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Performance enhancement of photovoltaic system integrated with a single-phase grid using advanced controllers

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ABSTRACT

This study offers a thorough examination of a photovoltaic (PV) system using a variety of maximum power point tracking (MPPT) methods, including fuzzy logic control (FLC), adaptive neuro-fuzzy inference systems (ANFIS), perturb and observe (P&O), and artificial neural networks (ANN). Optimizing power extraction from PV systems under various environmental circumstances, including temperature variations and irradiance, is the main goal of these MPPT algorithms. Despite its widespread use and affordability, the P&O algorithm may have performance issues in dynamic circumstances. By using fuzzy logic to adjust to non-linear changes in environmental conditions, FLC improves P&O and offers more dependable and seamless operation. Although they demand a large amount of data and processing power, ANN-based MPPT approaches provide sophisticated capabilities by predicting optimal operating points by learning from historical system actions. By fusing fuzzy logic and neural networks, ANFIS offers a reliable solution that can more accurately adjust in real time to changing circumstances. These algorithms' incorporation into a PV system allows for more flexible and effective power management, guaranteeing peak performance in a range of climatic conditions. By combining many MPPT techniques, hybrid approaches can further reduce the drawbacks of individual approaches and improve the overall dependability and efficiency of PV systems.

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1. INTRODUCTION

The efficiency of a photovoltaic (PV) system, which uses solar to generate electricity, is mostly reliant on environmental factors, including temperature and sunshine intensity. Operating the PV system at its maximum power point (MPP), which fluctuates with shifting environmental variables, is essential to maximizing energy output [1]. Techniques from maximum power point tracking (MPPT) are useful in this situation. The PV system's operating point is dynamically modified using MPPT algorithms to harvest the most electricity feasible [2]. Using a buck-boost converter, this study investigates a number of MPPT strategies, such as perturb and observe (P&O), fuzzy logic control (FLC), adaptive neuro-fuzzy inference systems (ANFIS), and artificial neural networks (ANN). The system uses a buck-boost converter because it can adjust the voltage to keep the output steady even when the input voltage of the PV array fluctuates. Regarding tracking effectiveness, response time, and complexity, each MPPT technique has advantages and disadvantages of its own [3]. The objective is to assess how well these methods function in maximizing the

PV system efficiency and guaranteeing ideal power extraction in a range of environmental circumstances by modeling them with a buck-boost converter.

Several essential elements usually cooperate to optimize the energy collected from the PV array in a block diagram for a buck-boost converter in a PV system and different MPPT techniques (FLC, ANFIS, P&O, and ANN). The main element that transforms sunlight into electrical energy and produces direct current (DC) power is the PV array. Various MPPT techniques, such as FLC, ANFIS, P&O, and ANN, are fed the PV array's output (current and voltage). These techniques are employed to verify the MPP by adjusting the operating voltage and current of the system to achieve optimal power generation based on varying environmental conditions, such as temperature and the amount of sunlight. After processing the outputs from the chosen MPPT algorithm, the MPPT controller modifies the buck-boost duty cycle of the converter. To match the MPP established by the MPPT controller, this converter steps the voltage up or down. A steady output voltage can be supplied by the buck-boost converter to power a DC load, recharge a battery, or supply electricity to the grid. The MPPT technique is continually adjusted based on feedback from the PV array's current and voltage sensors as well as the output of the converter, guaranteeing that the system runs at the best possible point for highest power extraction. Overall, the PV system with MPPT techniques and a buck-boost converter ensures efficient operation by dynamically adjusting to the environmental conditions, optimizing energy harvesting, and delivering reliable power to the load, battery, or grid. Figure 1 depicts a grid-tied PV system block diagram.

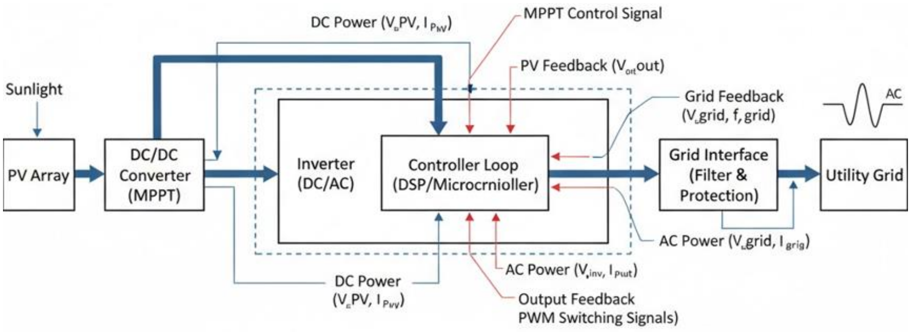

Figure 1. Grid-tied PV system block diagram

According to Haq *et al.* [4], a nonlinear generalized Gaussian sliding mode control (GGSMC) is introduced to use a DC-DC buck-boost converter to maximize power harvesting from a PV array. Research by Carmona *et al.* [5] describes a controller for hyper twisting sliding modes-based MPPT technique. The fundamental concept is resolving the traditional trajectory tracking control problem, in which the reference route is defined by the MPP. According to Metry *et al.* [6], a model predictive control (MPC) method for sensorless current (SC) MPPT is introduced. This paper's main objective is the elimination of the current sensor, which is often needed for popular MPPT approaches like P&O, by using the model-based predictive control concept. For various DC-DC converter topologies, the impact of operational point (choosing a load line) on MPPT operation has been investigated and empirically verified [7]–[11]. Using an evolutionary genetic algorithm (GA), the performance of an MPPT approach based on intelligent FLC has been improved [12]. The authors assess the viability of MPPT techniques for mitigating the adverse effects of partial shade, focusing on their ability to accurately and quickly detect the panels' MPP [13]–[17]. Two conventional MPPT techniques, FLC and P&O, have been altered to get over drawbacks, including oscillations in steady-state voltage and enhance transient response [18], [19] compares two popular MPPT techniques for a PV system with a resistive load and a step-up converter: incremental conductance (INC) and P&O. ANFIS is used to optimize the grid integration of wind and PV energy in hybrid systems using intelligent control tactics. The ANFIS control seeks to optimize the use of renewable energy (RE), improve power management, and increase grid stability [20].

P&O MPPT technique is proposed in [21] for a PV system linked to the grid at 3-ϕ. This idea makes use of an MPPT application to increase the PV array's efficiency in the event of unstable weather conditions. Because temperature and irradiation conditions are stochastic, it is crucial to include an MPPT algorithm into a DC-DC converter to optimize the power output of a solar system [22]. Waijung blocksets are used in embedded programming for a 32-bit ARM Cortex microcontroller-based modified DC-P&O approach (STM32F407VGT6) [23]. This provides the problem's highly anticipated results in order to make the standalone system effective with fast-tracking [24], outlining a cutting-edge strategy for optimizing PV module power generation and connecting it with the electrical network in a smooth manner. The invention is a clamped Z-source boost converter that increases PV voltage to enable effective power transmission to the grid. Luo converter and cascaded ANN, a machine learning-MPPT technique, are used under partial shading conditions (PSC) [25] for monitoring the PV system's ideal power.

2. MODELING OF PV SYSTEM

A PV system's components and interactions are modeled in order to forecast performance under various circumstances. Usually, single- or double-diode models are used to depict the solar panels, and MPPT algorithms and efficiency curves are used to model the inverter. The output of the panel is affected by environmental elements such as temperature and sun radiation. PV system software or MATLAB/Simulink are examples of tools that aid in performance modeling, system efficiency evaluation, energy output prediction, and design optimization under a range of operating conditions. Figure 2 depicts an equivalent solar cell circuit.

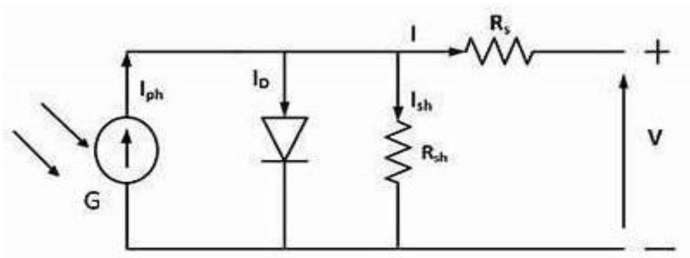

Figure 2. An equivalent solar cell circuit

The following relationship is given by the equivalent circuit (1).

$$I_{ph} = I_p + I_d + I \tag{1}$$

The diode's current, I_d is determined using by (2).

$$I_d = I_0 \left[\exp\left(\frac{R_d + v}{y_2 G}\right) - 1\right] \tag{2}$$

The flow of current in the diode Id is provided by (3).

$$I_p = \left(\frac{R_r + F}{R_p}\right) \tag{3}$$

In (1) gives us the current I expression as in (4).

$$I = -I_d + I_{ph} - I_p \tag{4}$$

In (2) and (3), substituting (4), the characteristic formula becomes into (5).

$$I = I_{ph} - I_0 \left[exp \langle\frac{V + R_S I}{V_t \propto}\rangle - 1\right] - \langle\frac{R_S I + V}{R_p}\rangle \tag{5}$$

Where V is the voltage of the cell; R_s is the series cell of resistance [Ω]; R_p is stands for parallel resistance; I_o is current of saturation (A); V_t is the module's thermal voltage. With N_s being the quantity of interconnected cells in series $V_t = N_s\, kT/q$; T is the cell's temperature [°K]; q is charge of an electron $e = 1.6 \times 10 - 19C$; k is a constant of the diode is the Boltzmann constant $(1.3854 \times 10 - 23\, J°K - 1)$; and a is the diode's constant.

3. MAXIMUM POWER POINT TRACKING CONTROLLERS

By monitoring the MPP and employing techniques like FLC, ANFIS, P&O, and ANN, MPPT controllers maximize the power of PV systems. Although P&O is straightforward, oscillations could occur. In dynamic situations, FLC offers more stable and fluid performance. Fuzzy logic and neural networks are combined in ANFIS to provide efficient tracking with fewer oscillations and lower processing demands.

3.1. Perturb and observe controller

The P&O controller is a mostly used MPPT technique in solar systems. It works by making little adjustments to the operational voltage or current of the solar panel and then tracking the change in power production that results. If power consumption rises after a disturbance, the controller continues to adjust in that direction; whenever the power decreases, the adjustment direction is reversed. The system can track the MPP, where the solar panel produces the greatest energy, thanks to the continual repetition of this process.

3.2. Fuzzy logic control controller

Fuzzy logic principles are used by an FLC to make decisions based on imprecise or uncertain input data. FLCs can handle ambiguity in the real world because they operate with values between 0 and 1, unlike standard control systems that employ binary logic. FLCs employ fuzzy rules that are created by experts, like "IF temperature is high, then fan speed is high." Fuzzification (turning inputs into fuzzy sets), inference (using fuzzy rules), and defuzzification (turning fuzzy output into exact actions) are the three processes in the process.

3.3. Artificial neural networks controller

An ANN controller is perfect for complex, nonlinear, and unpredictable systems since it models and controls dynamic systems using neural networks. ANN controllers learn and adapt from data, enhancing performance through training, in contrast to more conventional controls like proportional integral derivative (PID). They are made up of layers of linked neurons that use weighted connections and activation functions to process inputs. They are useful in dynamic contexts because of their capacity to manage unanticipated actions.

3.4. Adaptive neuro-fuzzy inference systems controller

An ANFIS controller is a hybrid intelligent system that models complicated systems and carries out control tasks by combining the benefits of neural networks and fuzzy logic. It combines the learning powers of neural networks with fuzzy inference systems, which are predicated on human-like reasoning using linguistic factors. The end result is a strong controller that can manage system uncertainties, adjust to changes, and learn from data. By learning from training data, ANFIS employs a neural network to modify the functions of membership.

– Layer 1: defines the input variables and their membership functions (e.g., low, medium, and high).
– Layer 2: calculates the degree of membership of each input with respect to the fuzzy sets.
– Layer 3: applies a rule-based mechanism to calculate the output of each rule.
– Layer 4: computes the weighted sum of outputs, using the rule strengths.
– Layer 5: produces the final output by combining the results from all rules.

4. RESULTS AND DISCUSSION

Table 1 shows simulations of a solar system with a buck-boost converter and MPPT algorithms (P&O, FLC, ANN, and ANFIS), showing that P&O achieved 95-98% efficiency with oscillations. FLC improved efficiency to 96-99%, while ANN reached 98-99% with minimal power loss and high accuracy. ANFIS outperformed all, with 99-100% efficiency, fast responsiveness, and no oscillations, making it ideal for fluctuating conditions.

Table 1. Performance comparison of MPPT controllers

MPPT controllers	Output voltage (volts)	Settling time (ts)	Total harmonic distortion (THD)%
P&O	221.5	0.155	7.75
FLC	224.8	0.655	5.78
ANN	227.8	0.02	3.83
ANFIS	230.1	0.01	1.90

Figures 3 and 4 describe using P&O, FLC, ANN, and ANFIS techniques, the simulated graph of PV power and voltage under steady-state circumstances demonstrates differing tracking efficiency of the MPP.

Generally speaking, FLC shows smoother convergence than P&O, which oscillates about the MPP. By reducing power fluctuations and accelerating convergence to the ideal operating point, ANN and ANFIS techniques enhance system performance in general. Figure 5 shows that under unsteady conditions, the P&O method exhibited significant voltage and current fluctuations, leading to inefficiencies. In contrast, FLC, ANN, and ANFIS methods provided more stable voltage and current profiles, with ANFIS offering the most consistent performance and minimal variation.

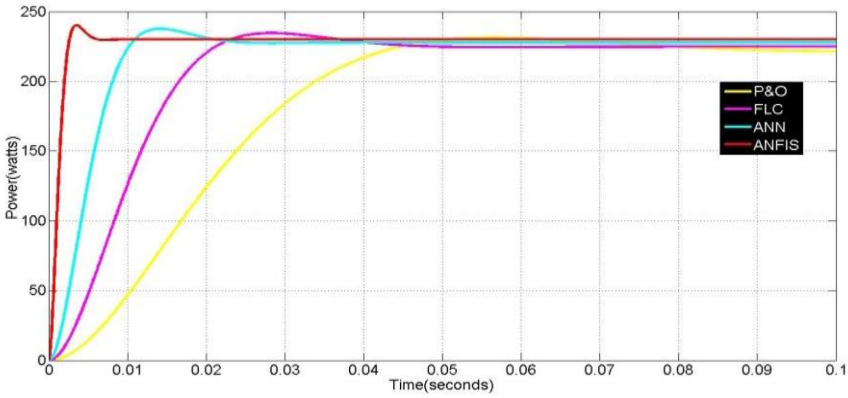

Figure 3. PV power by P&O FLC, ANN, and ANFIS under steady state conditions

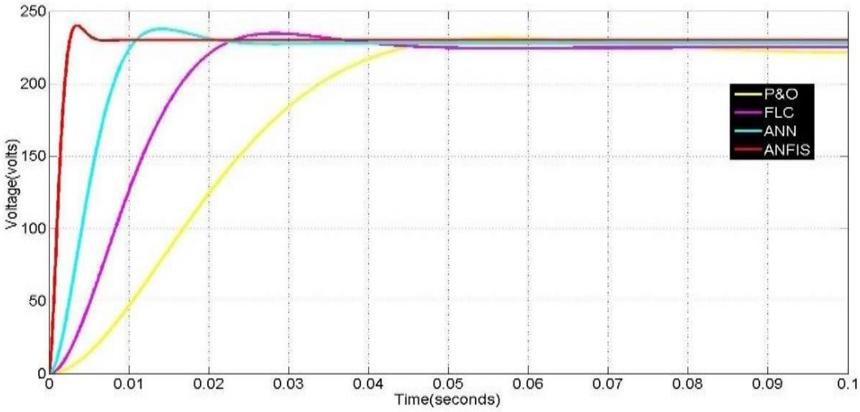

Figure 4. PV voltage by P&O, FLC, ANN, and ANFIS under steady state conditions

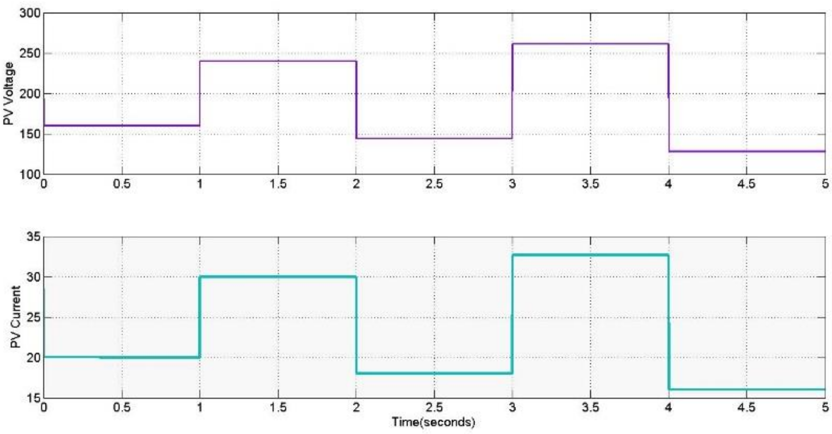

Figure 5. PV voltage and current under unsteady conditions

Under dynamic environmental conditions, the P&O approach suffers from power fluctuations and decreased efficiency, as seen in Figure 6, which represents unstable temperature and irradiance. On the other hand, Figure 7, which shows constant temperature and irradiance, emphasizes the 95-98% steady-state efficiency of the P&O approach. In both situations, the FLC, ANN, and ANFIS approaches performed better; FLC reduced oscillations, ANN offered rapid flexibility, and ANFIS achieved maximum efficiency with the least amount of power loss. In particular, ANFIS remained the most stable and efficient under all circumstances. Figures 8 and 9 depict ANFIS output voltage and ANFIS threshold value.

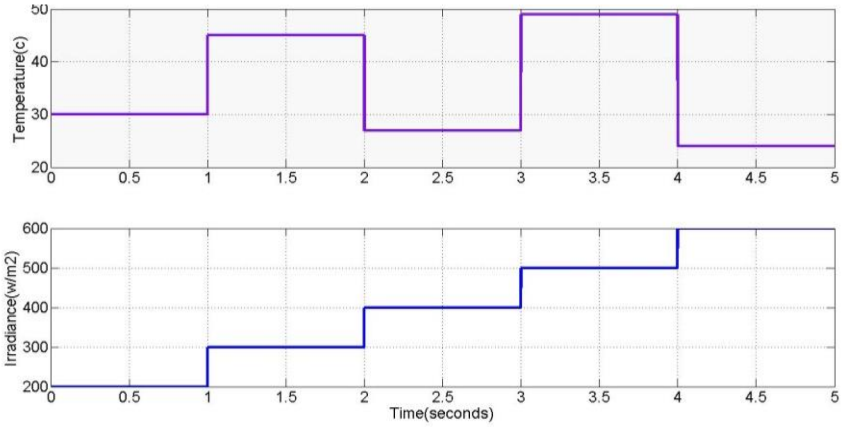

Figure 6. Unsteady temperature and irradiance by PV system

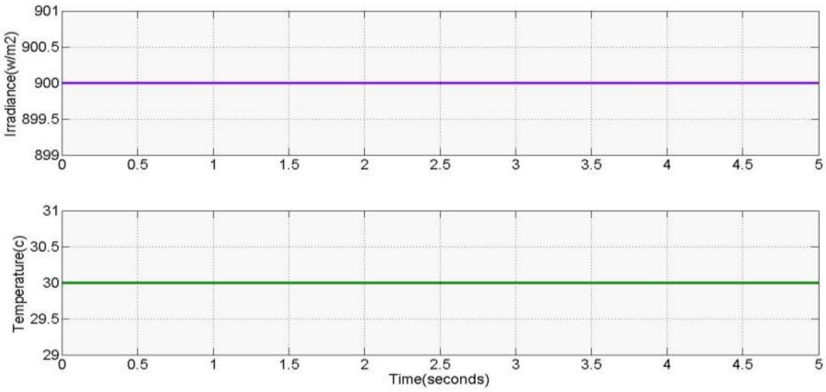

Figure 7. Constant irradiance and temperature by PV system

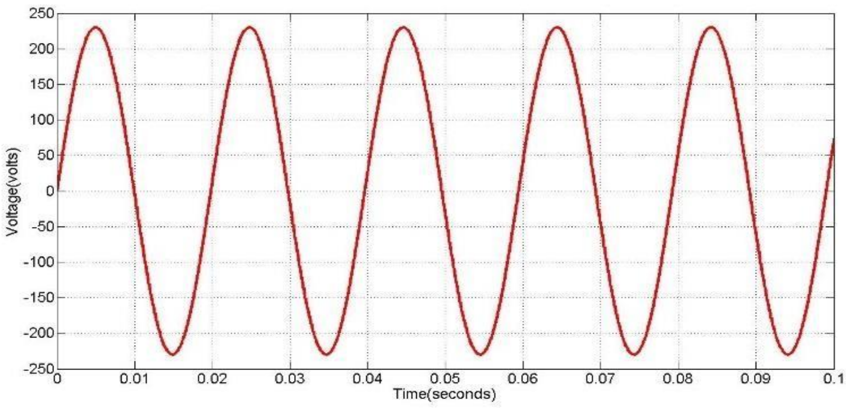

Figure 8. ANFIS output voltage

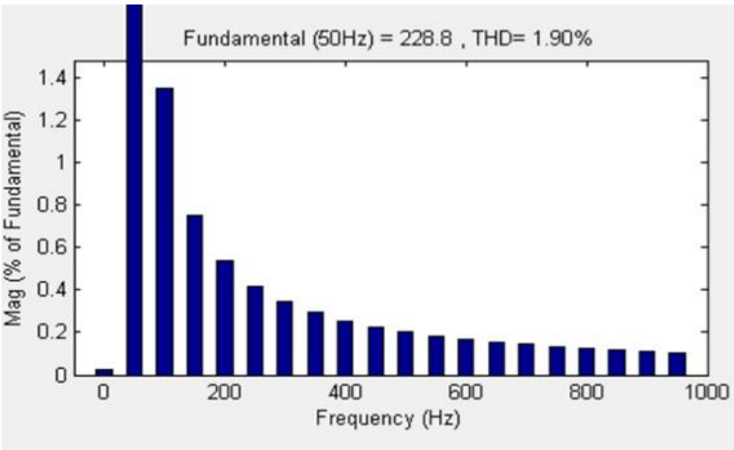

Figure 9. ANFIS threshold value

5. CONCLUSION

Complexity affects how well a PV system with a buck-boost converter and different MPPT algorithms (P&O, FLC, ANN, and ANFIS) performs. Under dynamic situations, FLC enhances stability, whereas P&O is straightforward but less effective. ANFIS delivers the best performance with quick convergence and low error, whereas ANN offers high accuracy but more resources. Overall, the best efficiency, stability, and flexibility across a range of environmental circumstances are provided by ANFIS-based MPPT in conjunction with a buck-boost converter. Future research may focus on developing hybrid intelligent MPPT techniques that combine the strengths of ANFIS and other AI-based controllers to further enhance tracking accuracy, reduce computational complexity, and improve real-time response.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Thiramdasu Chandana	✓	✓	✓		✓	✓	✓	✓	✓		✓		✓	✓
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [MT], upon reasonable request.

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