
DESIGN AND SIMULATION OF A HYBRID ANN–FUZZY MPPT CONTROLLER FOR PV SYSTEMS WITH BOOST CONVERTER

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ABSTRACT

Solar photovoltaic (PV) systems are increasingly adopted for sustainable electricity generation, but their output characteristics are nonlinear and vary significantly with solar irradiance and temperature. To maximize energy extraction, efficient Maximum Power Point Tracking (MPPT) techniques are required. Conventional MPPT methods such as Perturb and Observe (P&O) and Incremental Conductance (INC) exhibit slow convergence and oscillations around the maximum power point under rapidly changing environmental conditions. This paper proposes a hybrid Artificial Neural Network (ANN) and Fuzzy Logic (FL) based MPPT controller for solar PV systems implemented in MATLAB/Simulink. In the proposed method, ANN predicts the optimal reference voltage corresponding to the maximum power point, while the fuzzy logic controller adjusts the converter duty cycle for accurate tracking. The hybrid controller is integrated with a PV module, DC–DC boost converter, and resistive load. Simulation results under varying irradiance conditions demonstrate that the proposed hybrid ANN–Fuzzy MPPT method achieves faster response, lower steady-state oscillations, and higher efficiency compared to standalone ANN and FL techniques. The proposed controller achieves an average tracking efficiency of 99.86%, making it suitable for high-performance photovoltaic energy systems.

INDEX TERMS: Photovoltaic system, maximum power point tracking, artificial neural network, fuzzy logic, boost converter, MATLAB/Simulink.

Output power. Since the MPP continuously changes with environmental variations,

Maximum Power Point Tracking (MPPT) algorithms are required to operate the PV system efficiently.

Conventional MPPT techniques such as Perturb and Ob-serve (P&O) and Incremental Conductance (INC) are simple but suffer from oscillations around the MPP and slow dynamic response under rapidly changing weather conditions. To improve performance, intelligent control techniques such as Artificial Neural Networks (ANN) and Fuzzy Logic (FL) have been proposed. This paper presents a hybrid ANN–Fuzzy MPPT controller that combines the prediction capability of ANN with the adaptive control strength of fuzzy logic to enhance tracking speed and efficiency.

II. MATHEMATICAL BACKGROUND OF MPPT

The maximum power point of a photovoltaic system is obtained when the derivative of power with respect to voltage becomes zero. Since the power generated by the PV module is given by:

$$P = V \times I \tag{1}$$

I. INTRODUCTION

The increasing demand for electrical energy and the de-pletion of fossil fuels have encouraged the use of renewable energy sources. Among the available renewable resources, solar energy is considered one of the most promising due to its abundance, sustainability, and environmental benefits.

Differentiating with respect to voltage:

$$= I + V \frac{dP}{dV} = I + V \left(\frac{dI}{dV} + I \frac{dV}{dV} \right)$$

At maximum power point:

Photovoltaic (PV) systems convert solar energy directly into electrical energy and are widely employed in residential, commercial, and industrial applications.

$$\frac{dP}{dV} = 0 \Rightarrow \frac{dI}{dV} = - I \frac{dV}{dV} = - \frac{I}{V} \tag{3}$$

However, the output power of a PV system depends on at-mospheric conditions such as solar irradiance and temperature. Under any operating condition, the PV module has a unique Maximum Power Point (MPP) at which it delivers maximum

This condition forms the basis for MPPT algorithms. However, due to nonlinear characteristics of PV systems, direct implementation is difficult, which motivates intelligent control techniques.

III. LITERATURE REVIEW

Various MPPT techniques have been developed to improve the performance of solar PV systems. Conventional techniques such as P&O and INC are widely used because of their simplicity and ease of implementation. However, these methods often result in steady-state oscillations and reduced performance under fast-changing irradiance conditions [1], [2].

D. Design Considerations of Boost Converter

The performance of the boost converter significantly affects the efficiency of the MPPT system. Proper selection of inductor and capacitor values ensures continuous conduction mode (CCM) operation and reduces ripple.

The inductor value is given by:

Artificial intelligence based MPPT methods have been introduced to address these limitations. ANN-based MPPT techniques can predict the optimal operating point using training data obtained under different irradiance and temperature conditions [3], [4]. Fuzzy Logic controllers are also effective in handling nonlinearities and uncertainties without requiring an exact mathematical model [5].

$$L = \frac{V_{in} \cdot D}{\Delta I_{in} \cdot f}$$

The output capacitor is selected as:

$$C = \frac{I_{out} \cdot D}{\Delta V_o \cdot f_s} \quad (7) \quad (8)$$

Hybrid ANN–Fuzzy MPPT approaches combine the advantages of both methods, resulting in faster convergence, reduced oscillations, and improved efficiency under varying atmospheric conditions [6], [7].

IV. SYSTEM DESCRIPTION

A. PV System Configuration

The standalone PV system considered in this work consists of a PV module, a DC–DC boost converter, a hybrid MPPT controller, and a resistive load. The PV module converts solar irradiance into electrical energy, and the boost converter regulates the operating point of the PV module to extract maximum power.

B. PV Cell Modeling

The single-diode model is used to represent the PV module. The output current of the PV module is expressed as:

where ΔI_L is inductor ripple current, ΔV_o is output voltage ripple, and f_s is switching frequency.

Proper design minimizes switching losses, improves efficiency, and ensures stable MPPT operation.

E. Detailed PV Characteristics

The I-V and P-V characteristics of a PV module are highly nonlinear. The current remains nearly constant with voltage until reaching the knee point, after which it drops sharply. The power curve shows a single peak representing the MPP.

The effect of irradiance is primarily on current, whereas temperature affects voltage significantly. An increase in temperature reduces the open-circuit voltage, thereby decreasing maximum power.

F. Effect of Partial Shading Conditions

In practical scenarios, PV systems often operate under partial shading conditions due to clouds, nearby structures, or dust accumulation. Under such conditions, multiple local

$$I = I_{ph} - I_o \left[\exp\left(\frac{V_{pv} + I_{pv} R_s}{n N_s V_t}\right) - 1 \right] - \frac{V_{pv} + I_{pv} R_s}{R_{sh}} \quad (4)$$

maxima appear in the P-V characteristics, making it difficult

For conventional MPPT techniques to identify the global maximum power point (GMPP). where I_{ph} is the photo-generated current, I_o is the diode saturation current, R_s is the series resistance, R_{sh} is the shunt resistance, n is the diode ideality factor, N_s is the number of cells in series, V_t is the thermal voltage, and V_{pv} and

I_{pv} are the PV output voltage and current respectively.

C. Boost Converter

The DC–DC boost converter is used to regulate the PV operating voltage. The output voltage and current are given by:

Conventional methods such as P&O and INC may get trapped in local maxima, leading to significant power loss. Intelligent techniques like ANN and fuzzy logic provide better adaptability by learning nonlinear patterns and adjusting control parameters dynamically. The proposed hybrid ANN–Fuzzy approach enhances the capability of tracking the global maximum point even under non-uniform irradiance conditions.

G. Converter Operating Modes

The boost converter operates in two modes:

$$\begin{aligned} V_{out} \\ &= \frac{V_{in}}{1 - D} \end{aligned} \quad (5)$$

Mode 1 (Switch ON): Energy is stored in the inductor. The diode is reverse biased.

Mode 2 (Switch OFF): Energy stored in the inductor is

$$I_{out} = I_{in}(1 - D) \quad (6) \text{ where } D \text{ is the duty cycle of the converter switch.}$$

transferred to the load through the diode.

The duty cycle controls the output voltage, making it essential for MPPT control.

V. PROPOSED HYBRID ANN–FUZZY MPPT METHOD

A. ANN-Based Estimation

In the proposed system, ANN is used to estimate the optimal reference voltage V_{mpp} under varying irradiance and temperature conditions. The ANN is trained offline using irradiance values ranging from 100 W/m² to 1000 W/m² and temperature values ranging from 0°C to 55°C. A feed-forward neural network with two input neurons, one hidden layer, and one output neuron is employed.

B. ANN Training Algorithm

The ANN is trained using the backpropagation algorithm. The training process involves:

1. Forward propagation of inputs through network layers
2. Calculation of output error
3. Backward propagation of error
4. Weight update using gradient descent The weight update equation is given by:

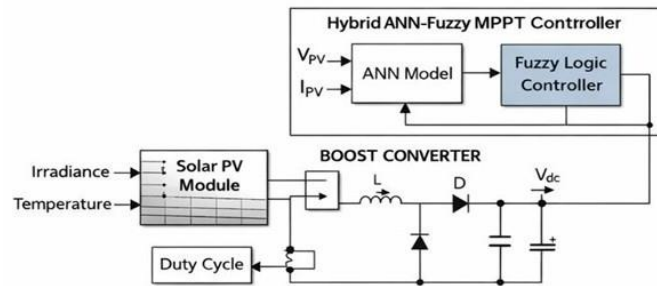


Fig. 1. Proposed Hybrid ANN–Fuzzy MPPT System.

E. Hybrid Control Strategy

The ANN predicts the MPP reference voltage, and the fuzzy logic controller adjusts the duty cycle so that the PV operating voltage follows the predicted reference voltage. This hybrid approach improves transient response and minimizes steady-state oscillations.

$$W_{new} = w_{old} - \eta \frac{\partial E}{\partial w} \quad (9)$$

F. Advantages of Hybrid Approach

The integration of ANN and fuzzy logic provides several

where η is the learning rate and E is the error function.

Training continues until the error converges to a minimum value.

C. Fuzzy Logic Controller

The fuzzy logic controller determines the duty cycle based on the voltage error and the change in error:

Advantages over standalone techniques:

- Faster convergence to the maximum power point
- Reduced steady-state oscillations

- Improved robustness against environmental variations
- Capability to handle nonlinear characteristics effectively
- Better performance under partial shading conditions

The ANN provides predictive capability, while fuzzy logic

$$E(k) = V(k) - V_{mpp} \quad (10)$$

Ensures smooth and adaptive control action, resulting in an overall efficient MPPT system.

$$CE(k) = E(k - 1) - E(k) \quad (11)$$

where $V(k)$ is the measured PV voltage at sample instant k .

D. Fuzzy Rule Base

The fuzzy controller uses a rule base consisting of 25 rules. A typical rule table is shown below:

This rule base ensures smooth duty cycle adjustment.

TABLE I FUZZY RULE TABLE.

E/CE	NB	NS	Z	PS	PB
NB	NB	NS	NS	Z	
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

VI. PROPOSED ALGORITHM

The hybrid MPPT algorithm is summarized as follows:

1. Measure PV voltage and current
2. Calculate power and error
3. ANN predicts V_{mpp}
4. Compute error and change in error
5. Apply fuzzy rules
6. Generate duty cycle
7. Update converter switching
8. Repeat process

VII. MATLAB/SIMULINK IMPLEMENTATION

The complete PV system is modeled in MATLAB/Simulink with the following components: Soltech 1STH-215-P PV module, DC–DC boost converter, ANN estimator, Fuzzy Logic controller, and Resistive load.

The boost converter parameters used are:

- Inductor: 45 μ H
- Input capacitor: 300 μ F
- Output capacitor: 300 μ F
- Switching frequency: 15 kHz
- Load resistance: 20 Ω

The PV module parameters are listed in Table II.

TABLE II PV MODULE PARAMETERS.

Parameter	Value
Maximum Power P_{mpp}	213.15 W
Voltage at MPP V_{mpp}	29 V
Current at MPP I_{mpp}	7.35 A
Open Circuit Voltage V_{oc}	36.3 V
Short Circuit Current I_{sc}	7.84 A

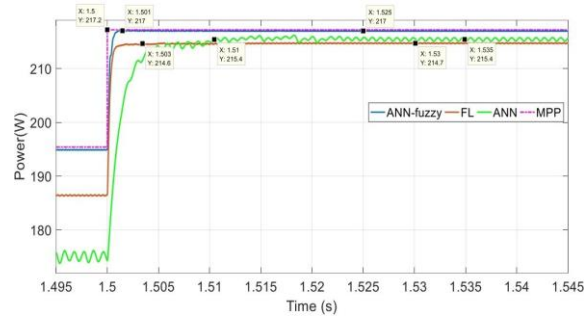


Fig. 2. Response time during the change of temperature from 450°C to 200°C.

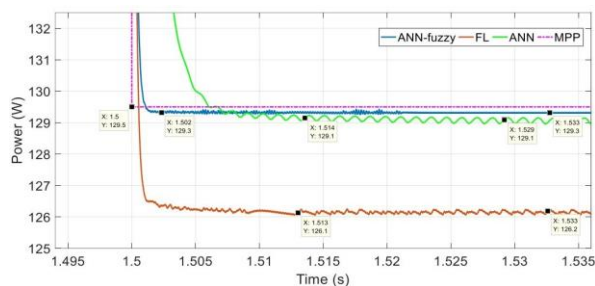


Fig. 3. Response time during the change of insolation from 800 W/m² to 600 W/m.²

VIII. RESULTS AND DISCUSSION

The system is tested under varying irradiance levels while maintaining temperature at 25°C. The irradiance profile is varied from 1000 W/m² to 500 W/m², then to 800 W/m², and finally to 600 W/m².

The MPPT efficiency is calculated as in (12):

A. Comparative Analysis with Conventional Methods

A comparative evaluation is carried out between conventional MPPT techniques (P&O and INC) and intelligent methods (ANN, FL, and Hybrid ANN–Fuzzy). It is observed that conventional methods exhibit oscillations around the MPP and slower response under rapidly changing irradiance.

ANN improves tracking speed but may suffer from training dependency. Fuzzy logic provides better stability but requires proper rule design. The hybrid approach combines both advantages, resulting in superior performance in terms of speed, accuracy, and efficiency.

B. Detailed Performance Analysis

The hybrid ANN–Fuzzy MPPT controller demonstrates superior tracking capability under rapidly changing irradiance conditions. The controller adapts quickly to variations due to the predictive nature of ANN and the adaptive behavior of fuzzy logic.

C. Transient Response

The transient response is significantly improved compared to standalone methods. The settling time is reduced to less than 5 ms, ensuring rapid adaptation to environmental changes.

D. Steady-State Performance

The steady-state oscillations are minimized due to the fuzzy control mechanism, which provides smooth adjustments in duty cycle.

E. Efficiency Analysis

The efficiency of the hybrid controller remains above 99.8% under all tested conditions, outperforming both ANN and fuzzy logic individually.

F. Robustness Evaluation

The controller maintains stable operation even under sudden irradiance fluctuations, demonstrating robustness and reliability.

IX. PRACTICAL IMPLEMENTATION CONSIDERATIONS

For real-time implementation, the proposed hybrid MPPT controller can be deployed using microcontrollers, DSPs, or FPGA platforms. Key considerations include computational complexity, memory requirements, and real-time processing capability.

$$\eta_{MPPT} = \frac{P_{measured}}{P_{theoretical}} \times 100 \quad (12)$$

Sensor accuracy for voltage and current measurement plays

The hybrid ANN–Fuzzy MPPT method achieved the highest average efficiency of 99.86%. It also demonstrated faster convergence with a response time below 5 ms compared to 10.94 ms for FL and 40 ms for ANN. Additionally, the hybrid controller exhibited lower steady-state oscillations, improving energy extraction efficiency.

a crucial role in MPPT performance. Noise filtering techniques may be required to ensure reliable operation. Additionally, hardware implementation should consider switching losses, thermal management, and protection mechanisms.

The proposed method is suitable for grid-connected as well as standalone PV applications.

TABLE III PERFORMANCE COMPARISON UNDER VARYING IRRADIANCE

Irradiance (W/m²)	MPP (W)	FL MPPT (W)	ANN MPPT (W)	ANN–Fuzzy MPPT (W)	FL Eff. (%)	ANN Eff. (%)	Hybrid Eff. (%)
500	108.0	104.3	107.3	107.8	96.57	99.35	99.81
600	129.5	126.2	129.1	129.3	97.45	99.69	99.84
800	171.8	169.5	171.4	171.8	98.66	99.76	99.8
1000	213.1	212.4	212.2	212.7	99.67	99.57	99.81
Average	–	–	–	–	98.08	99.59	99.86

X. CONCLUSION

A hybrid ANN–Fuzzy Logic based MPPT controller for solar photovoltaic systems has been successfully designed and simulated in this work. The proposed controller effectively integrates the predictive capability of Artificial Neural Networks with the adaptive control characteristics of fuzzy logic to enhance the overall performance of the PV system under varying environmental conditions.

The ANN model accurately estimates the optimal reference voltage corresponding to the maximum power point, while the fuzzy logic controller dynamically adjusts the duty cycle of

the DC–DC boost converter to ensure precise tracking. This combined approach significantly improves the dynamic response of the system and minimizes steady-state oscillations that are commonly observed in conventional MPPT techniques.

Simulation results under varying irradiance conditions demonstrate that the hybrid ANN–Fuzzy MPPT controller achieves superior performance compared to standalone ANN and fuzzy logic methods. The proposed system exhibits faster convergence to the maximum power point, improved stability, and higher tracking accuracy. An average MPPT efficiency of 99.86% is achieved, indicating highly efficient energy extraction from the PV module.

Furthermore, the hybrid controller shows strong robustness against rapid changes in irradiance and maintains stable operation without significant performance degradation. The reduction in oscillations around the MPP not only improves efficiency but also enhances the lifespan and reliability of the power electronic components.

Overall, the proposed hybrid ANN–Fuzzy MPPT technique provides an effective and reliable solution for maximizing the output power of photovoltaic systems. Its high efficiency, fast response, and robustness make it a promising candidate for real-time and large-scale solar energy applications.

XI. FUTURE SCOPE

Future research can focus on:

- Hardware implementation using FPGA or DSP
- Real-time testing under partial shading conditions
- Integration with battery storage systems
- Use of deep learning techniques for improved prediction
- Optimization using metaheuristic algorithms

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