Fuzzy logic control based MPPT for standalone photovoltaic system with battery storage

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ABSTRACT

Considering its favorable characteristics, photovoltaic energy is widely recognized as highly beneficial to the environment. To achieve continuous maximum output power across the PV system, an efficient control strategy is developed after studying several maximum power point detection (MPPT) techniques. Consequently, this paper presents a useful control technique for maximizing power extraction from PV systems under varying conditions. The paper focuses on the design of a fuzzy logic control (FLC)-based maximum power point tracking (MPPT) system for a standalone photovoltaic (SAPV) system with battery storage. The FLC is employed to extract the maximum power from a PV module and integrate it with the battery to supply the load. The FLC offers advantages over conventional MPPT methods, such as accurate and rapid response to changes in environmental conditions, including solar irradiance and temperature. The PV system exhibits low total harmonic distortion (THD), making it ideal for household appliances, and can deliver 230 Vrms of single-phase output AC power. The system is designed and implemented in MATLAB/Simulink, incorporating a solar module, DC-to-DC converters, battery storage, and an inverter for supplying AC loads. Simulation results for selected test conditions are presented and discussed. The system performance is evaluated through steady state tests and dynamic tests in simulations.

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1. INTRODUCTION

Energy generation is decreasing exponentially while energy demand is increasing worldwide due to the depletion of conventional energy sources and their serious impact on the environment. Consequently, active support for research on photovoltaic (PV) generation systems aims to minimize environmental challenges such as the greenhouse effect and air pollution. PV generation systems face two major issues: relatively poor electric power generation efficiency in low irradiation situations, and fluctuating electric power output based on weather conditions, specifically solar radiation intensity (irradiation) [1]. As a result, the implementation of a real-time maximum power point tracking (MPPT) control mechanism becomes essential in PV generation systems [2]. One disadvantage of PV systems is their dependence on sunlight, which is not available 24 hours a day. Therefore, PV systems require batteries that need periodic maintenance and replacement every three to five years [3].

A review of various maximum power point tracking (MPPT) techniques for PV systems, including conventional, mathematical models, and artificial intelligence (AI) methods, was conducted in [4]. It showed that AI methods are widely used for their accuracy and efficiency. Ishaque *et al.* [5] developed an approach based on the particle swarm optimization (PSO) algorithm, which demonstrated outstanding performance. However, this approach requires the user to specify several settings, making it challenging for commercial utilization. The perturbation and observation (P&O) approach is often employed in some PV systems [6]–[11]. The P&O approach works by changing the sample rate while perturbing the reference value [7]. Although this method exhibits steady-state inaccuracy and damped dynamic response. Femia *et al.* [12] the issue with artificial neural networks (ANN) based algorithms is their reliance on accessible training data under varying environmental conditions, necessitating data updating whenever the array configuration changes. The authors in [13]–[15] reviewed several algorithms, including artificial bee, ant colony, PSO, flashing firefly, and grey wolf algorithms. While the genetic algorithm is more stable, its application is more complex as it requires intricate calculations, equations, and user input for some variables. Additionally, the maximum power operating point varies with the insolation level and temperature [16], making the tracking control of the maximum power point a complicated problem. To overcome these challenges, a fuzzy logic control (FLC) based MPPT technique is proposed.

This paper presents the design of a single-phase inverter integrated with a DC-to-DC converter for a standalone photovoltaic (SAPV) system. The converter incorporates fuzzy logic control (FLC) based maximum power point tracking (MPPT) technique to generate a pulse width modulation (PWM) signal. This technique enables rapid tracking of the maximum power (MP) from the PV module. The proposed SAPV system consists of a PV array, DC-to-DC converter, batteries, single-phase boost inverter, and load. The power from the PV module is extracted and boosted by the DC-to-DC boost converter. To regulate the converter output voltage and extract the MP from the PV module, the duty cycle of the converter is controlled using FLC-based MPPT. The boost converter charges the batteries, and the energy from the batteries is transported to the AC load through a single-phase boost inverter. The current and voltage total harmonic distortion (THD) are measured and comply with IEEE 519.

The findings of this study contribute to the performance and efficiency of the project. By utilizing the FLC-based MPPT method, the efficiency of the PV system can be improved, especially under rapidly changing irradiance. Moreover, compared to other MPPT techniques, the proposed method provides a stable response as the FLC adjusts the perturbation size based on the situation. The FLC approach also eliminates the need for precise knowledge of PV characteristics [17]. Therefore, with the implementation of this technology, the PV system can be enhanced and optimized.

2. METHODOLOGY

The proposed fuzzy logic control (FLC) based maximum power point tracking (MPPT) system for standalone photovoltaic (SAPV) with battery storage is depicted in Figure 1. The solar module converts incident solar radiation into DC electricity within the system [18]. The boost converter, controlled by FLC based MPPT, maximizes power extraction from the solar module while accounting for variations in solar radiation, temperature, and protects the battery from overcharging and under-discharging. The battery stores excess energy when the solar module generates more power than the load demand or supplies power to the load during periods of low solar generation, such as cloudy or rainy days or at night. The inverter converts the DC power into AC power at the same voltage level and frequency as the power grid, enabling the use of standard AC loads and electric appliances [19]. As the output power of the solar array is subject to weather conditions, the successful operation of the SAPV system relies on determining the optimal size of the solar module and battery to meet the load demand.

2.1. PV characteristics and modeling

Figure 2 illustrates the overall simulation model for this project, implemented using a MATLAB/Simulink model. For this study, the Yingli Energy (China) YL265C-30b solar PV array is selected as the power source. The specifications of the module are provided in Table 1. The PV array consists of 1 series-connected module per string and 1 parallel string. The simulation model is evaluated under various environmental conditions, including different temperatures and solar radiation. The PV array typically generates low-voltage energy, which can be challenging to handle depending on the required power output. To address this issue, a boost converter can be employed in specific scenarios [20], [21]. Figure 3 illustrates a boost converter powered by the PV array.

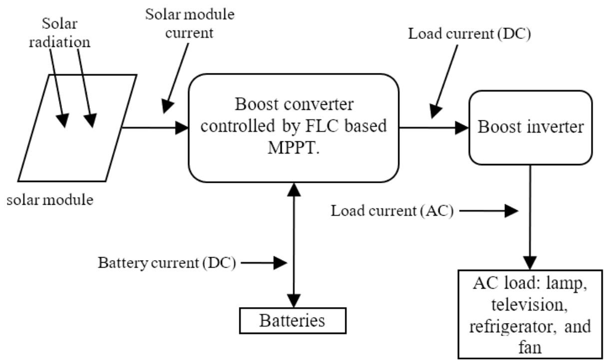

Figure 1. SAPV system

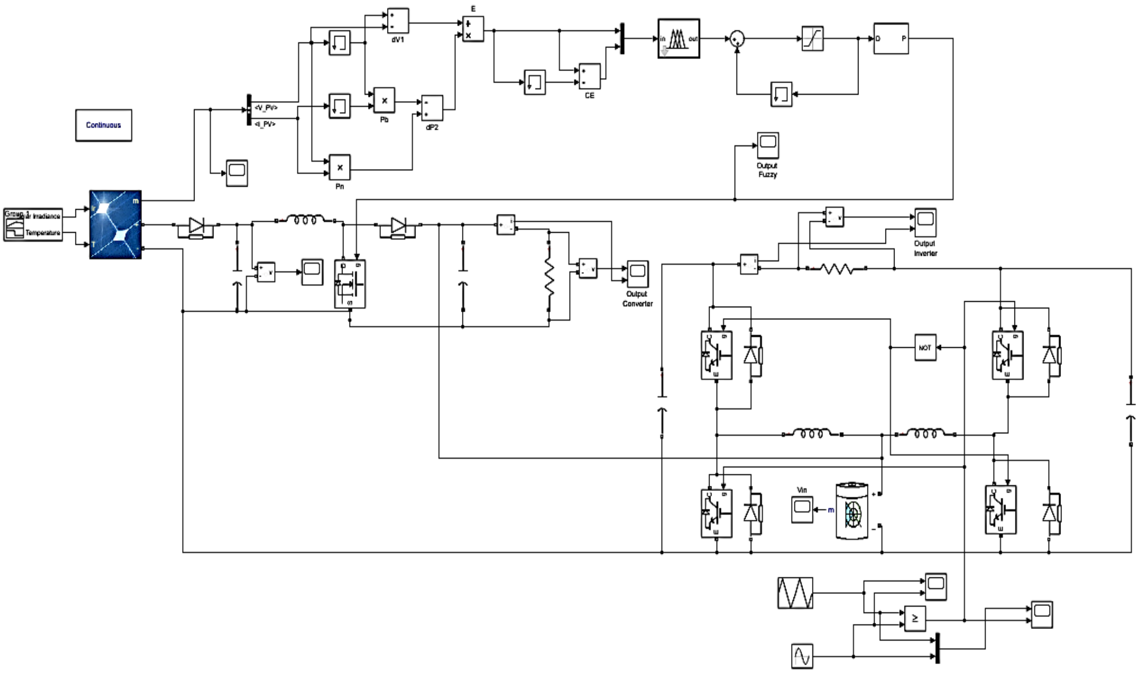

Figure 2. Overall simulation model using MATLAB/Simulink

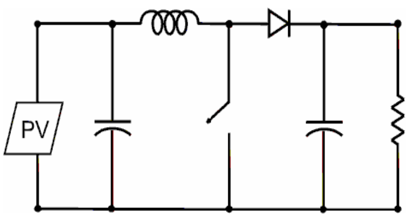

Figure 3. Boost converter powered by the PV array

Table 1. Specification of PV array

Parameter	Value
Max power	265.2174 W
Voltage at max power point, V_{mpp}	30.38 V
Current at max Power Point, I_{mpp}	8.73 A
Open circuit voltage, V_{oc}	38.28 V
Short circuit current, I_{sc}	9.35 A
Total number of cells per module, N_{cell}	60
Number of parallel string, N_p	1
Number of PV module in series per string, N_s	1

2.2. FLC MPPT Technique

FLC is utilized to control the duty cycle of the DC-DC Boost converter, enabling the extraction of the maximum power (MP) from the PV module. The FLC's primary function is to measure the voltage and current of the PV module at specific radiation and temperature levels in order to calculate the power. This calculated power value serves as the input for the FLC [22]. As depicted in Figure 3, the fuzzy inference process usually includes four parts: fuzzification, fuzzy rules base, inference method, and defuzzification. The final output of the defuzzification process is determined by the defuzzification factor, which sets the duty cycle for the operation of the boost converter switches [23].

- Fuzzification: this process involves converting specific input values into degree of membership of fuzzy sets through the use of membership functions. The membership functions scale and normalize the voltage and current measurements. In this fuzzy control system, the linguistic variables are assigned membership function values using five fuzzy subsets: negative big (NB), negative small (NS), zero (ZE), positive small (PS), and positive big (PB). Triangular membership functions are employed in the fuzzy control design.
- Fuzzy rule base: this is the "brain" of fuzzy logic inference, storing all the "IF-THEN" rules required for fuzzy inference. For example, a rule may state: "IF (I_{pv} is NB) AND (V_{pv} is PB), THEN (ΔD is ZE)," which means that when the current PV is "negative big" and the voltage PV is "positive big," the resulting duty ratio is set to "zero" in order to decrease the output voltage. These rules are typically described by experts using natural language based on their experience. The rule base of the FLC is presented in Table 2 [24].
- Inference method: this refers to the approach used to derive the final fuzzy conclusion based on the degree of membership of input variables to fuzzy sets and the detailed fuzzy rules. There are various methods for fuzzy inference, and the choice of method can lead to different conclusions. Among the methods, the Mamdani inference method based on the max-min compositional rule is commonly employed.
- Defuzzification: this process involves converting the fuzzy conclusions into specific output values. The most commonly used method is the center of gravity (CoG) method. The output of the FLC represents the duty cycle that controls the DC-to-DC converter's switch through the generation of pulse width.

The output of the FLC represents the duty cycle of the DC-DC converter, as illustrated in Figure 4. Membership functions are used to scale and normalize the voltage and current measurements. Five fuzzy subsets, namely negative big (NB), negative small (NS), zero (ZE), positive small (PS), and positive big (PB) are assigned membership function values for the linguistic variables. Triangular membership functions are employed in the fuzzy control system developed in this study. The rule base of the FLC, shown in Table 2 [24], utilizes voltage (V_{pv}), current (I_{pv}), and duty ratio (ΔD) as inputs to the converter.

The output from the PV module is fed into the boost converter. The voltage (V_{pv}) and current (I_{pv}) of the PV module serve as inputs to the fuzzy MPPT controller. The fuzzy MPPT generates control pulses for the boost converter, using the duty cycle output. Figures 4 to 6 illustrate the membership functions of the input variables and the output [25].

Table 2. Rule base of fuzzy logic controller

V_{pv} I_{pv}	NB	NS	ZE	PS	PB
NB	NB	NS	NS	ZE	ZE
NS	NS	NS	ZE	ZE	PS
ZE	ZE	ZE	PS	PS	PS
PS	ZE	PS	PS	PS	PB
PB	PS	PS	PS	PB	PB

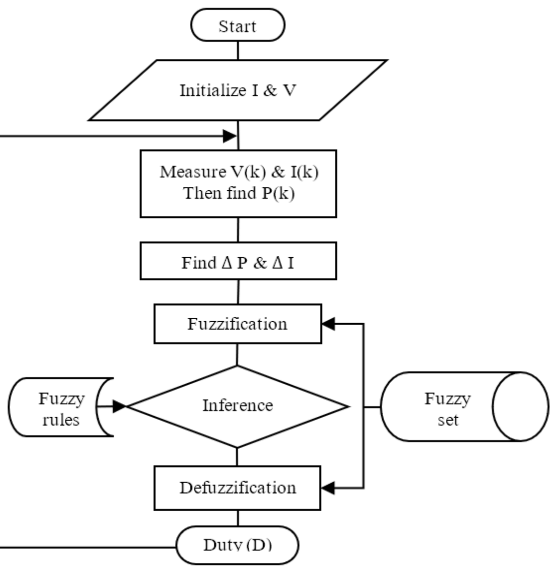

Figure 3. FLC MPPT flow chart

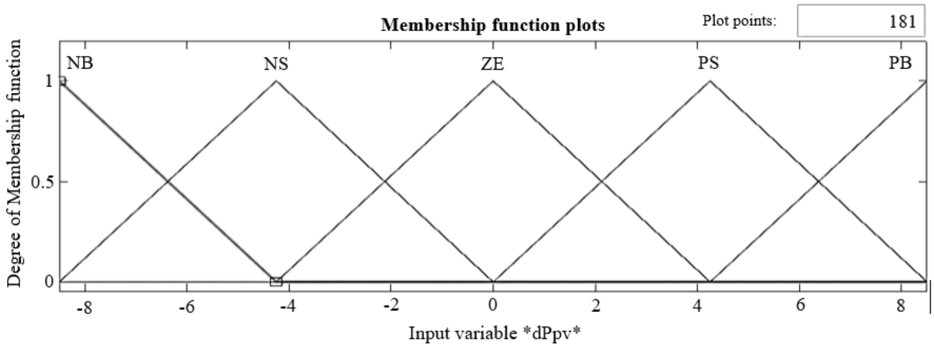

Figure 4. Membership function of input variable 1 (V_{pv})

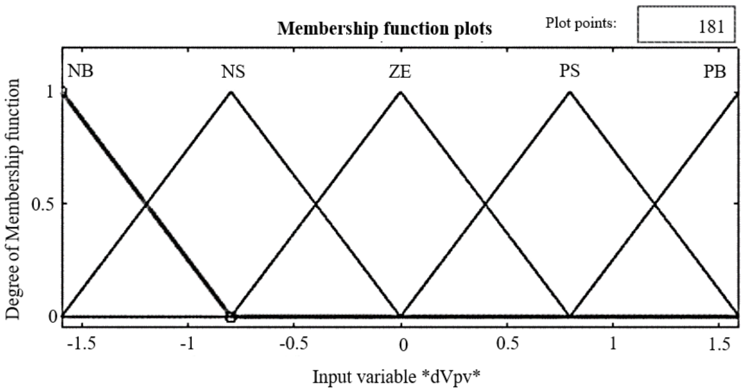

Figure 5. Membership function of input variable 2 (I_{pv})

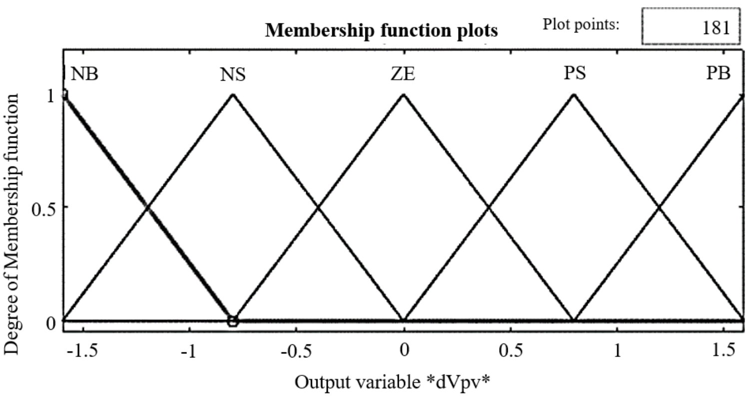

Figure 6. Membership function of output variable (ΔD)

3. RESULTS AND DISCUSSION

This section presents and discusses the results of the FLC-based MPPT for SAPV systems with battery storage. The output was implemented using MATLAB based on the obtained results. The evaluation of the system performance includes two types of tests: steady-state tests and dynamic tests.

3.1. Steady-state test

The steady-state or static state refers to the operation of the MPPT algorithm under constant solar irradiance and temperature. In this study, simulation results were generated using a solar irradiance of G=1000 W/m² and a cell temperature of T = 65 ^{0}C. Figure 7 illustrates the simulation results of the DC voltage, which is 194 V, and the DC current, which is 1.94 A, from a PV module using the FLC-based MPPT algorithm. Figure 8 shows the simulation results of the AC voltage, which is 230 Vrms, and the AC current, which is 1.22

Irms. The simulation involves a boost conversion from 180 V (nominal voltage) and 200 Ah (rated capacity) batteries. Overall, the results in this section demonstrate that the proposed fuzzy algorithm performs well, exhibiting a fast response time, low total harmonic distortion (THD), and no overshoot or undershoot during steady-state operation.

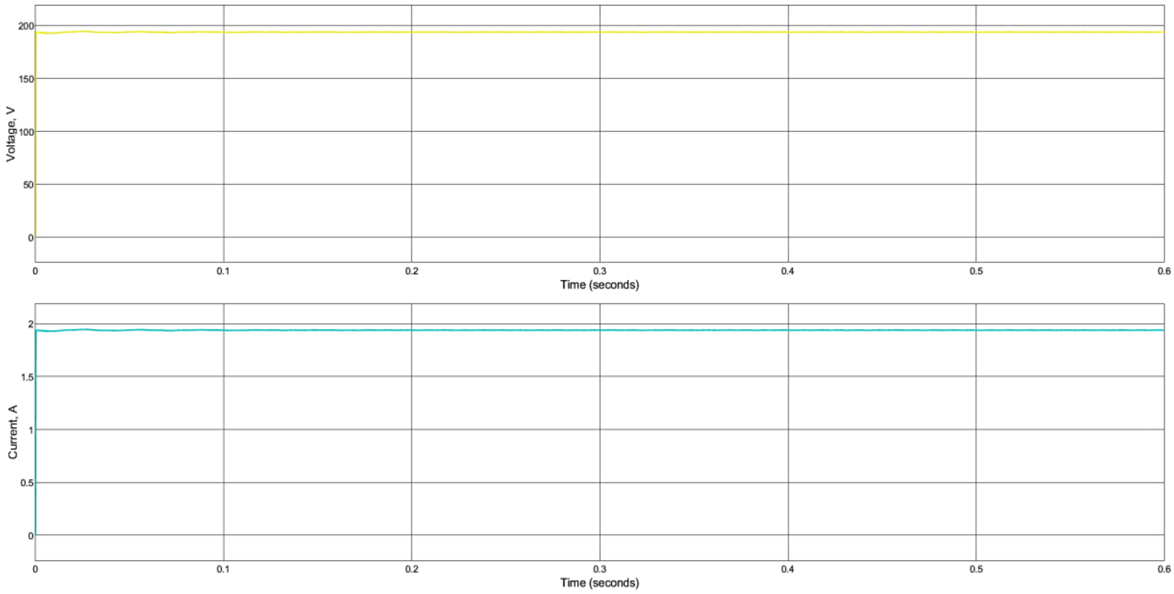

Figure 7. DC voltage and DC current at solar irradiance, G = 1000 W/m² and cell temperature, T = 65 °C

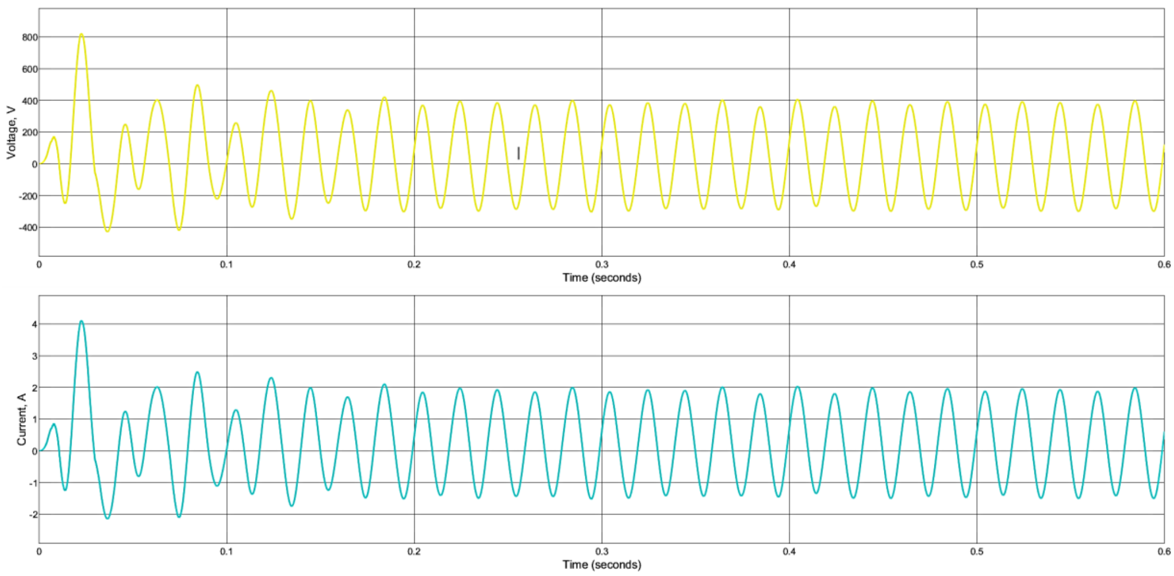

Figure 8. AC voltage and AC current at solar irradiance, G = 1000 W/m² and cell temperature, T = 65 °C

3.2. Dynamic test

In the second part, the dynamic response of the MPPT is tested by varying the solar irradiance and module temperature. The MPPT dynamic response test is conducted using a staircase irradiance and temperature profile, which is a commonly used method for analyzing the performance of MPP trackers. In the simulation, the solar irradiance and temperature are linearly increased from 600 W/m² at 45 °C to 1000 W/m² at 65 °C, as shown in Figure 9. Simulations were conducted to observe the overall response of the system over a period of 1 second. In real conditions, solar radiation can change in as little as 300 ms, necessitating rapid response from MPP trackers.

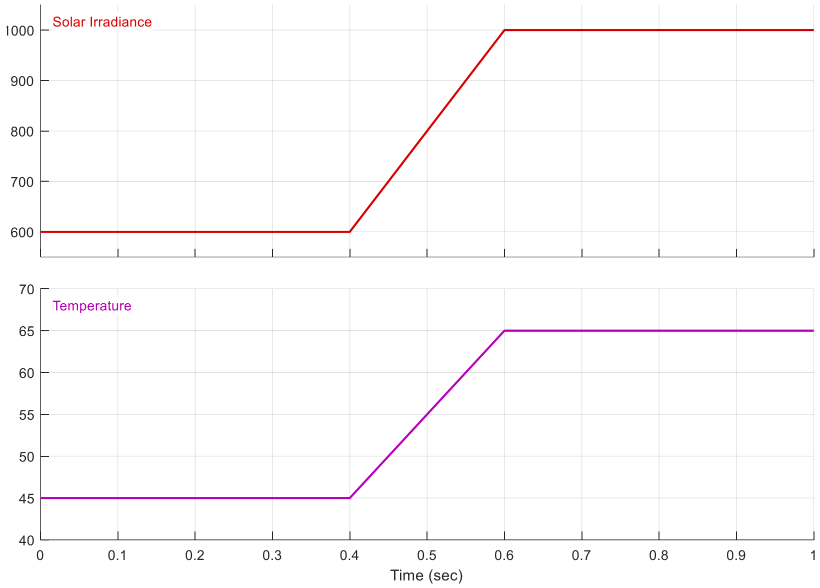

Figure 9. The solar irradiance and temperature are increased linearly from 600 W/m² with 45 °C to 1000 W/m² with 65 °C

Figure 10 shows the DC output voltage at 194 V and current at 1.94 A. Despite the linear increase in solar radiation and temperature, there is no significant impact on the voltage and current values. Once a DC voltage is present at the battery terminal, it is sent to the DC boost inverter to be converted to AC. The inverter efficiently transforms the DC voltage of 180 V to an AC voltage of 230 V_{rms} and a readily available AC current of 1.167 I_{rms} for residential loads, without the need for a transformer. The simulation results are depicted in Figure 11. The AC output of the inverter dynamically adjusts with the variations in solar radiation, temperature, and the maximum power point reached in each second. From the figure, it can be observed that the voltage (V_{mp}), current (I_{mp}), and power (P_{mp}) reach their respective maximum points smoothly, without any overshoot or undershoot.

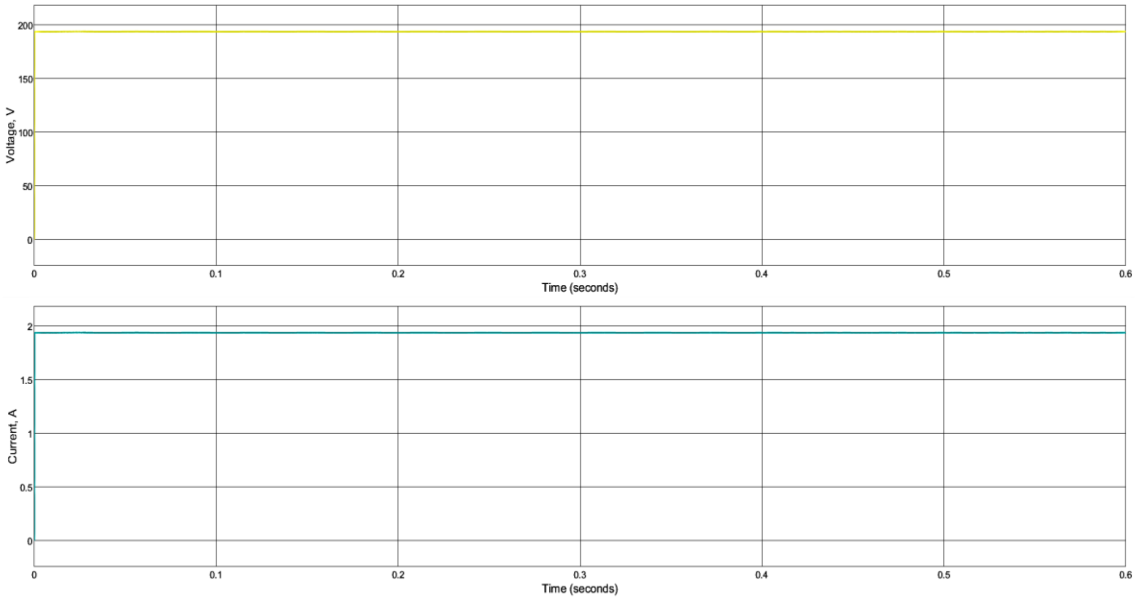

Figure 10. DC voltage and DC current as solar irradiance and temperature increase linearly from 600 W/m² at 45 °C to 1000 W/m² at 65 °C

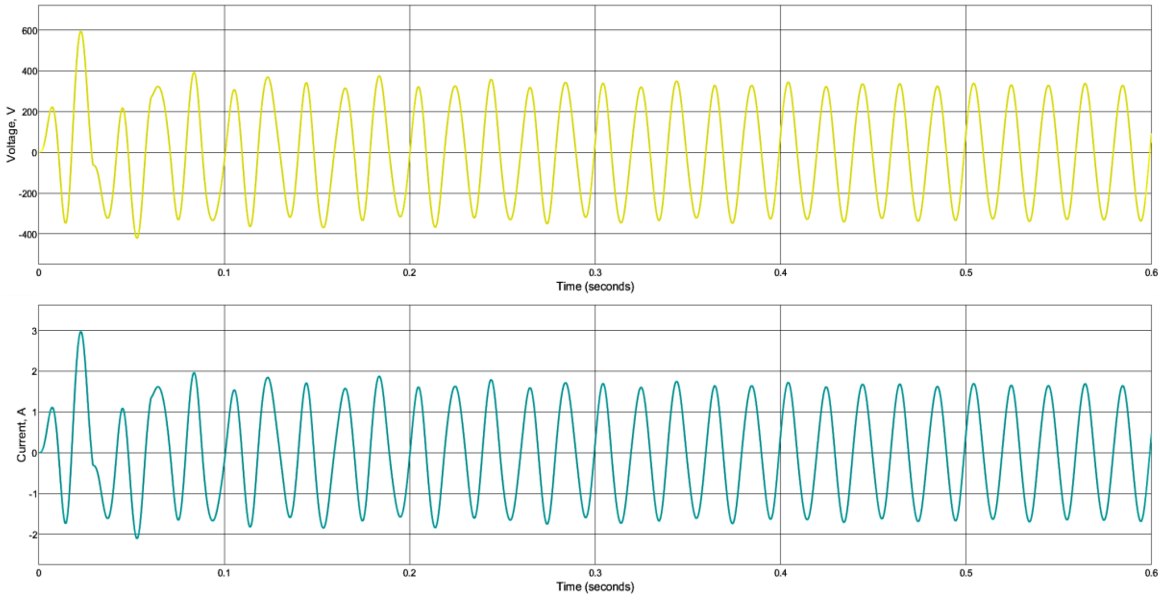

Figure 11. AC voltage and AC current as solar irradiance and temperature increase linearly from 600 W/m² at 45 °C to 1000 W/m² at 65 °C

For the AC load shown in Figure 12, the total harmonic distortion (THD) of the proposed system is measured at 2.06%. This value is well within the compliance limits set by the IEEE 519 standard, which states that the total harmonic current distortion (THDi) of rated inverters should be less than 5%. This achievement brings both economic and technical advantages. The simulation results demonstrate that the system can efficiently adjust the fuzzy parameters, ensuring fast response, good temporary performance, and insensitivity to external interference variations. The system effectively supplies energy to the utility grid with low harmonics. Furthermore, the results indicate that the harmonic distortion of the output inverter current waveform can be maintained close to the regulatory limits set for the utility, even at different solar panel voltage levels.

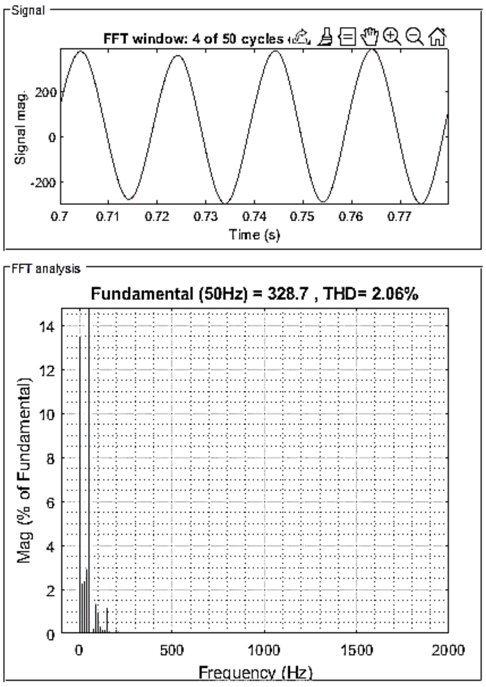

Figure 12. The total harmonic distortion of the proposed system

4. CONCLUSION

The proposed FLC-based MPPT system for SAPV system with battery storage has been determined to be a cost-effective and efficient conversion system. This system converts the output DC voltage from a PV module to AC 230 V_{rms}, which can power a single-phase domestic load at 230 V_{rms}. To enhance energy conversion efficiency, an intelligent control technique based on fuzzy logic control is integrated with the MPPT controller in this study. Compared to traditional voltage source inverters, the boost inverter used in this system offers both economic and technological advantages. Simulation results on various loads demonstrate that the system operates within the permissible THD range. This proposed technique offers several benefits, including lower overall system costs, smaller size, and higher efficiency.

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