ANFIS-Based Incremental Conductance MPPT Controller for Enhanced Photovoltaic Energy Extraction

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Abstract*-- Photovoltaic (PV) power systems have strong environmental dependencies on factors like solar irradiance and operating temperature; thus, they exhibit non-linear characteristics in their current-voltage and power-voltage curves. Consequently, efficient Maximum Power Point Tracking (MPPT) strategies have to be adopted to ensure maximum energy harvesting from PV arrays. In this paper, a simulation-based Adaptive Neuro-Fuzzy Inference System (ANFIS) hybrid Inc-Cond MPPT controller for photovoltaic power systems is introduced. The technique stemmed from the complementary goal of combining the analytical correctness of Inc-Cond MPPT with the adaptive learning aspect of ANFIS for enhanced tracking speed and robustness performance, especially under rapidly fluctuating atmospheric situations. An in-depth Simulink simulation platform has been established in a MATLAB environment and implemented with authentic PV module parameters and DC-DC boost converters. Simulation testing on the MPPT control technique is conducted in varying irradiance and temperature conditions and is compared against existing standard P&O and Inc-Cond MPPT strategies. Simulation results confirm that ANFIS hybrid Inc-Cond MPPT methods exhibit optimized tracking speed performance with reduced oscillations around the maximum power point and thus have potential applications in high-performance photovoltaic energy conversion processes.

***Index Terms*— Adaptive Neuro-Fuzzy Inference System (ANFIS), Incremental Conductance, Maximum Power Point Tracking, Photovoltaic systems, MATLAB/Simulink.**

I. INTRODUCTION

The increasing demand for clean, sustainable, and renewable energy resources has led to an increase in the adoption of solar photovoltaic systems. Among all renewable energy resources, solar energy is found to be one of the most potential resources as it is abundant, eco-friendly, and renewable. Although there is lot of development and enhancement in this regard, the efficiency of PV systems has largely been restricted because of its non-linear nature and high dependence on environmental factors like irradiance and cell temperature levels [1], [2].

Power output of the PV array changes continuously with varying operating conditions, and for that reason, there exists a different MPP for a given level of irradiance and temperature. If not controlled, a PV system may run off the MPP, resulting in substantial power waste. To counter that, Maximum Power Point Tracking (MPPT) algorithms are used to change the operating point of the PV system in order to extract the maximum available power at all times [3].

Conventional MPPT algorithms such as Perturb and Observe (P&O) and Incremental Conductance (Inc-Cond) methods are commonly used because of their simplicity. But these algorithms also have limitations such as oscillations about the MPP, insufficient dynamic performance for fast-changing scenarios, and low efficiency for partial shading situations [4]-[6]. To address such drawbacks, intelligent MPPT algorithms using Artificial Intelligence have received considerable interest during recent years.

Adaptive Neuro-Fuzzy Inference Systems (ANFIS) integrate the human intelligence feature of fuzzy logic systems with learning and adaptation characteristics of artificial neural networks. The hybridization makes ANFIS more effective in dealing with non-linearities and uncertainties in a system compared to traditional models [7]-[9]. In this paper, an ANFIS-based Incremental Conductance MPPT control system is designed and developed.

II. PHOTOVOLTAIC SYSTEM MODELING

A solar cell involves the direct conversion of solar energy to electrical energy by the photovoltaic effect. However, for a more precise assessment of the performance of solar cells, an equivalent circuit has to be used to describe solar cells. In this paper, the single-diode model will be employed for its relative simplicity.

A simple model of a PV cell uses a current source to model the photocurrent, a diode, a series resistance, and a parallel resistance. The expression for the current output of a PV cell is given in a non-linear form involving the cell terminal voltage, solar irradiance, and cell temperature.

Operating under uniform irradiance and temperature, the PV array possesses a sole I-V and P-V characteristic featuring a single maximum power point. From these, irradiance changes affect the output current the most, while temperature changes have the most effect on the output voltage. These nonlinear characteristics require the MPPT controllers to track the MPP constantly due to changes in the environment.

In this work, a PV array of series- and parallel-connected modules is modeled in MATLAB/Simulink. The parameters of the PV module are selected based on realistic operation conditions and are summarized in Section V.

III. REVIEW OF CONVENTIONAL MPPT TECHNIQUES

Various MPPT techniques have been proposed in the literature, each of which provides a trade-off between complexity, accuracy, and implementation cost. Among these, the most widely used in commercial PV systems are the P&O and the Inc-Cond methods.

The P&O algorithm perturbs the operating voltage or duty cycle of the DC–DC converter and observes the resulting change in output power. If the power increases, the perturbation continues in the same direction; otherwise, it is reversed. Although simple, P&O inherently oscillates around the MPP in steady state and may fail under rapidly changing irradiance conditions.

Thus, the Incremental Conductance method enhances P&O by taking into consideration the slope of the P–V curve: at the MPP, $dP/dV = 0$. The algorithm compares the incremental conductance, dI/dV, with the instantaneous conductance, I/V, in order to determine the relative position of the operating point with respect to the MPP. Being more accurate, Inc-Cond requires more sensing and computational effort than P&O [13], [14].

These limitations motivate the inclusion of intelligent controllers, such as ANFIS, to further boost MPPT performance.

IV. PROPOSED ANFIS-BASED INCREMENTAL CONDUCTANCE MPPT

The proposed MPPT controller combines Adaptive Neuro-Fuzzy Inference System with the Incremental Conductance algorithm. Inc-Cond offers accurate mathematical data on the mP-PV slope, whereas ANFIS brings adaptability to the process of updating the duty cycle value.

The architecture of the ANFIS includes five layers: fuzzification layers, rule layers, normalization layers, defuzzification layers, and output layers. The input to this ANFIS controller may take values like error and change in error, depending upon the Inc-Cond condition, whereas its output is a control signal, which is further used for changing the duty cycle in a DC-DC boost converter [15]-[18].

The training of the ANFIS with typical operating data of a PV system enables the controller to acquire the best possible actions for control as a function of irradiance and temperature. The hybrid method suppresses oscillations at the steady state, increases the speed of convergence, and increases robustness with respect to variations of environmental factors.

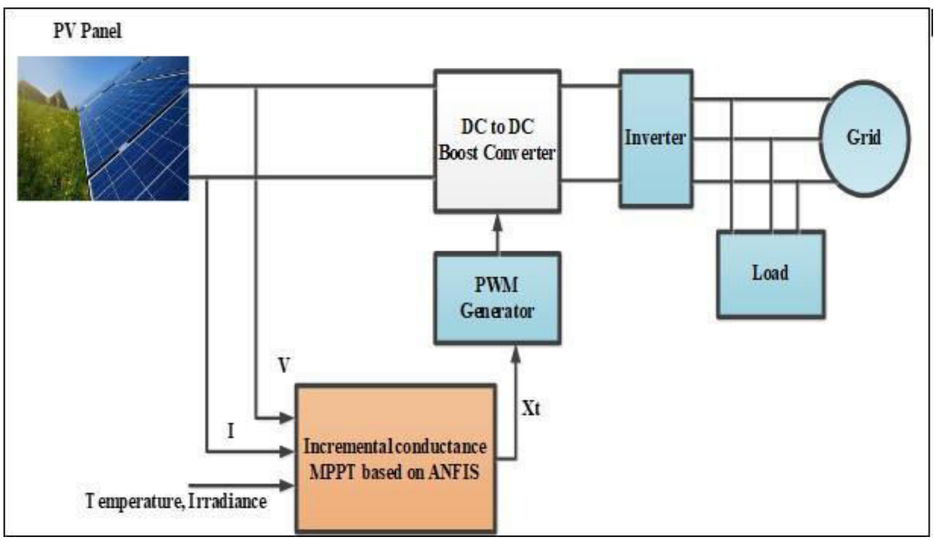

Figure 1: ANFIS based Photovoltaic (PV) systems

V. SIMULATION SETUP AND PARAMETERS

The proposed ANFIS–Inc-Cond MPPT controller is implemented in MATLAB/Simulink. Thereafter, a PV system composed of a PV array connected to a DC–DC boost converter feeding a resistive load is used.

TABLE I: PV MODULE ELECTRICAL SPECIFICATIONS

Parameter	Value
Maximum power	215.196 W
Open-circuit voltage	32.9 V
Short-circuit current	8.21 A
Voltage at MPP	31.6 V
Current at MPP	6.81 A
Cells per module	96

Simulations are run for standard test conditions of 1000 W/m² at 25°C, as well as dynamically varying irradiance in a range from 400 to 1000 W/m² and temperature variation between 25° and 50°C. The proposed controller performance is compared with that of P&O and conventional Inc-Cond MPPT algorithms.

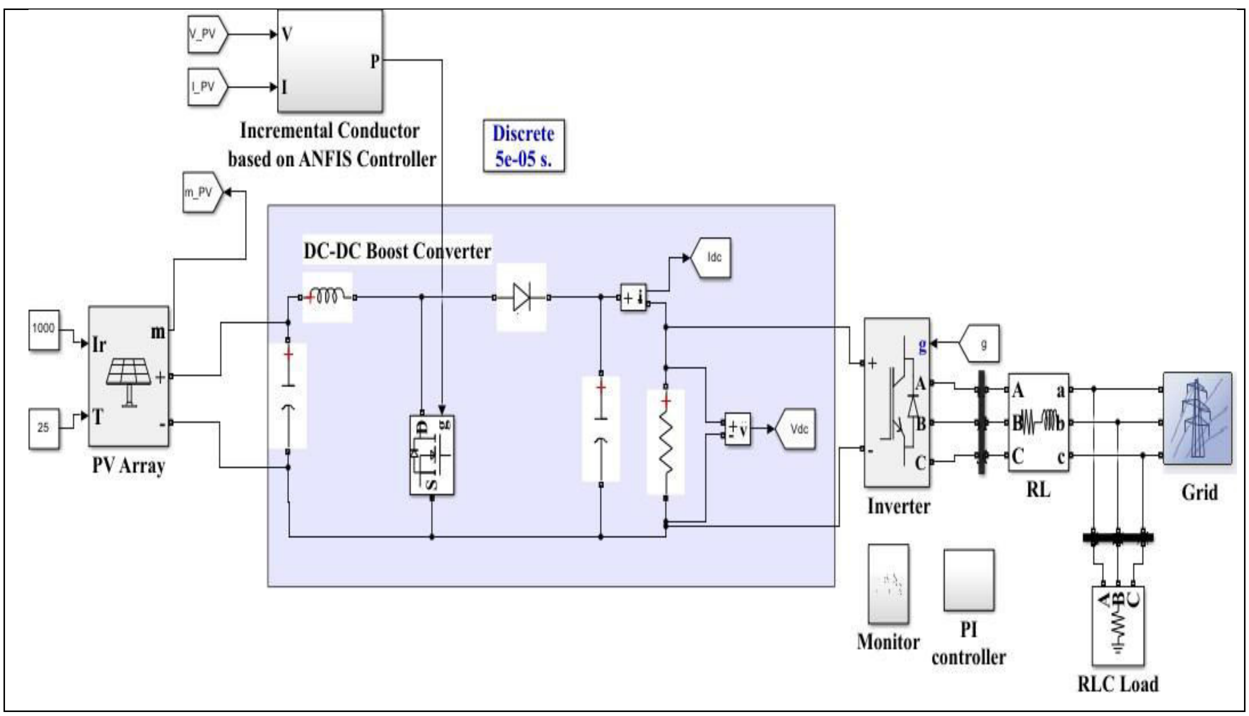

Figure 2: Incremental Conductance based ANFIS controller

Figure 2 shows the MATLAB/Simulink model of the grid-connected PV system using an ANFIS-based Inc-Cond MPPT controller. In the given diagram, the solar-generated PV array produces DC power as an output based on the irradiance and temperature values. Additionally, the

ANFIS-based Inc-Cond controller receives the PV system's voltage and current as its input and produces an optimal duty cycle value for the boost converter. This enables the AC-DC power to be converted to AC by the Voltage Source Inverter (VSI), which is then filtered by the RLC filter before being injected into the grid as the final output. Additionally, the output is controlled by the PI controller.

A. Case 1: Standard Test Conditions (Irradiance of 1000 W/m² and temperature of 25°C)

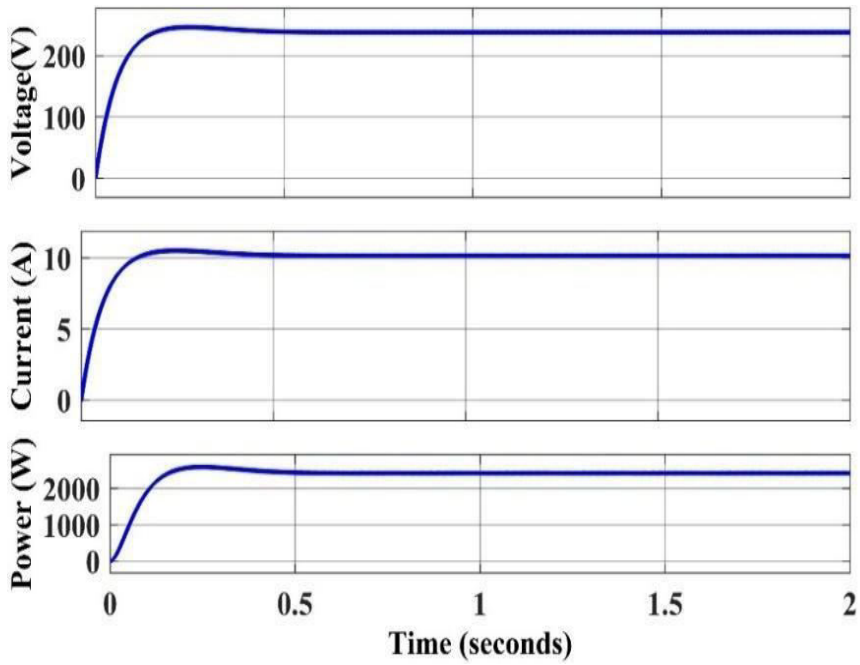

Figure 3: Case 1 MPPT tracking for voltage, current and power

Figure 3 simulation results show the dynamic response of the system over a time period of 2 s. The voltage takes a constant level of approximately 230 V with a slight overshoot before 0.5 s, as does the current, stabilizing at a constant level of about 10 A. As such, the output power momentarily attains a peak of approximately 2300 W before stabilizing at this point.

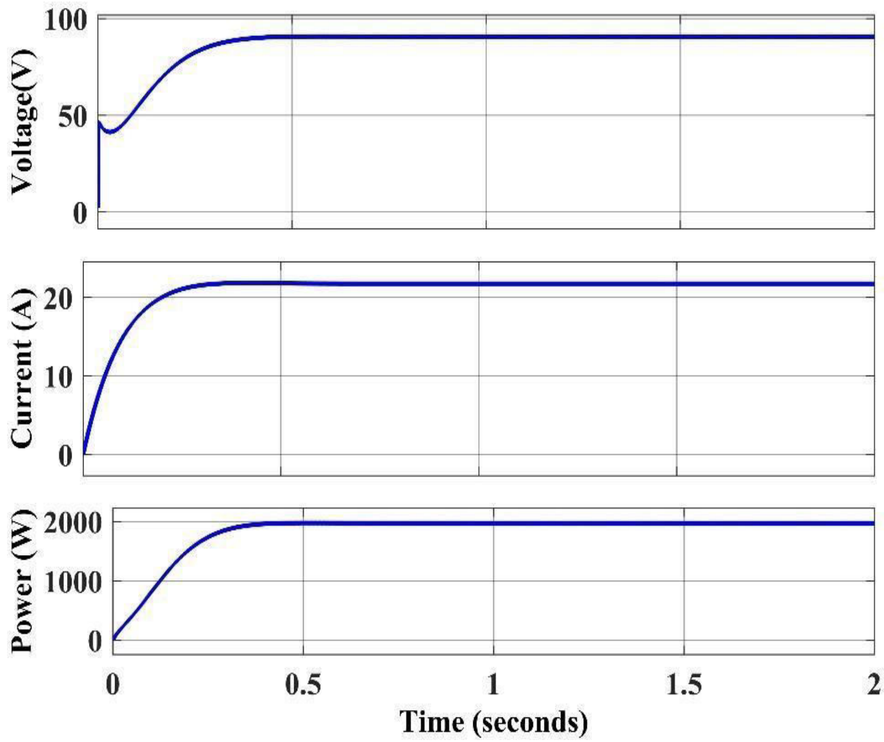

Figure 4 : Case 1 PV current, PV voltage, PV power

Figure 4 simulation results show the system's response for a 2-s duration. The voltage grows steeply from 50 V to stabilize at 90 V at 0.4 s, while the current also grows steeply to stabilize at 24 A at 0.3 s. This causes the output power to peak at 2000 W for a short time during the transient phase and stabilize smoothly around this value.

B. Case 2: Rapidly Changing Irradiance (Irradiance is varied from 1000 W/m² to 600 W/m² at constant temperature)

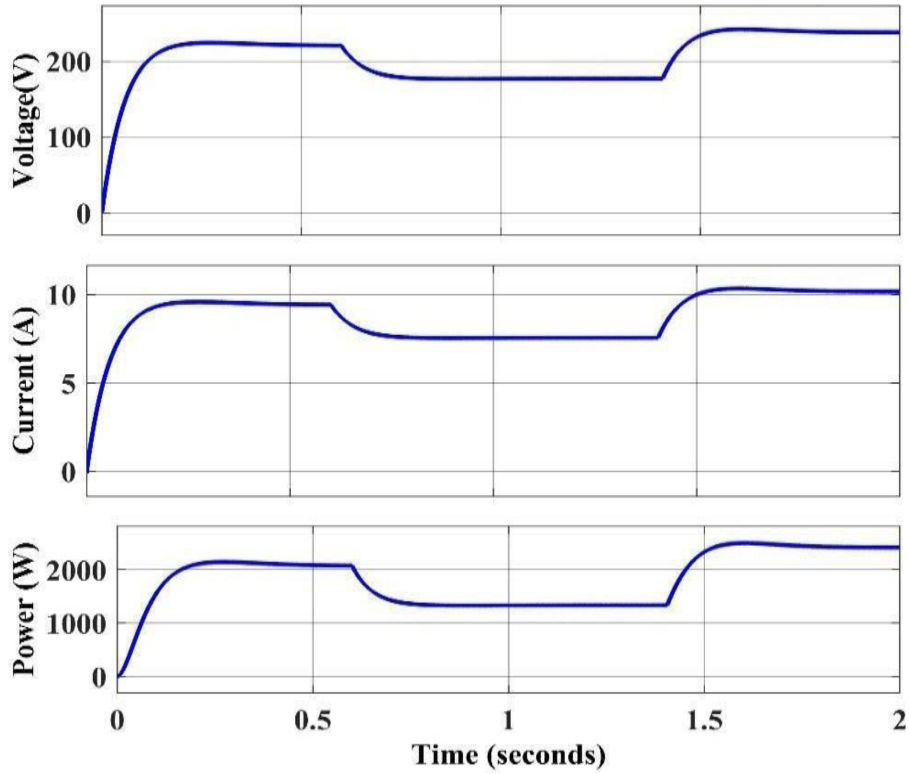

Figure 5: Case 2 MPPT tracking for voltage, current and power

Based on the simulation results obtained in Fig. 5, the dynamic response of the MPPT controller in a 2-second time interval indicates that the voltage levels started increasing rapidly to around 200 V in the initial 0.2 s, held steady until 0.6 s, decreased to around 150 V until 1.4 s, and then increased further to settle around 200 V. Similarly, the current trend also indicates that the current levels started increasing to around 10 A, then decreased to around 7 A, and then recovered further to around 10 A. As a result, the output power levels also started peaking around 2000 W, then decreased to around 1300 W, and then increased further to approach the initial peak.

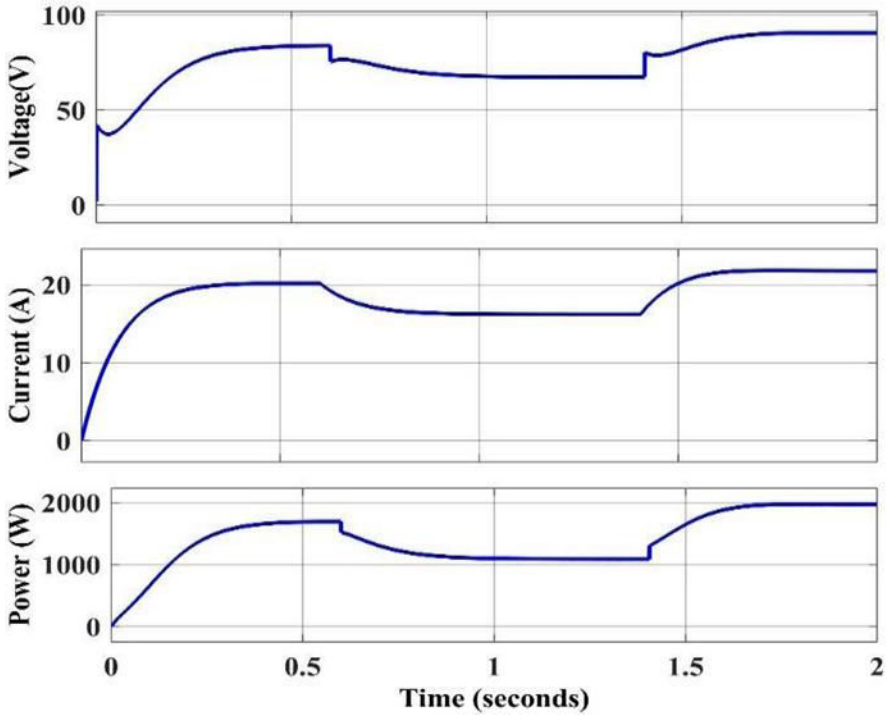

Figure 6: Case 2 PV current, PV voltage, PV power

Figure 6 shows the PV system performance for a 2-s period regarding voltage, current, and power. The voltage rises and settles around 90 V, showing significant drops at 0.6 s and 1.3 s, and then recovers. At the same time, the current shows a significant increase up to 20 A, then a drop at 0.6 s, and an increase again after 1.3 s. Therefore, the system output power shows significant values above 1800 W, then significant drops at the system disturbance periods, and finally stabilization.

C. Case 3: Simultaneous Irradiance and Temperature Variation

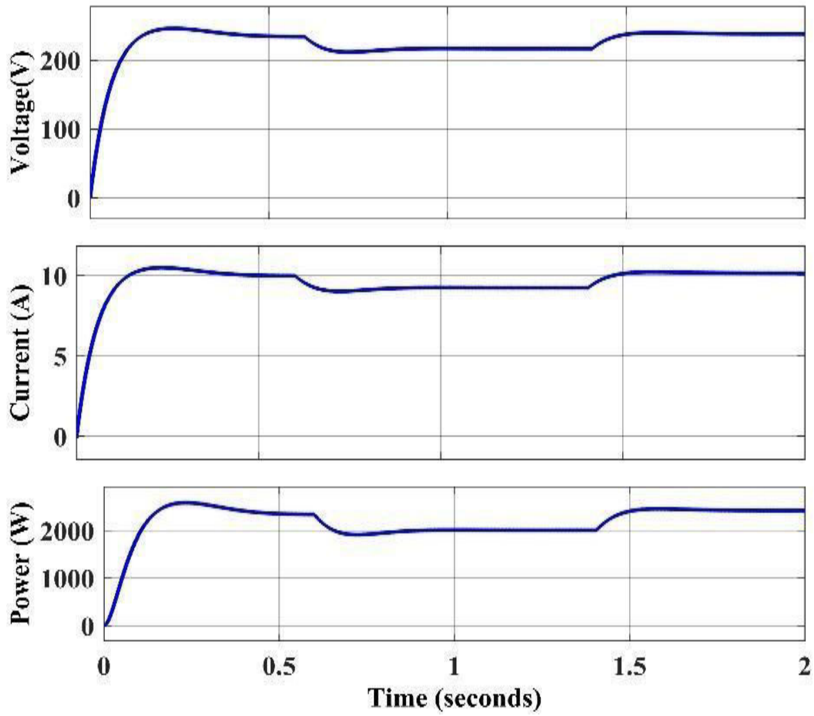

Figure 7: Case 3 MPPT tracking for voltage, current and power

From the results of the simulation obtained in Fig. 7, it can be seen that after the 2s period, the system output reveals that the voltage first increases to around 200 V at 0.2 s, holds its position until 0.6 s, slightly reduces until the middle period, and again advances to around 220 V at the end of the simulation. A similar pattern is observed in the case of the current, which first advances to around 10 A, slightly reduces, and then recovers to its initial position. As a result, the output power first reaches its peak at around 2600 W, reduces until the middle period, and again advances to its peak. between 0.6 and 1.4 seconds due to the drop in both voltage and current. After 1.5 seconds, the power rises again to around 2500 W and stays steady until the end. This simulation shows that the system experiences an initial fast response, a short period of reduced performance, and then a recovery to a stable operating condition. [10] discussed that using wireless technologies like Wi-Fi or WiMAX, a VANET enables communication between and among moving vehicles as well as Road Side Units. As VANETs develop, their potential uses will increase. [12] discussed that A robot is a machine that can automatically do a task or a series of tasks based on its programming and environment. They are artificially built machines or devices that can perform activities with utmost accuracy and precision minimizing time constraints.

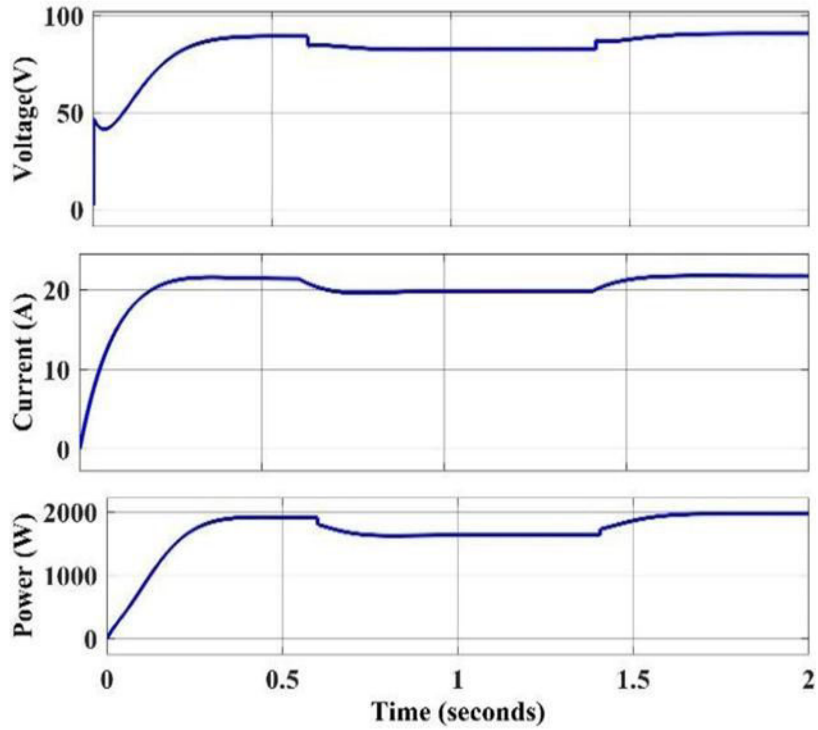

Figure 8: Case 3 PV current, PV voltage, PV power

Figure 8 depicts the performances of the PV system over a span of 2 s. The voltage increases rapidly and reaches 90 V, remains at that value up to 0.6 s, then decreases slightly to approximately 80 V until 1.4 s and then recovers to 90 V. The current similarly rises to nearly 22 A in a short span, reduces to nearly 20 A, and finally rises to 22 A again. Hence, the output power reaches a peak of nearly 2000 W, decreases to nearly 1800 W for the mid-interval, and finally is again nearly 2000 W after fast dynamic response and stability recovery.

VI. RESULTS AND DISCUSSION

A. Efficiency

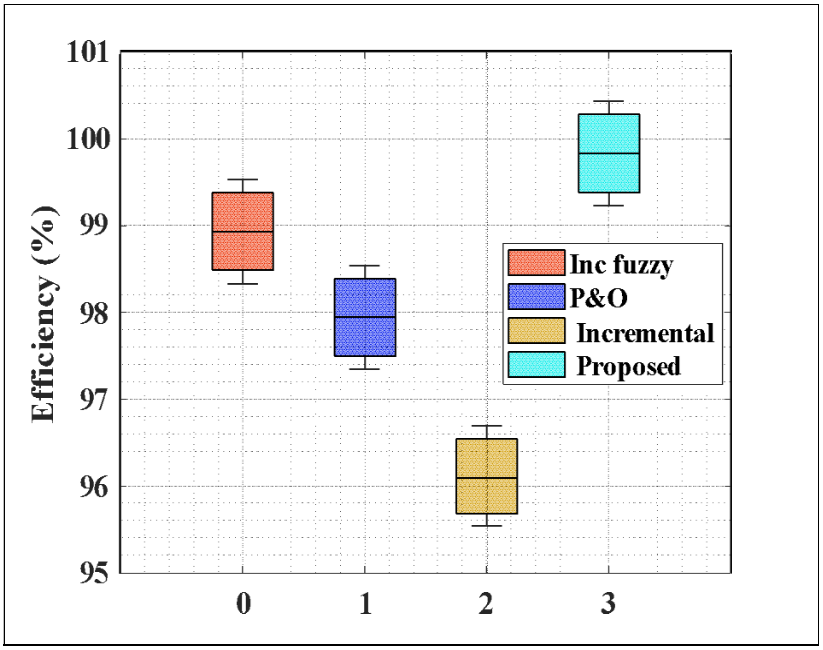

Figure 9: Comparison analysis of efficiency

Figure 9 presents the box-plot analysis of the efficiencies of the four MPPT algorithms. First, the new method presents the highest efficiency, always hovering around 100%. Inc-Fuzzy presents the next best results with efficiencies ranging from 98.5% to 99.5%. Efficiency for the P&O algorithm presents moderate values between 97.5% and 98.5%, while the lowest efficiencies lie within the scope of the Incremental algorithm, ranging from 95.5% to 96.5%.

B. Power

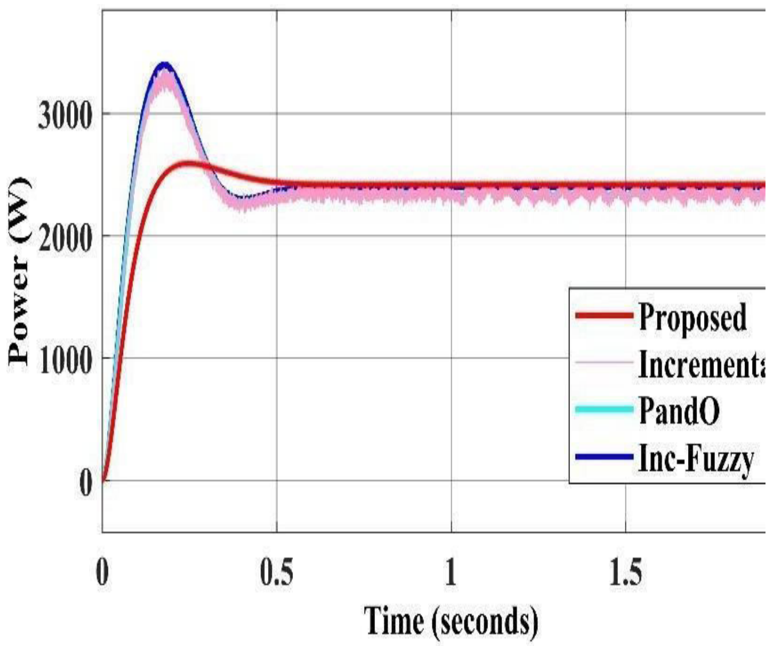

Figure 10: Comparison analysis of power supply

The graph in Figure 10 illustrates the power output response comparison of the four MPPT techniques. The result reveals that the power output response of the proposed algorithm gradually reaches a steady state of about 2500 W without any overshoot. In contrast, the Incremental, P&O, and Inc-Fuzzy algorithms reach their initial peaks beyond 3000 W. Moreover, the result also reveals that there are overshoots in the power output responses in the Incremental, P&O, and Inc-Fuzzy algorithms. The comparative analysis of the power output response of the mentioned techniques is presented in Table 3. The parameters employed in the comparison are rise time, peak time, settling time, and peak overshoot.

TABLE 2: COMPARATIVE ANALYSIS OF PROPOSED TECHNIQUE

Comparative techniques	Rise Time	Peak Time	Settling Time (Ts)	Peak Overshoot (Mp)
Proposed	**0.0213**	**0.2489**	**0.8696**	**7.19**
Incremental fuzzy	**0.0595**	**0.8847**	**0.9091**	**8.43**
P&O	**0.0605**	**0.9103**	**2**	**39.81**
Incremental	**0.0599**	**1.761**	**0.9524**	**44.15**

The simulation outcomes show that the ANFIS-based Incremental Conductance algorithm has a significantly better performance than the existing Incremental Conductance method. Model ANFIS-Inc-Cond takes less time to approach the MPP point with reduced oscillations, even in comparison to the existing methods. For the irradiation variation case, the ANFISIS-Inc-Cond model remains under steady-state stabilization with proper MPP identification, proving to be more efficient than the existing methods, including the Proportionate Order algorithm, in terms of tracking performance. In summary, ANFISIS performance improves the overall output, settling time, and ripple effect of the PV model by a considerable margin.

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