exponential rise in their applications across various domains including surveillance, agriculture, infrastructure inspection, and environmental monitoring (Del Cerro et al., 2021). However, the limited flight endurance of the conventional UAVs can significantly hamper its flight time and operational range. With the increasing demand for extended flight durations and autonomous operations, there is a growing interest in developing sustainable power solutions for UAVs (Boukoberine et al., 2019; Mohsan et al., 2022). Among these, solar energy presents a promising avenue due to its abundance and environmental friendliness.

The power management system is a critical component of solar-powered unmanned aerial vehicles (UAVs) as it regulates the energy flow from the solar panels to the propulsion system and energy storage units. Efficient power management ensures optimal performance, extended flight endurance, and reliable operation of the UAV (Gang & Kwon, 2018).

To effectively supply the UAV propulsion system with the necessary power from photovoltaic and other power sources, an energy management system (EMS) is required (Wu et al., 2018). The Maximum Power Point Tracking (MPPT) design is proposed utilizing a boost-converter topology. A closed-loop microcontroller-based control system monitors the power of the photovoltaic cells, and the Pulse Width Modulator (PWM) signal of the boost converter continuously adjusted to extract maximum power. The MPPT is used to charge the Lithium-ion Polymer battery and feed the electrical load of the unmanned aircraft.

Energy management plays a crucial role in achieving extended endurance for solar-powered Unmanned Aerial Vehicles (UAVs). Current studies in energy management primarily focus on natural energy harvesting and task-oriented path planning. Gao et al. (2023) optimized energy consumption during the climb and glide stages by exploring variable climb speeds and glide powers. It achieved this by establishing fitness functions for both the climb and glide stages, considering the maximum climb speed and glide power limits of the aircraft. It employed the particle swarm optimization (PSO) algorithm to solve the problem, resulting in significant energy savings of over 68% in the climb stage and 4.8% in the glide stage. To meet the demand for long-haul flights, this study suggests an energy-management plan based on an examination of optimization trends. The results of this study can be a useful guide for high-altitude flights that take longer than expected.

Murdoch, (2013) proposed a maximum power point tracking (MPPT) circuit for an Unmanned Air Vehicle. A boost converter topology for the utilization design of the MPPT was proposed. A closed-loop microcontroller-based control system was used to monitor the power of the photovoltaic cells, and the PWM signal of the boost convert was continuously adjusted to extract maximum power. The MPPT was used to charge the lithium-ion polymer battery and feed the electrical load of the unmanned aircraft.

An unmanned aerial vehicle (UAV) with a 200W class, low-speed, long-endurance design utilizes solar cells, a fuel cell, and a battery pack as its power sources. Lee et al. (2014) implemented an active power management approach to regulate the power output of each source based on the power supply and demand, in contrast to the passive method where power sources generate power based on their inherent characteristics. The power management system (PMS) under active management controlled the power output from each source. During the 3.8-hour flight test of the UAV with a PMS onboard, the active PMS demonstrated its feasibility by effectively managing the power sources within their operational limits and maintaining a target state-of-charge of 45% while responding to the various conditions associated with the power required. Moreover, the study involved examining the benefits, strengths, and weaknesses of employing an active power management approach in contrast to a passive method by analysing flight test findings alongside a power simulation of the latter.

Shiau et al. (2008) designed a solar power management system (SPMS) for an experimental unmanned aerial vehicle (UAV). The system provided the power required for the onboard electronic systems on the UAV. The power management system consisted of the maximum power point tracking (MPPT), the battery management, and the power conversion stages (Joseph & Dada, 2018). The MPPT stage attempted to obtain the maximum power from the solar cell panels. The battery management stage monitors and controls the charge and discharge processes of the Li-Ion polymer battery modules. The last stage was for power conversion that consisted of dc/dc synchronous buck converters used to generate +5 V and +12 V powers for the on-board computers and other electronic circuitries.

When comparing the performance of the Perturb and Observe (P&O) Algorithm for Maximum Power Point Tracking (MPPT) against other algorithms such as Incremental Conductance (IC), Artificial Neural Network Based (ANN-MPPT) and hybrid approaches, the following observation were made and also represented in
(Ubadike et al., 2024; Abouzeid et al., 2024; Boukoberine et al., 2019; Dolara et al., 2009; Sarang et al., 2024; Wu et al., 2018; Xu et al., 2022).

P&O offers a simpler and cost-effective approach to MPPT.

IC gives better accuracy when implemented in a dynamic environment.

ANN based MPPT algorithms produce higher efficiency and adaptability when compared with other approaches, however, it comes with a higher computational cost.

Hybrid MPPT approaches combine the best features in a single algorithm but result in a more complex and expensive system.

Table 1: MPPT Algorithm Comparison

S/N	Algorithm	Efficiency	Response Time	Complexity	Cost	Performance in Dynamics
1	P&O	94%-97.8%	Fast (~0.322 s)	Low	Low	Poor
2	IC	98.5%	Moderate (~0.326 s)	Moderate	Moderate	Good
3	ANN-MPPT	98%-98.6%	Fast (~1.3 s)	High	High	Excellent
4	Hybrid Approaches	98%-99%	Depends on combination	Very High	Very High	Excellent

MATERIALS AND METHODS

The developed diagram (Figure 1) for the PV system includes power and control and the control circuit. The power circuit has a solar DC link, boost converter and the load. The control circuit varies the voltage and current sensed from the PV solar (Table 2) then used to implement the MPPT. The output of the MPPT generates the reference value, this reference value is compared with the actual PV solar voltage to find the error which then feeds the PID controller, the output of the PID controller will gain the required duty ratio for the PWM generation, the duty ratio then compared with a carrier signal and given to the terminal of IGBT as a control signal.

Table 2: Parameters of the Solar Array

S/N	Quantity	Unit	Value
1	Maximum Power	P_{max}(W)	56.25
2	Current at MPP	I_{mp}(Ampere)	1.5
3	Voltage at MPP	V_{mp}(Voltage)	37.5
4	Short Circuit Current	I_{scc}(Ampere)	1.73
5	Open Circuit Voltage	V_{oc}(Voltage)	45.6
6	Cells per Module	Ncell	60

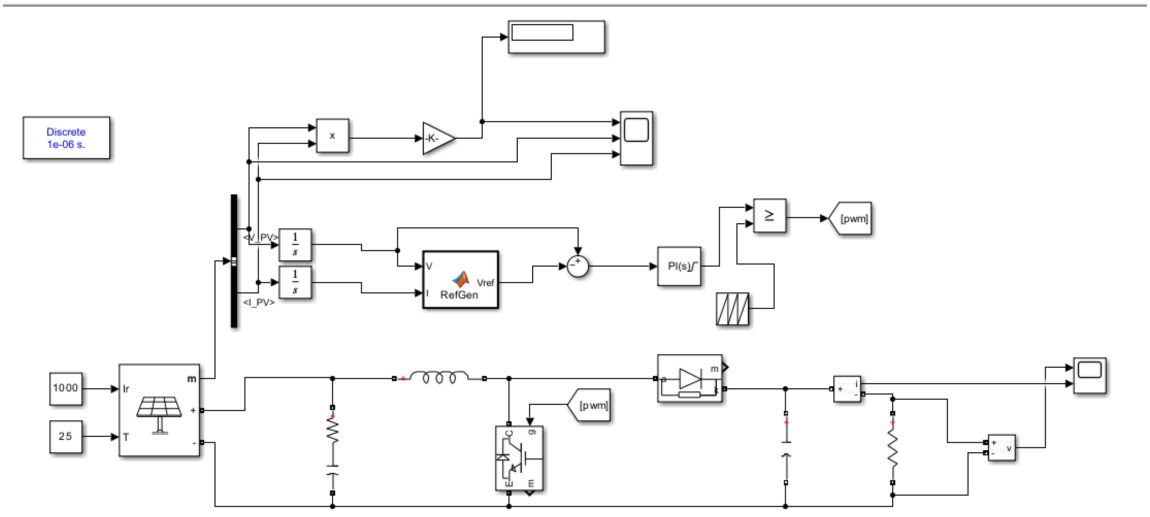

Figure 1: Simulink Model of MPPT System Using P And O Algorithm

In a PV system, the MPPT algorithm's general goal is to maintain the PV panel voltage near the MPP voltage. The perturb and Observe algorithm (Figure 2) measures the PV current and voltage. It operates by varying the panel voltage as the control variable on a regular basis and comparing the instantaneous PV power before and after the perturbation. The panel voltage is increased in the same direction as in the preceding cycle if the change in the output power increases. The system is running from the optimal point if the power change is negative, in which case the perturbation needs to be decreased to bring the operating point back to MPP.

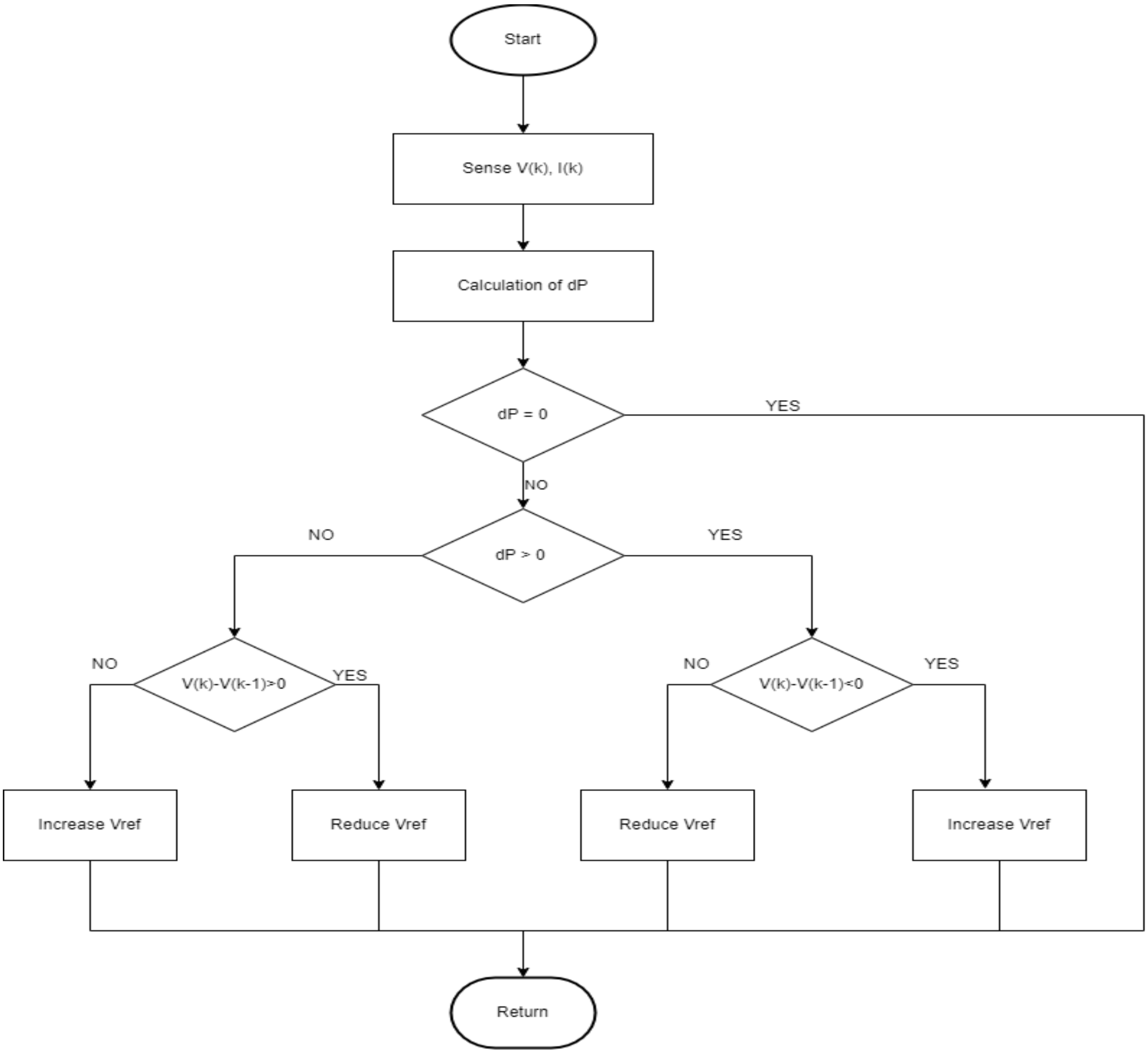

Figure 2: Flowchart of Perturb and Observe Algorithm

DC-DC Converter

A power electronic DC-DC converter is improvised and placed between the PV generator and the load to achieve duty cycle synchronization. In this design, a boost converter (Figure 3) is used due to its better efficiency in MPP based PV system. The PV module's output is efficiently raised with the use of the boost converter. Therefore, it serves as an impedance adapter for the load connected to the PV system. If the load power in a steady condition converges to the PV power input, the conversion is efficient. The equivalent circuit shown in the figure below consists of one inductor(L) one capacitor (C), an IGBT diode, a diode, and the load R.

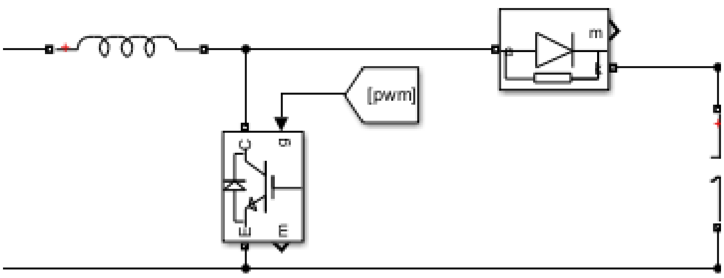

Figure 3: Equivalent Circuit of Boost Converter

Proportional Integral Controller
The Proportional Integral (PI) controller (Figure 4) with gains shown in
produces the output signal U(t) proportional to both the input signal, V(t) and the integral of the input signal.

The mathematical model of the PI controller is shown in the equation:
$$U_{(t)} = K_p V_{(t)} + K_i \int V_{(t)} dt \quad \text{Equation 1}$$

Table 3: PI Gains

S/N	Gain	Value
1	(K_p)	0.001
2	(K_i)	0.01

The control methodology of the PI + P and O controller is shown in the figure below

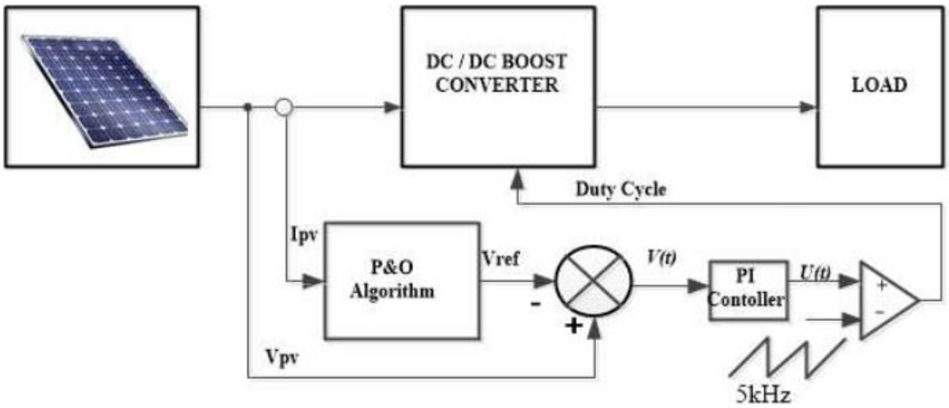

Figure 4: Block Diagram of The PI Controlled Perturb and Observe Control for PV System

Design of the Fuzzy Logic Controller
The fuzzy logic algorithm described in Figure 5 is used to design the fuzzy logic controller using MATLAB's fuzzy logic toolbox. The FLC was then integrated with the power management system as shown in Figure 6.

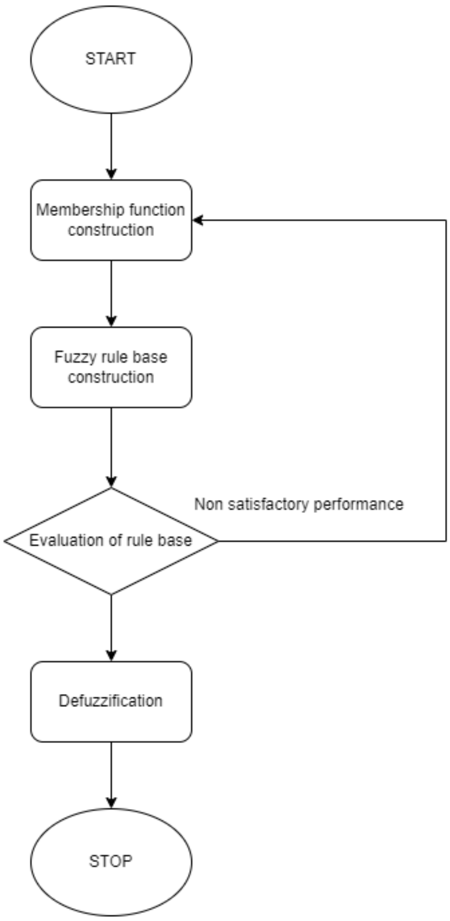

Figure 5: Fuzzy logic controller design process

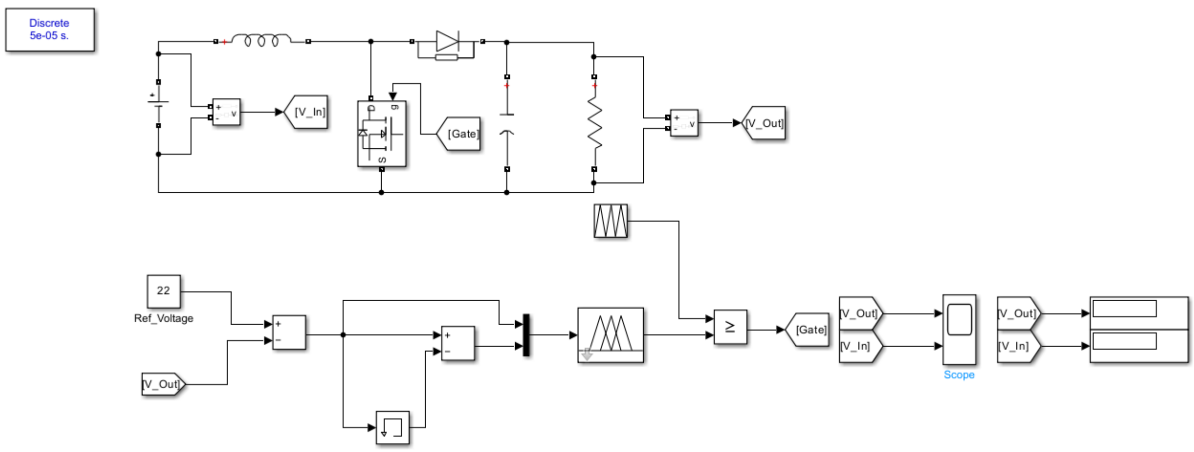

Figure 6: Fuzzy Logic Controller based on DC-DC buck converter

Fuzzy Logic Membership Function Rules

Table 4 shows the membership rules defined in modelling the fuzzy logic controller. It was defined using linguistic variable shown in Table 5.

Table 4: FL Membership Rules

D		e						
		PH	**PM**	**PS**	**Z**	**NS**	**NM**	**NH**
	NH	Z	DNS	DNM	DNH	DNH	DNH	DNH
	NM	DPS	Z	DNS	DNM	DNH	DNH	DNH
	NS	DPM	DPS	Z	DNS	DNM	DNH	DNH
e^*	Z	DPH	DPM	DPS	Z	DNS	DNM	DNH
	PS	DPH	DPH	DPM	DPS	Z	DNS	DNM
	PM	DPH	DPH	DPH	DPM	DPS	Z	DNS
	PH	DPH	DPH	DPH	DPH	DPM	DPS	Z

Table 5: FL Linguistic Variables

S/N	Linquistic Variable	Meaning
1	PH	Positive High
2	PM	Positive Medium
3	PS	Positive Small
4	Z	Zero
5	NS	Negative Small
6	NM	Negative Medium
7	NH	Negative High
8	D…	Delta…

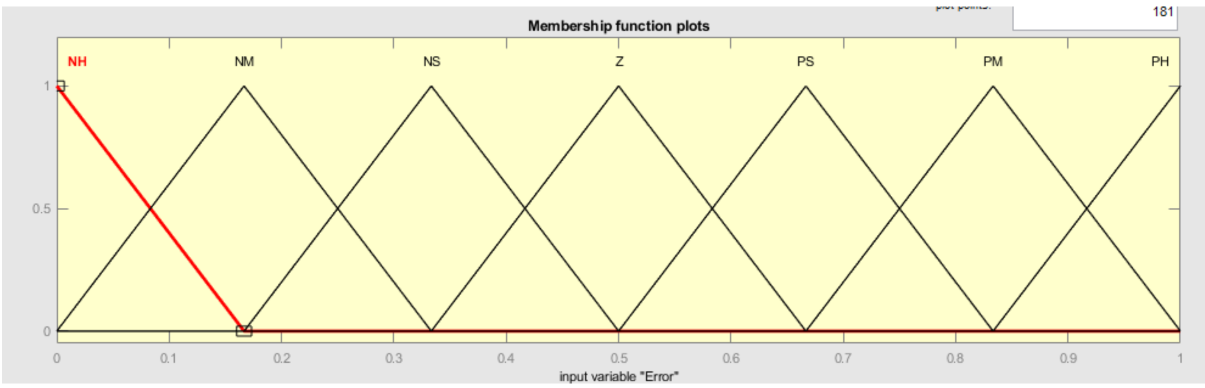

Figure 7: Membership Function Plot

FIS Rule Base

The FIS rules are listed below:

If (Error is NS) and (DError is PM) then (D is DPS) (1)

If (Error is NM) and (DError is PM) then (D is Z) (1)

If (Error is PS) and (DError is NH) then (D is DNM) (1)

If (Error is Z) and (DError is NM) then (D is DNM) (1)

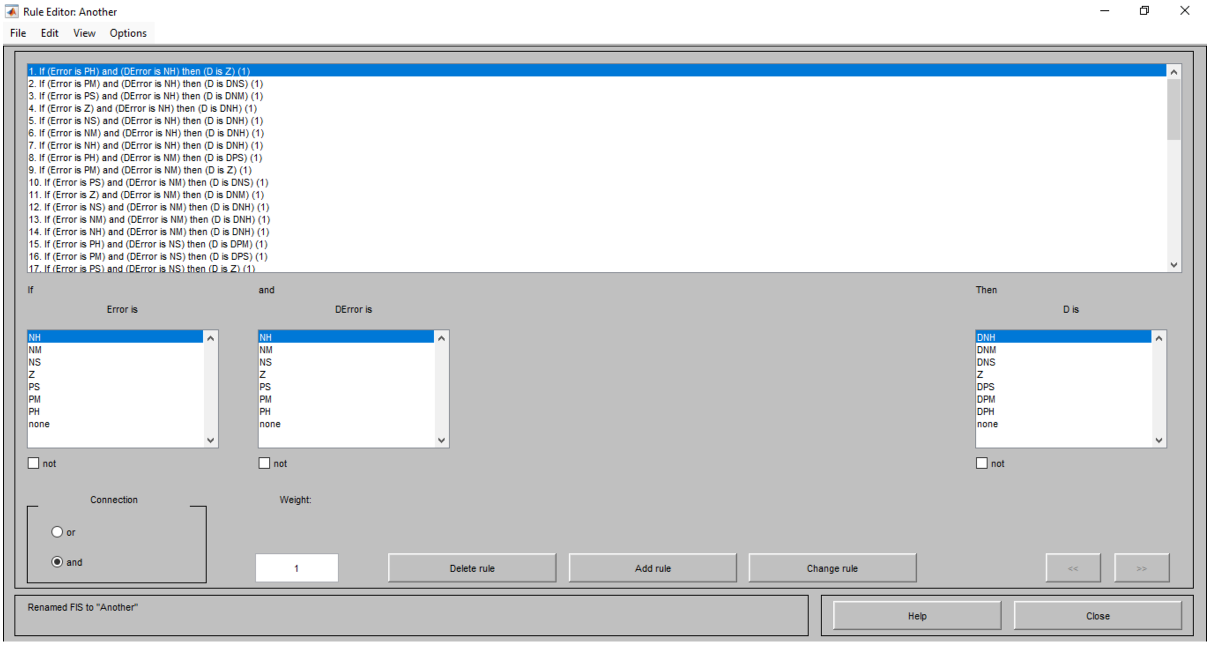

Figure 8: FIS Rule Base

RESULTS AND DISCUSSION

MPPT Based on Perturb and Observe Algorithm Controlled PI Controller

The results of the simulations P&O MPPT are shown in Figure 9, Figure 10 and Figure 11. The results show the measured voltage-PV current-PV, and the equivalent power output (Table 6).

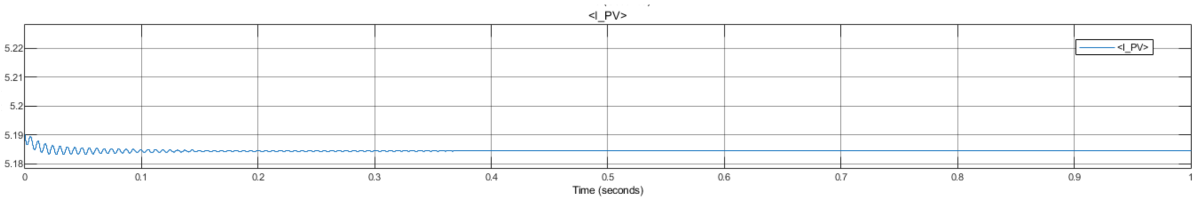

Figure 9: Graph showing Current against time with MPPT

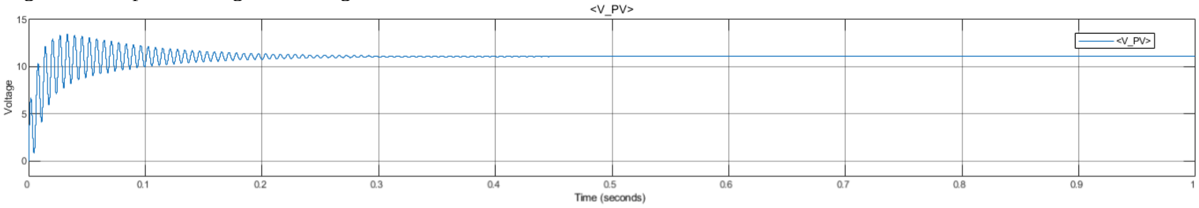

Figure 10: Graph showing Voltage against time with MPPT

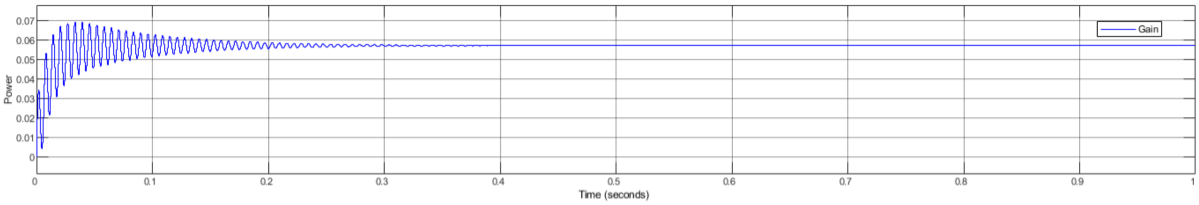

Figure 11: Graph showing power (Gain) against time with MPPT

Table 6: Settling time Gain, Voltage and Current

S/N	Quantity	Time to Settle (seconds)
1	Gain	0.4
2	Voltage	0.45
3	Current	0.2

From Figure 9, current of the system became stable at time t= 0.2 sec
From Figure 10, voltage stability occurs at time t= 0.45 sec
From Figure 11, the gain of the system became stable at time t = 0.4 sec

Fuzzy Logic Controller

The fuzzy logic controller was also integrated with the power management system and the response of the fuzzy logic-based control system is shown in the figure below.

The results from the simulation can be seen in Figure 12. The reference voltage (Vref) is equivalent to the output voltage (V-Out), and the input voltage (Vin) remains stable throughout the simulation.

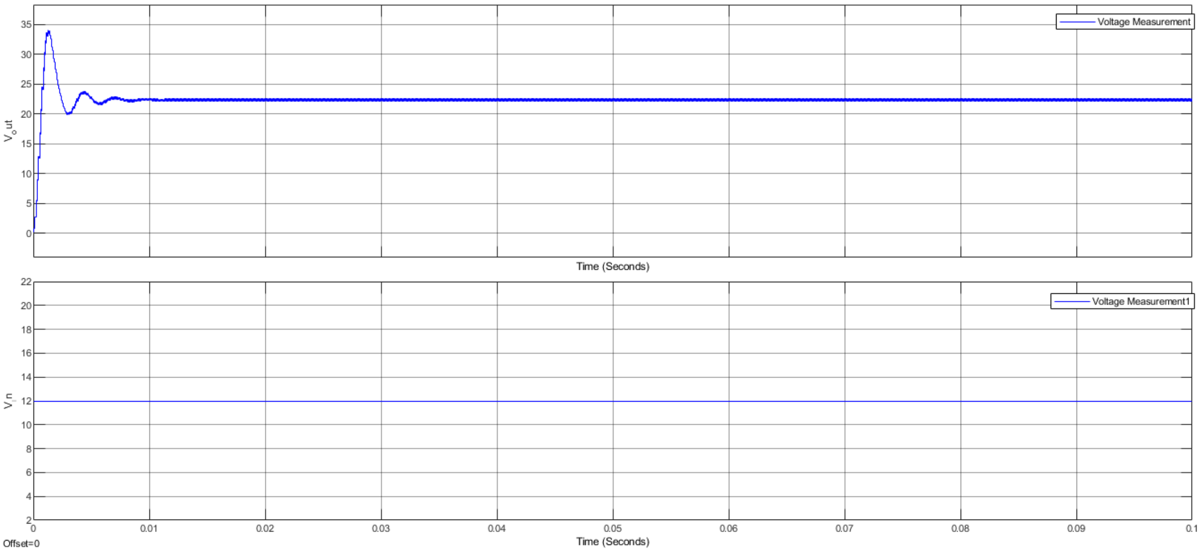

Figure 12: Graph showing V_in and V_out against time (seconds)

Table 7: Characteristics of perturb and observe, and fuzzy logic MPPT technique

S/N	MPPT Technique	Convergence speed	Voltage Stability time(seconds)
1	Perturb and observe	Varies	0.45
2	Fuzzy logic	Fast	0.01

As seen in Table 7, the Fuzzy Logic Controller outperformed the PI based on P & O by 97% efficiency improvement.

CONCLUSION

The design and simulation of a Power Management system (PMS) for solar-powered unmanned aerial vehicle (UAVs) demonstrate significant advancements in energy efficiency and operational reliability. The integration of the perturb and observe (P and O) algorithm with a proportional-integral (PI) controller effectively achieves maximum power point tracking (MPPT) ensuring that the UAV consistently operates at its optimal power output, even under varying environmental conditions such as temperature and solar irradiance. This makes it suitable for a wide range of aircraft applications, including slow moving gliders and faster UAVs. Furthermore, the incorporation of fuzzy logic control enhances the system's adaptability, allowing for real-time adjustments that improve responsiveness to fluctuations in solar energy availability. The results from MATLAB/Simulink simulations indicate that the Fuzzy Logic Controller with a settling time of 0.01 seconds performed at an efficiency of 97% compared to the PI-based P & O algorithm (0.45 settling time). The proposed system not only maximizes energy harvesting from solar panels but also optimizes the overall performance of the UAV.

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