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SANDEEP KANAUJIA
United University Prayagraj
AJAY SHARMA
United College Of Engineering & Research
RAJEV KUMAR SHARMA
United University Prayagraj
RAJAT YADAV
rajat.yadav@gla.ac.in

GLA University

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Development and Simulation of a Solar-Powered MPPT System for Energy-Efficient Wireless Sensor Networks

SANDEEP KANAUJIA[1], AJAY SHARMA[2] AND RAJEV KUMAR SHARMA[1], RAJAT YADAV[3]*

[1]Department of Electronics and Communication Engineering, United University Prayagraj, Uttar Pradesh -211012, India

[2]Department of Electronics and Communication Engineering ,United College Of Engineering & Research, Prayagraj, Uttar Pradesh -211010 ,India

[3]Institute of Engineering and Technology, GLA University, Mathura, Uttar Pradesh-281406, India,

corresponding authors: rajat.yadav@gla.ac.in

Abstract: Wireless sensor networks (WSNs) deployed in remote and inaccessible environments require reliable and sustainable energy sources to overcome the limitations of conventional battery-powered operation. This study presents the design and simulation of a solar energy harvesting system incorporating maximum power point tracking (MPPT) for powering WSN nodes. A fuzzy-logic-based MPPT controller is developed and evaluated against the conventional Perturb and Observe (P&O) technique using MATLAB/Simulink R2023a. The proposed system employs a DC–DC boost converter and a rechargeable battery to regulate harvested photovoltaic (PV) energy for the WSN load. The performance of the fuzzy MPPT controller is investigated under solar irradiance levels of 300–1100 W/m². The simulation results demonstrate that the system achieves output powers of 54.3, 102.4, 158.5, 211.3, and 260.4 W at irradiances of 300, 500, 700, 900, and 1100 W/m², respectively. The corresponding MPPT efficiencies are 92%, 92%, 95%, 96%, and 98%, demonstrating improved energy extraction under higher irradiance conditions. At 1100 W/m², the system achieves a maximum output power of 260.4 W from an input power of 268.3 W, corresponding to an efficiency of approximately 98%. The duty cycle varies from 0.47 to 0.75 across the investigated irradiance conditions. The proposed fuzzy-logic MPPT approach provides improved power tracking, reduced oscillations around the maximum power point, and enhanced battery charging performance compared with conventional P&O control. The results demonstrate the potential of fuzzy-based solar energy harvesting for improving the energy sustainability and operational reliability of WSN nodes.

Keywords: Wireless Sensor Networks; Solar Energy Harvesting; Maximum Power Point Tracking; Fuzzy Logic Control; Perturb and Observe; DC–DC Boost Converter; Renewable Energy.

1. Introduction

Several fields of applications. They are networks with sensor nodes that detect various environmental conditions and send the data they have gathered to central sink to be processed further (Kanaujia and Sharma, 2023; Sharma et al., 2024).

WSNs sensor nodes are usually powered by batteries, which might be refillable or non-refillable power sources. The non-refillable nature of batteries places implicit constraints on the life cycle of the operation of WSNs as well as impacting overall network performance which poses a major challenge to long term deployment. Although rechargeable batteries are widely used in WSNs, their periodic replacement or recharging can be challenging in remote, hazardous, or difficult-to-access locations where many wireless sensor nodes are deployed. Limited accessibility, maintenance requirements, and associated logistical constraints can significantly affect the reliability and continuity of network operation. Therefore, extending the operational lifetime of WSNs under constrained power conditions remains a significant research challenge. Researchers continue to investigate energy-efficient communication protocols, power-management techniques, and energy-harvesting approaches to minimize energy consumption and improve the long-term sustainability of wireless sensor networks (Akyildiz et al., 2002).

Energy harvesting (EH) technologies promise to provide a viable answer to the drawbacks linked with battery-powered sensor nodes because they allow harnessing energy available in the environment, and thus extend the lifetime of WSNs. This can be done using different EH sources like solar, wind, vibration, radio-frequency (RF),

and thermal energy (Sah et al., 2020). Of these, solar energy harvesting is especially popular because of the high-power density that can be attained with solar cells, reaching as high as15 mW/cm^3. The large energy potential of solar power makes it a feasible and desirable source of energy to support energy requirements of WSNs (Chalasani et al., 2008).

The following are this research article's primary contributions:

(1) A 3.3 volts recharger for solar energy using P&O type, tracking of maximum power (MPPT) control strategies using MATLAB (2023a).

(2) Insolation gathers 3.3 volts recharger using Fuzzy control logic (FLC) strategies using MATLAB-Simulink.

(3) Utilizing a MATLAB-Simulink comparison is done, between Perturb and Fuzzy controller based solar energy implementation to charge of 3.3-volt battery. It is believed that the WSN node is powered by this rechargeable battery.

MAXIMUM POWER POINT TRACKING (MPPT) TECHNIQUES:

MPPT is a control method that maximizes power extraction from a photovoltaic (PV) or energy-harvesting source (thermal, vibration, solar, or radiofrequency). MPPT continuously modifies the operating point so the harvester consistently supplies maximum power because the output power of these sources fluctuates with temperature, irradiation, load, and other factors (Katche et al., 2023).

a) The Maximum Power Point (MPP) is a distinct peak on PV power-voltage (P–V) and current-voltage (I–V) curves.
b) MPP is continually changing due to environmental factors such as temperature, shade, direction, and sunlight intensity.
c) Energy harvesters only produce 50–70% of their potential power in the absence of MPPT.
d) Efficiency increases significantly with MPPT (typically 90–99%).
Because nodes in Wireless Sensor Networks (WSNs) have limited energy budgets and frequently depend on gathered energy to survive, this is particularly crucial.

3. MPPT BY PERTURBATION AND OBSERVATION (P&O) TECHNIQUE:

To assess changes in photovoltaic (PV) voltage and power (PPV), the P&O algorithm continuously detects the voltage (V_{pv}) and current (I_{pv}) of the PV module. The algorithm uses the calculated values to incrementally adjust the converter's duty cycle (D) by a specified perturbation data, either increasing or decreasing it as needed(D=0.01). (D. Sera et al., 2013)

In the subsequent perturbation step, the duty cycle is increased according to ($D = D+\Delta D$) if $\Delta PPV > 0$ and $\Delta VPV > 0$ or $\Delta PPV < 0$ and $\Delta VPV < 0$. This adjustment is performed based on the change in photovoltaic power and voltage resulting from the previous perturbation.

Conversely, the duty cycle is reduced according to ($D = D-\Delta D$) if $\Delta P > 0$ and $\Delta VPV < 0$ or $\Delta PPV < 0$ and $\Delta VPV > 0$, The direction of the duty-cycle adjustment is therefore determined by the variation in PV power and voltage observed after the preceding perturbation.

This perturbation and observation process is continuously repeated, with the duty cycle being adjusted at each iteration, until the operating point approaches the maximum power point (MPP) of the photovoltaic system. At the MPP, the power variation becomes negligible, indicating that the system has reached or is operating very close to its maximum available power.

$$\text{i.e. } \Delta P_{PV} = 0 \text{ and } \Delta V_{PV} = 0$$

If the duty cycle value is permitted to vary in each perturbation step, the method does not meet the previous condition, which causes the P&O algorithm to bounce around the MPP. This procedure uses the P-V slope curve. Since the model is running at the MPP, the method assumes that the power slope and voltage curve are roughly zero.

The P&O approach operates on the principle of impedance matching between the load and solar panel. For the maximum power transfer through the DC-DC converter, impedance matching is needed. The duty cycle of the MOSFET switch of the DC-DC converter is changed to fit the impedance. The equation for duty cycle (D), output voltage (V_o) and input voltage (V_{in}) are as follows:

$$V_o = V_{in}. D$$

and,

$$R_{in} = RL / D^2$$

Consequently, the output voltage (Vo) of the solar energy harvester varies if the duty cycle (ΔD) changes. The output voltage (Vo) rises when duty cycle (D) increases, and vice versa.

To obtain highest power switches to the load and for optimization, the duty cycle (D) can be adjusted to match the input solar panel impedance with the load resistance (RL).

The procedure in the P&O algorithm is given in a flow chart and MATLAB coding as shown in figure 1.

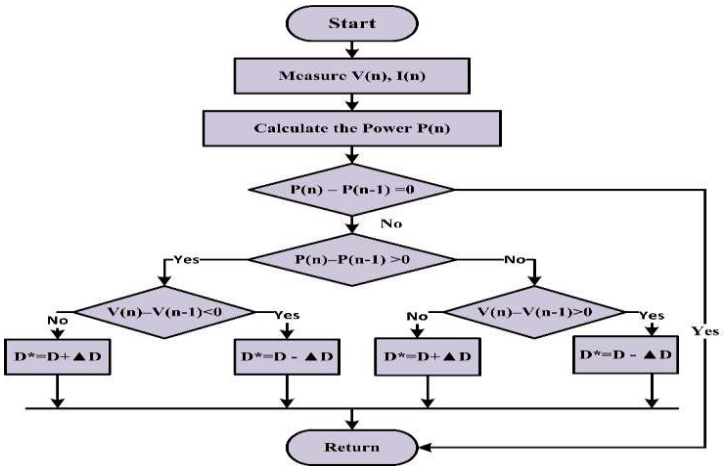


Figure 1: Flowchart of P&O Algorithm based MPPT algorithm.

Algorithm1. P&O MPPT algorithm.

functionduty cycle = PAndO MPPT Converter(V_pv, I_pv, V_ref, step_size, delta)

persistentpreviouspowerprevious duty.(Remoaldo D et al.,2021)

ifisempty (previous power)

previouspower = 0;

end

ifisempty (previous duty)

previousduty = 0.5;

end

% Calculate power

power = Vpv .* Ipv;

% Compare current power with previous power

ifpower> previous power

delta = -delta;

end

% Update duty cycle

duty cycle = previous duty + delta;

% Clamp duty cycle within [0, 1]

duty cycle = min(max(duty cycle, 0), 1);

% Update previous power and duty cycle

previouspower = power;

previous duty = duty cycle;

end

4. MPPT BY FUZZY LOGIC CONTROL TECHNIQUE:

The fuzzy logic control has become popular in the last 10 years, because it can deal with nonlinearity, interpret imprecise data and operate without having a precise mathematical formulation. The introduction of microcontrollers has substantially extended the usage of fuzzy logic control. The approach consists of three major phases. Fuzzification is the process of converting crisp inputs into fuzzy values. Inference system is the application of fuzzy rules to make conclusions. Defuzzification is the reverse process of fuzzification (Dash and others, 2015).

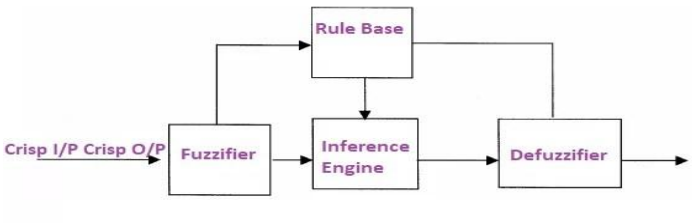


Fig 2: Diagrammatic representation of fuzzy logic control

Fuzzification is the conversion of "crisp" mathematical input into "fuzzy" semantic variables, based on the amount of membership in specified sets. Benchmarks of Fuzzy control are often structured as IF-THEN (Nabulsi et al., 2012; Sutikno et al., 2021).

PV modules' maximum power point is extracted using fuzzy logic methods. Because it continuously monitors control variables like duty cycle and voltage, this technique needs to be updated. In solar photovoltaic systems, MPPT (Maximum Power Point Tracking) is typically considered to maximize power extraction under various circumstances (Priyadarshi et al,2019). MPPT chooses the right load to optimize the output power. The relationship between total resistance and solar cell temperature is intricate. Both cell temperature and solar radiation intensity have an impact on PV arrays' maximum power point (MPP). The tracker may stray from MPP because to variations in light intensity, necessitating quick corrections to conserve energy. It is still difficult to track the MPP efficiently and fast under real-world circumstances (Sharma and others, 2024).

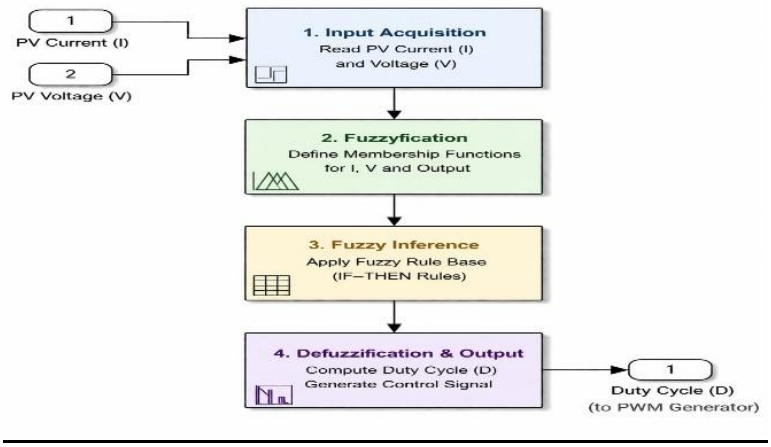


Fig 3: Proposed model for fuzzy logic algorithm

The variable step size (ΔD) is determined using a fuzzy logic method to enable automatic change of the operating points of PV arrays. In fuzzy logic system two inputs are defined by the power variance (ΔP_{pv}) and voltage variance (ΔV_{pv}) to obtain the adjustable step size (ΔD) as illustrated in Figure 2 and 3. Figure 4. The five triangular MFs of inputs and outputs: negative big (NB), negative small (NS), zero (ZE), positive big (PB) and positive small (PS). The fuzzy rule base based on P&O approach provides the use of adaptive step-size control for faster convergence. This improves the tracking performance and stability of the system. These five membership functions are selected to provide a good balance that provides precision and computational complexity to achieve accurate MPPT management. A smaller number of membership functions leads to coarser control whereas too many (which is a common mistake) adds too much complexity but not much more. The decision guarantees an

adequate granularity to distinguish between changes in power and voltage, and is fast and efficient to execute (Torabi et al., 2025).

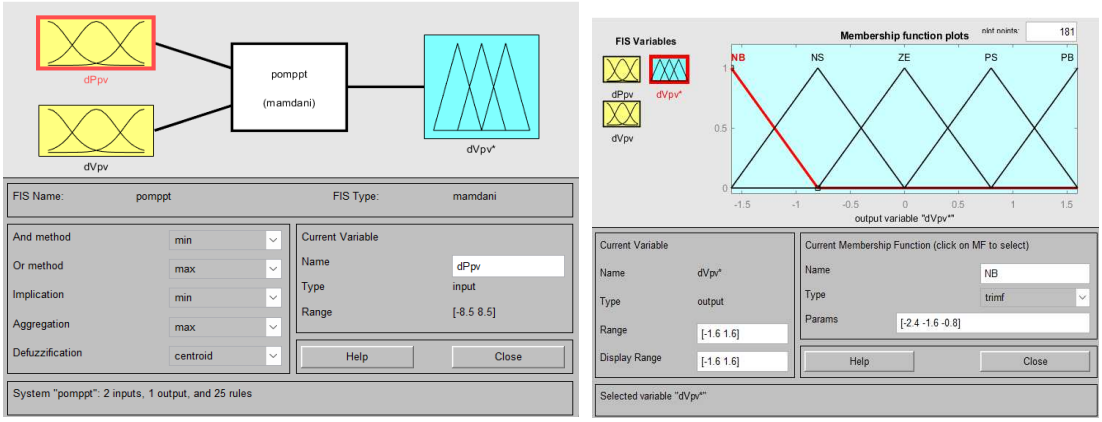


Fig 4: MATLAB diagram of the implemented FLC based MPPT controller

The variable step size (ΔD) is determined by the fuzzy controller with two input variables. The FLC uses the differential voltage and differential power determined by (1) and (2).

$$\Delta(K)=P(K)-P(k-1) \qquad (1)$$

$$(K)=(K)-V(k-1) \qquad (2)$$

For inference Mamdanis' Max-Min composition approach is employed. The defuzzification is performed via the center-of-gravity approach, which transforms the fuzzy subset of the variable-step-size into real integers.

$$\Delta D = \frac{\sum_{j=1}^{n} \mu(\Delta D_j) = * \Delta D_j}{\sum_{j=1}^{n} \mu(\Delta D_j)} \ldots\ldots\ldots\ldots (3)$$

5. SIMULATION EXPERIMENT SETUP

Figure 5, shows simulated solar-powered switching regulator with P&O logic control for a WSN node battery energy storage using MATLAB Simulink 2023a. The MPPT control by P&O is represented by a MATLAB Simulink model in Figure 4. The solar panel receives 500 watts per square centimeter of incident solar radiation at a room temperature of 25 degrees Celsius. Only this sun energy can be converted by the solar planeinto15 mW/cm2 at 15% efficiency.

Figure 6 shows Simulink results of MPPT control by P&O which contain solar panel voltage, current, power and load voltage, current and irradiance.

Figure 7 shows Simulink model using Fuzzy logic control with WSN battery as load.

Simulation Results of 8(a) Duty Cycle 8(b) Figure 8. Irradiance & Temperature,8 (c) Fuzzy controller output voltage

The DC-DC converter in simulink gets energy from the solar cell and increases the output potential energy. The battery is charged by the output potential of the converter. The rechargeable battery powers the WSN node. resistance of 100 ohms dc load. The WSN load is simulated as output in this example. Table 2 displays the different simulation parameters, such as temperature, duty cycle, WSN load, solar cell current, voltage, and power, battery and voltage, and irradiance.

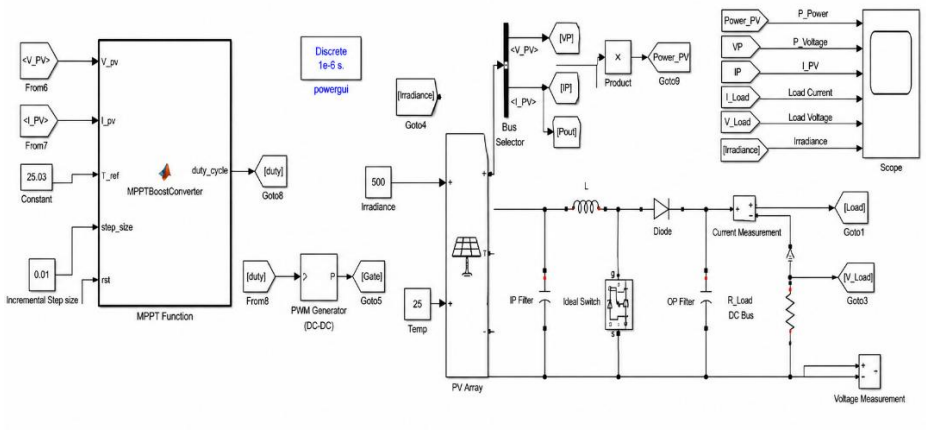


Fig 5: solar powered DC-DC boost converter using P&O control for battery charging of WSN node

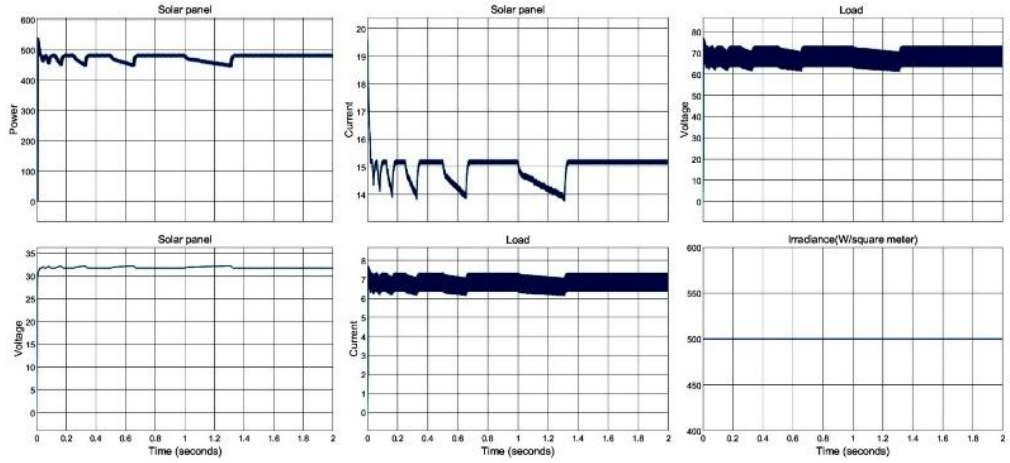


Fig 6: Simulink Results

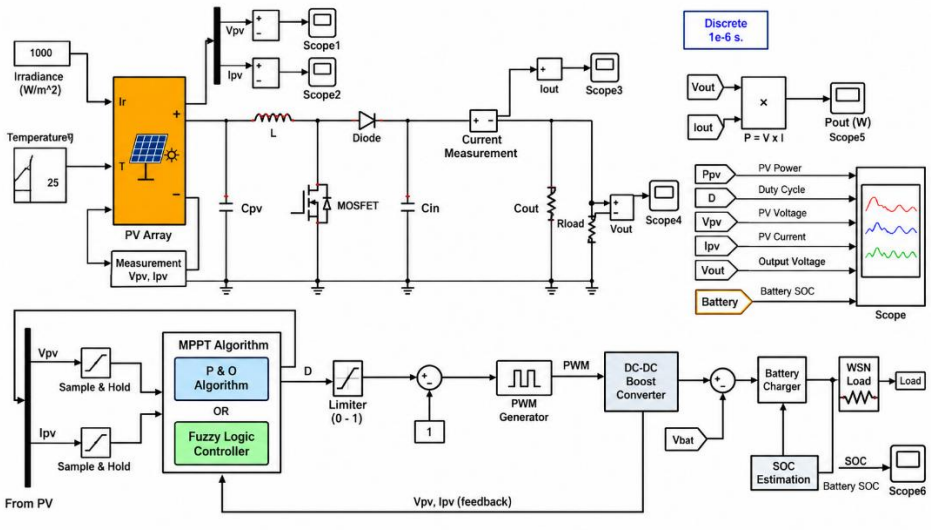
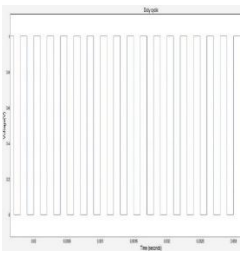
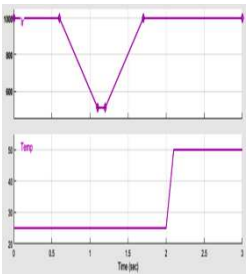


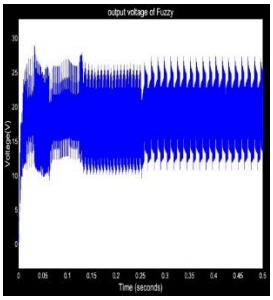
Fig 7: MPPT control Fuzzy logic with WSN battery as load



δ(a): Duty cycle



8(b): Irradiance& Temperature



8(c): Output voltageof Fuzzy

Fig 8: Simulation Results

Table 2: Simulation Parameters.

Specifications	**Value in unit**	**Specifications**	**Value in unit**
Irradiance (W/m2)	500Watts/m2	Temp (T)	25^0 Celsius
Capacitors (C)	100 uF	DC-DC Converter	Boost
MOSFET Switch Freq(f)	4 KHz	Max. Solar output potential (Vm)	
Initial duty Cycle	0.5	Max. Solar cell output current (Im)	5 v
Switching Voltage Loss (V_{sw})		Max. Power from Solar Cell(Pm)	
Inductor conduction Power Loss	0.3 v	Battery Voltage	400 mA
(PL)		Inductor (L)	
MOSFET Switching Power	50 mW	WSN Load Model	3 watts
Losses (P_{sw})			3v
Rechargeable Battery Type	0.4 mW		200 uH
	NiCd		10 Ω

6. SIMULATION RESULTS

Based on the modeling, simulation, and optimization experiments conducted for the Solar Energy Harvesting Wireless Sensor Node (SEH-WSN), it was observed that the fuzzy-logic-controller (FLC) based MPPT approach yields improved power-tracking performance for the photovoltaic (PV) module. Comprehensive simulation results for the FLC-based MPPT method were obtained using MATLAB/Simulink (R2023a).

The complete PV energy-harvesting system was modeled and simulated under varying solar irradiation levels to evaluate the dynamic response and efficiency of both the DC–DC converter and the fuzzy controller. Solar irradiance levels of 1100, 900, 700, 500, and 300 W/m² were applied to assess the input and output power, while the corresponding duty-cycle variations were also recorded.

Table 3 summarizes the simulation outcomes for the fuzzy-based MPPT method. The results indicate that although the output power of the MPPT controller increases as irradiance decreases, the overall system efficiency shows a reduction compared to the conventional perturb-and-observe (P&O) technique. This performance variation highlights the influence of environmental conditions on controller behavior and underscores the need for further optimization of fuzzy-based MPPT strategies under low-irradiance scenarios.

The tracking efficiency (η) statistics to assess how well MPPT approaches operate. Typically, it is described as (Devireddy et al., 2022).

$$\eta = \frac{\sum \mathrm{PMPPT(i)}}{\sum_{j=1}^{n} \mathrm{PMax(i)}} * 100 \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where PMPPT: output power of the photovoltaic system using the MPPT controller, and Pmax: maximum possible output power of the PV system at MPP.

Table 3: output of Fuzzy logic controller

Irradiance (Watts/Sq.Meter)	**P_{in} (Watts)**	**P_{out} (Watts)**	**η(%)**	**DC**
1100	268.3	260.4	98	0.75
900	219.6	211.3	96	0.72
700	166.25	158.5	95	0.61
500	110.11	102.4	92	0.53
300	58.82	54.3	92	0.47

Fuzzy control's higher efficiency results in a better Charge state of battery, battery Current (IB), and battery voltage (VB) than P&O MPPT.

7. Limitations and Potential Enhancements for the Proposed Approach

Although the suggested fuzzy logic-based MPPT controller proves to be more effective in operating under different conditions, there are still a number of constraints and obstacles. Other optimization strategies can be considered to make controllers even more robust and efficient:

• Hybrid Optimization Techniques:

The performance of optimization-based techniques can be further enhanced by integrating two or more complementary algorithms into a hybrid optimization framework. Such an approach combines the exploration capabilities of population-based methods with the refinement ability of other optimization strategies. For example, Particle Swarm Optimization (PSO) can be integrated with Genetic Algorithms (GA), while Grey Wolf Optimization (GWO) can be coupled with gradient-based techniques to achieve improved convergence, solution accuracy, and robustness. These hybrid schemes can potentially address the performance limitations of single optimization techniques and can result in more precise and quicker convergence of MPPT (Kumar et al., 2024).

Adaptive and Self-Tuning Fuzzy Logic MPPT Controllers:

The other potential area of advancement is the creation of adaptive or self-tuning fuzzy MPPT controllers that can autonomously modify their membership functions and rule bases to changes in real-time environment and operation. This feature can greatly lessen the reliance on manual parameter adjustment and improve its performance in dynamic settings (Refaat et al., 2020, Al-Gizi et al., 2017; Yap et al., 2020; Kanaujia et al., 2024).

8. CONCLUSION

An adequate power-matching mechanism is used to derive maximum available power using photovoltaic (PV) power system. Here, any unused power of the solar module is wasted away as surface heat, and the significance of efficient maximum power point tracking (MPPT). The suggested Simulink model shows a high level of performance, especially in autonomous WSN nodes, in which the MPPT controller with a fuzzy logic approach has its maximum efficiency in high-irradiance conditions.

Solar Energy Harvesting Wireless Sensor Nodes (SEH-WSNs) were thoroughly modeled, simulated and experimented. The solar energy harvester system has been established in MATLAB/Simulink (R2023a) where two MPPT techniques were evaluated, the standard perturb and observe (P&O) and the fuzzy logic-based controller.

The results confirm that the fuzzy logic MPPT controller has always provided a better performance than P&O algorithm. The comparative simulation results show that the fuzzy based MPPT has higher efficiency, higher power extraction and less oscillation around the highest power point as compared to the conventional controller. Hence, the total performance of the solar energy harvester system using a fuzzy logic is superior.

More advanced MPPT techniques such as neural networks and models based on machine learning, optimization techniques such as particle swarm optimization, dragonfly optimization and genetic algorithms which have shown high potential in previous research can be considered in future studies to extend this research.

Ethics Statement

This study does not involve human participants, animals, or human/animal-derived experimental data. Therefore, ethical approval was not required.

Competing Interests

The authors declare that they have no competing financial or non-financial interests that could have influenced the work reported in this manuscript.

Figure permission

All figures in this manuscript were created by the authors.

Author contribution

SK-Prepare the manuscript, Arrange the data and figure
AS- Analysis and Validation of the manuscript
RKS-arrange the data
RY- Analysis and Validation of the manuscript

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