A Comparative Study between Single-loop and Dual-loop Tracking Control Schemes for MPPT of Solar Tracking System

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Received: 2 November 2024 | Revised: 27 December 2024 | Accepted: 7 January 2025

 DOI: https://doi.org/10.48084/etasr.9477

ABSTRACT

Solar energy is one of the principal renewable energy sources for electric power generation. However, maximizing the power extraction from solar Photo-Voltaic (PV) systems remains a challenge due to their inherent low conversion efficiency. To address this issue, a Maximum Power Point Tracking (MPPT) controller is necessary to optimize power extraction in a PV system. This paper aims to conduct a comparative study between two distinct MPPT control schemes. The first is a simple single-loop system employing the Perturb and Observe (P&O) algorithm. The second is an advanced dual-loop system integrating the P&O algorithm with a Proportional-Integral (PI) controller. The comparison evaluates the systems' performance in terms of steady-state accuracy. For this purpose, a MATLAB/Simulink model of a stand-alone PV panel was developed. The proposed MPPT schemes were then implemented on this PV system under varying environmental conditions to assess their ability to track the MPPT. The simulation results indicate that the dual-loop control scheme outperforms the single-loop scheme in terms of steady-state performance, particularly during abrupt environmental changes.

Keywords-perturb and observe; MPPT; PV panels; PI controller

I. INTRODUCTION

Solar power is a form of renewable energy that is considered an appealing energy solution owing to its unlimited supply source and non-polluting characteristics. If solar energy is utilized effectively, it has the potential to fulfill all future energy needs. Solar energy does not emit any toxic components or greenhouse gases during operation, and it also contributes to reducing the environmental impact by diminishing reliance on fossil fuels [1, 2]. The voltage generated by a solar panel fluctuates based on solar irradiation and temperature. As the voltage produced by the PV system varies, numerous electronic devices cannot be directly connected to the PV system. Consequently, in a Direct Current (DC) system, a DC/DC boost converter is employed between the power source and the load to convert the DC input voltage into a higher DC output voltage. This is achieved by adjusting the duty cycles of the main switches in the circuits [3, 4].

The maximization of the power transfer from the PV generators to loads is a key challenge in PV solar energy, stemming from the non-linear electrical properties of PV cells. These properties are influenced by variations in solar irradiation and temperature, which impact the output voltage of PV cells [5]. To enhance the output power of PV systems, it is essential to operate the PV panel at its Maximum Power Point (MPP). Consequently, the utilization of MPPT methods has been proposed to optimize the power extraction from PV panels and maximize their utilization. Numerous researchers have investigated different tracking control systems to regulate boost converters in order to extract the MPPT of PV sources and increase their output power.

An artificial neural network (ANN) method with minimal overshoots to track the MPP was proposed in [6]. With the aim of implementing quick MPPT action on PV systems using a single control stage, authors in [7] undertook a thorough analysis and design of an MPPT solution derived from the sliding-mode control theory. Particle Swarm Optimisation (PSO) [8] helped to maximise a PI-Derivative (PID) controller design for a DC/DC boost converter PV system. Using an isolated push-pull boost converter to maximise output power and get high DC gain and isolation for DC/AC inversion, a Fuzzy Logic Control (FIC) technique was applied in [9] to increase MPPT performance in solar models. Examining the PV model within a fuzzy integral state feedback controller and deriving stabilisation conditions using Linear Matrix Inequalities (LMI) and the Takagi-Sugeno (T-S) fuzzy model with the Lyapunov approach [10] the proposed fuzzy saturated control approach was proposed to enhance the MPPT of PV systems in the face of external perturbations and actuators saturation.

An innovative adaptive control technique was employed to enhance the performance of MPPT and enable effective operation of PV systems under varying external conditions [11]. A non-inverting buck-boost converter was utilized to develop the MPPT on the PV model. A robust integral backstepping controller was proposed to improve the MPPT performance of the PV system, using a non-inverting DC/DC buck-boost converter to extract the maximum power from a PV array [12]. The reference voltage for MPPT was generated by a Neuro-Fuzzy network, and the asymptotic stability of the entire system was verified using Lyapunov stability criteria. A Fractional-Order Proportional Integral Derivative (FOPID) controller was deployed to track the MPPT of the PV system, with the controller gains having been optimized using the Aquila Optimizer (AO) and Moth Flame Optimizer (MFO) [13]. A comparative performance study was carried out between the proposed AO-based FOPID controller and the one optimized using the MFO. In [14], a sliding mode extremum seeking control was proposed to improve the MPPT performance of the PV cell, and used a sliding layer concept to reject the chattering phenomenon caused by high-frequency switching. A sliding mode controller was employed to rapidly and accurately track the MPP and output current under varying climatic conditions.

II. MATHEMATICAL MODELS OF THE PHOTO-VOLTAIC SYSTEM AND THE DC/DC BOOST CONVERTER SYSTEM

A. *Single-Diode Model of a Photo-Voltaic Cell*

Solar cells are considered semiconductor devices that generate DC flowing through the PV panels when solar irradiation penetrates the solar cells' surfaces. The schematic representation of the PV cell is depicted in Figure 1 [16]. In Figure 1, I_{ph} refers to the photocurrent, the current generated by the cell due to sunlight. Additionally, the diode represents the PV cell's p-n junction, R_s or series resistance represents the resistance within the cell due to the movement of electrons through the material, and R_{sh} or shunt resistance represents the leakage current paths within the cell.

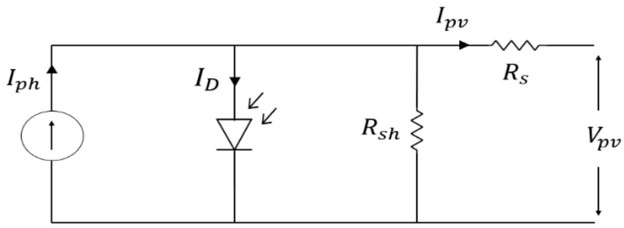


Fig. 1. Schematic representation of the PV cell.

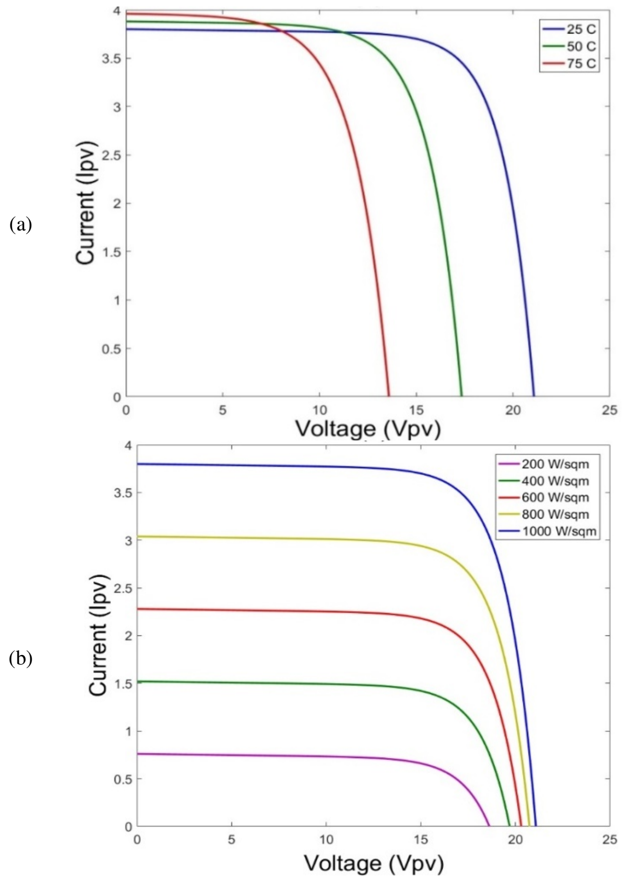


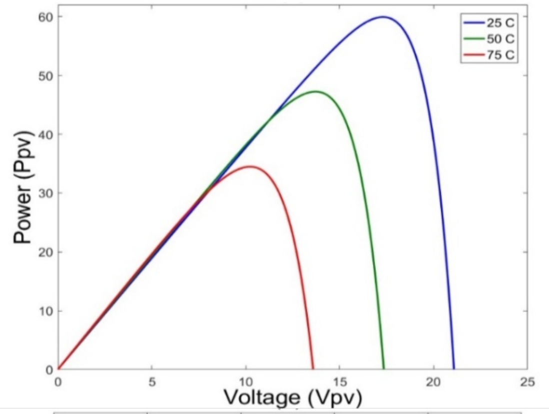
Fig. 2. I-V characteristic with (a) variable temperature, (b) variable irradiance.

The current-voltage (I-V) relationship of the PV cell is given by [3]:

$$I_{pv} = I_{ph} - I_o\left(exp\frac{q(V_{pv}+R_sI_{pv})}{nN_sKT} - 1\right) - I_{sh} \tag{1}$$

where I_{pv} is the output current of the PV cell, V_{pv} is the output voltage of the PV cell, I_o is the saturation current of the diode, n is the ideality factor of the diode and has a value of 1.6, N_s is the number of cells in series and has a value of 36, k is Boltzmann's constant, T is the operating temperature of the cell measured in Kelvin, and q is the charge of an electron [17]. Determining a PV panel's MPP is a crucial step that involves analyzing its I-V and Power-Voltage (P-V) characteristic curves. As the irradiation increases, the PV panel's power and voltage also rise, but they are negatively impacted by the increasing temperature. The I-V and P-V characteristic curves under varying temperature and irradiance conditions are illustrated in Figures 2 and 3, respectively.

(a)



(b)

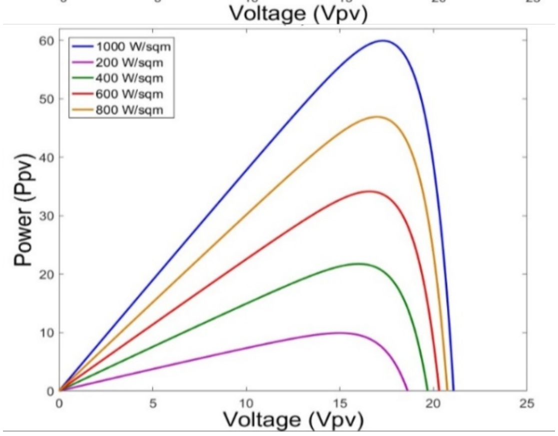


Fig. 3. P-V characteristic with (a) variable temperature, (b) variable irradiance.

B. DC-DC Boost Converter Model

In this structure, several converter circuits are utilized. The commonly employed DC-DC boost converter model is frequently selected owing to its high efficiency, straightforward implementation, and widespread application [18]. The purpose of this converter is to elevate the DC input voltage to a higher magnitude. The circuit employed by the DC-DC boost converter, which includes an input filter capacitor, is depicted in Figure 4. The circuit is analyzed under two cases, contingent on the state of the switch Q, whether it is in the ON or OFF state. When the duty ratio is denoted as D, the switch is in the ON state and the diode is reverse-biased during the interval $0 < t < DT$. The voltage across the inductor is $V_L = V_{pv}$. The switch is in the OFF state and the diode becomes forward-biased during the interval $DT < t < T$. The voltage across the inductor is $V_L = V_{pv} - V_O$. Over a switching period, the total current change on the inductor must be zero at the steady-state condition [3].

$$\frac{V_O}{V_{in}} = \frac{1}{1-D} \tag{2}$$

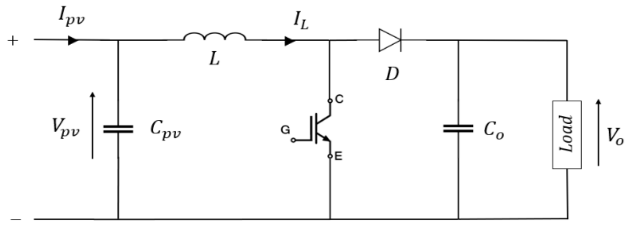


Fig. 4. The used boost DC-DC converter circuit.

III. MAXIMUM POWER OF PHOTO-VOLTAIC PANEL

The P-V and I-V characteristics of a PV system are non-linear, and the power produced by the system is influenced by environmental factors, such as solar irradiation and temperature [19]. The maximum power of a PV system is achieved at the knee point of the P-V characteristic, which is also referred to as MPP. The MPPT is an essential technique that is used to maximize the solar panels' efficiency. MPPT algorithms adjust the electrical operating point of the modules or array to ensure that the system generates the maximum attainable power. The output power of the PV panel is $P_{pv} = V_{pv} I_{pv}$. A derivative of the solar panel power (P_{pv}) with respect to the solar panel voltage (V_{pv}) is equal to zero at MPP. Typically, DC converters are employed to connect the PV cells and the load for MPP tracking, as shown in Figure 5. However, to control this converter, a tracking controller is required.

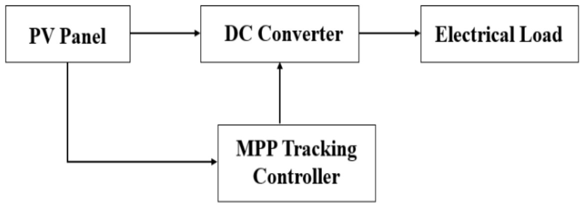


Fig. 5. A typical photovoltaic power source.

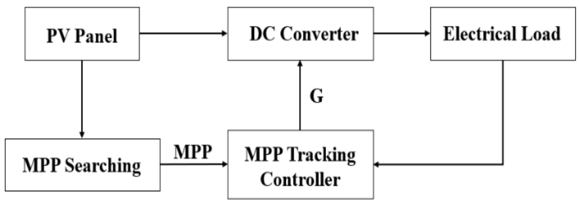


Fig. 6. The block diagram of dual-loop control scheme.

There are two tracking control schemes that can be used to ensure that a PV system delivers the maximum expected power under varying external conditions. The first is the single-loop tracking control scheme, and the second is the dual-loop tracking control scheme. The block diagram of the dual-loop control scheme is illustrated in Figure 6.

IV. SINGLE-LOOP TRACKING CONTROL SCHEME

In a single-loop tracking control approach, a single feedback loop is utilized to optimize the operating point of the PV system and maximize its power output. This feedback loop typically monitors the output power and adjusts the duty cycle of a DC-DC converter to maintain the MPP. Common MPPT techniques include P&O, incremental conductance, and hill climbing. In this study, the classic P&O algorithm will be employed to locate the MPP in accordance with the single-loop tracking control scheme [14].

The P&O algorithm is commonly utilized in practice due to its simplicity and straightforward implementation. As displayed in Figure 7, the fundamental P&O MPPT approach operates by perturbing the duty cycle and then monitoring the power output of the PV system. If the perturbation leads to an increase in the output power, the operating point is shifted towards the maximum power point, prompting a continuation of the perturbation in the same direction. Conversely, if the output power decreases, a new perturbation in the opposite direction is applied.

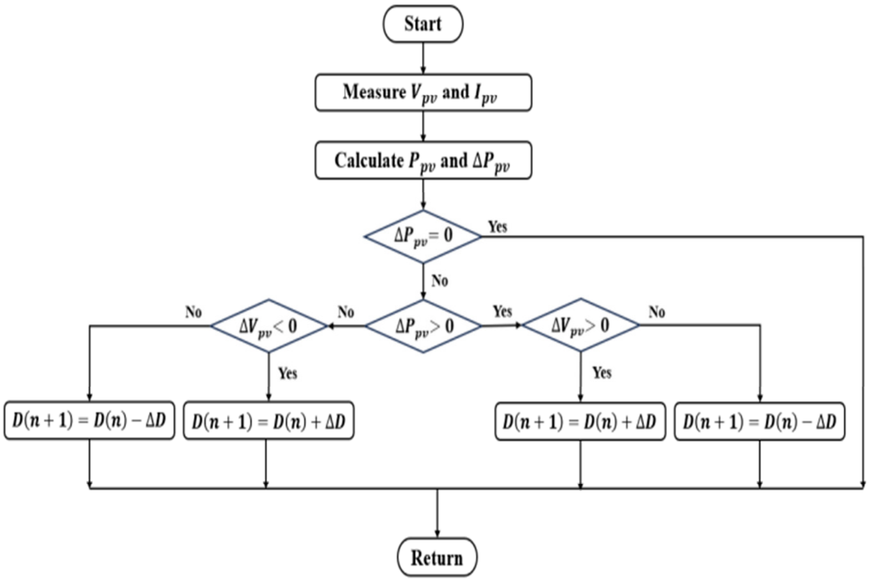


Fig. 7. Flowchart of classic P&O MPPT method.

V. DUAL-LOOP TRACKING CONTROL SCHEME

A dual-loop tracking control scheme, involves two feedback loops. The first and second loops are used for MPP searching and MPP tracking, respectively. The MPP tracking loop or inner loop controls a fast dynamic variable, the duty cycle of a DC-DC converter. It provides a rapid response to changes, ensuring that the system operates within safe and optimal ranges. The MPP searching loop or outer loop adjusts a slower dynamic variable, the reference voltage, based on the MPPT algorithm. The designing procedure has to take into account the interaction between the loops, which means that the searching loop must be slower than the tracking loop. In this work the P&O algorithm will be utilized to find the reference voltage in the MPP searching loop and PI controller in MPP tracking loop to produce an appropriate duty cycle of a DC-DC converter according to the dual-loop tracking control scheme.

A. *Perturb and Observe -based Voltage Maximum Power Point Tracking Controller*

The P&O-based Voltage Maximum Power Point Tracking (VMPPT) controller generates the reference voltage by iteratively perturbing the voltage and observing the resulting power changes. By continuously adjusting the reference voltage based on these observations, the controller ensures that the PV array operates at or near the MPP, thus maximizing the efficiency of the solar PV system. This technique entails the perturbation of the PV module's operating voltage by a small increment ΔV, and then observing the resulting change in power, ΔP. A positive value of ΔP indicates that the operating point has been shifted closer to the MPP. Therefore, additional voltage perturbations ΔV in the same direction should move the operating point toward the MPP. A negative value of ΔP indicates that the operating point has shifted away from the MPP, and to move back toward the MPP, the direction of perturbation should be reversed. The algorithm continues to iterate until it reaches the MPP. The update law for V_{ref} is given by the following rules:

$$\begin{cases} V_{ref}(k) = V_{ref}(k-1) + \Delta V, \ if \ \Delta V \times \Delta P > 0 \\ V_{ref}(k) = V_{ref}(k-1) - \Delta V, \ if \ \Delta V \times \Delta P < 0 \\ V_{ref}(k) = V_{ref}(k-1), \ if \ \Delta P = 0 \end{cases} \quad (3)$$

B. *The PI Controller*

The control equation for the PI controller is formulated as:

$$u = k_p e(t) + k_i \int e(t)\, dt \quad (4)$$

where k_p and k_i *are* the variables to be tuned for the reference output from the PV system and the error equation is:

$$e(t) = V_{pv} - V_{ref} \quad (5)$$

Proportional gain (k_p) is a controllable constant that adjusts the proportional response. In the PI controller, the integral is a representation of the sum of the instantaneous error over time and provides the accumulated offset that should have been previously corrected. Afterwards, the integral gain (k_i) is multiplied by the accumulated error and added to the output of the PI controller.

VI. RESULTS AND DISCUSSION

The MXS 60W PV panel's electrical characteristics are listed in Table I [17]. A PV panel has been created using MATLAB/Simulink and the "Ode23t" is applied as a numerical solver. The output power, voltage and current of the MXS 60W PV panel without any MPPT method under standard test conditions with T equal to 25 °C and G equal to 1000 W/m^2 are shown in Figure 8.

TABLE I. SPECIFICATIONS OF MXS 60W PV MODULE.

Parameter	Value
The power at MPP	60 W
The voltage at MPP	3.5 A
The current at MPP	17.1 V
Short circuit current	3.8 A
Open circuit voltage	21.1 V

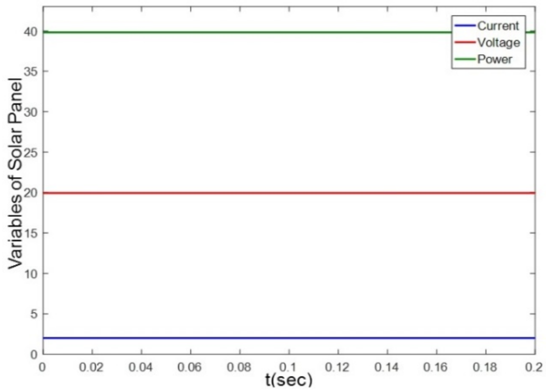


Fig. 8. Power, voltage, and current of the PV panel without any MPPT method under STC.

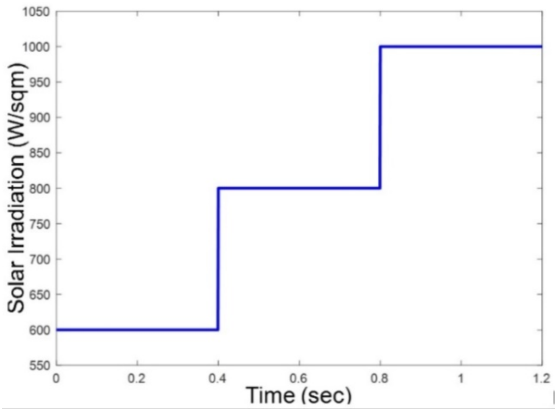


Fig. 9. Variation of irradiation level.

For the dynamic analysis, the current study tested the responses of the two MPPT schemes under varying solar irradiation in the range of 600-1000 W/m^2 with T equal to 25 °C, and the responses of the two MPPT schemes under varying temperature in the range of 25-50 °C with G equal to 1000 W/m^2. The variation of solar irradiation used to analyze the proposed MPPT schemes in the first test is depicted in Figure 9. The power of PV panel, the load power, and the duty ratio of these implemented MPPT schemes are presented in Figure 10.

(a)

(b)

(c)

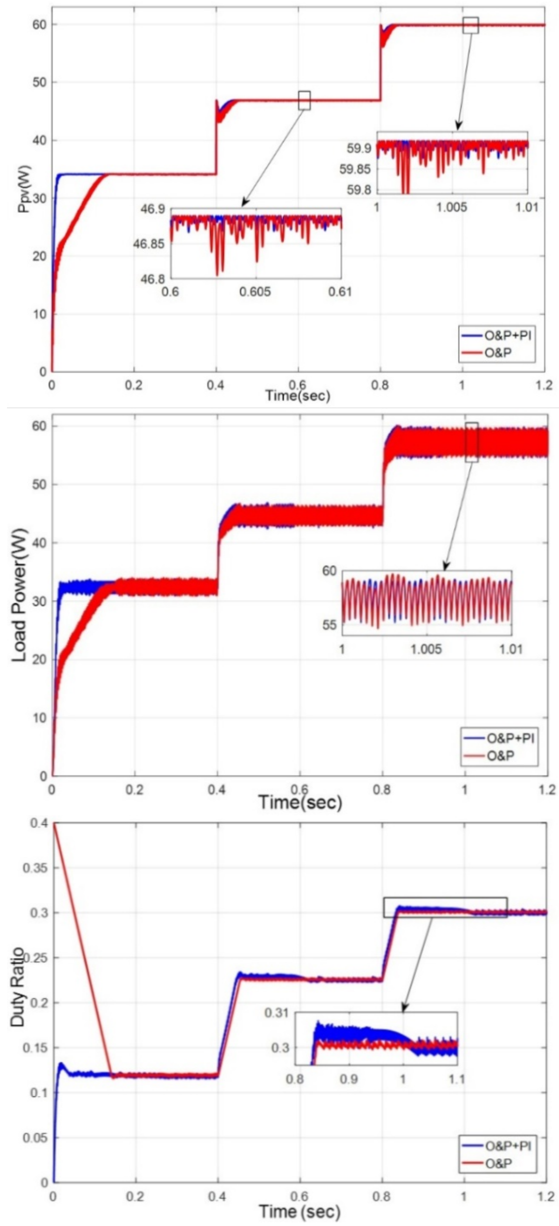


Fig. 10. Dynamic response of the proposed MPPT schemes under variable irradiation conditions: (a) power of PV panel, (b) load power, and (c) duty ration.

The variation of temperature used to analyze the different MPPT schemes in the second test is depicted in Figure 11, while Figure 12 shows the power of the PV panel and the duty ratio under the variation of temperature. The tracking efficiency of a PV system can be evaluated using:

$$\zeta = \left(1 - \frac{P_{MPP} - P_O}{P_{MPP}}\right) 100\% \quad (6)$$

where P_{MPP} is the power at MPP and P_{MPPT} is the output power of the implemented MPPT method. A comparison of the efficiency of a PV system with the proposed MPPT schemes is illustrated in Table II.

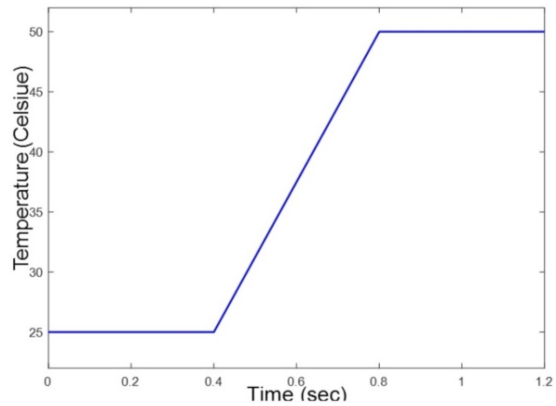
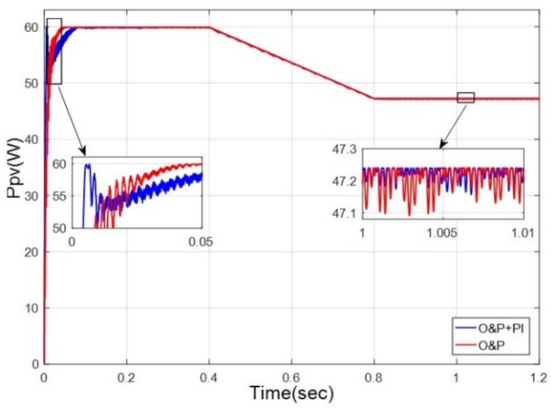
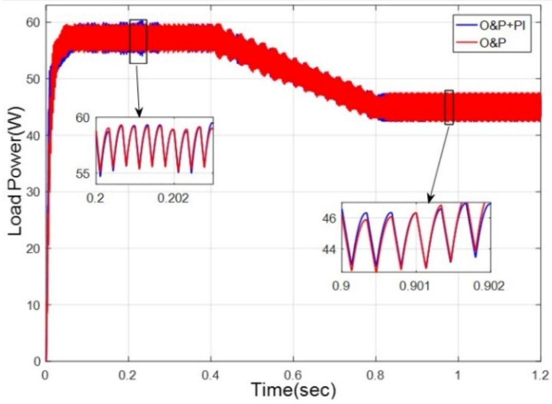


Fig. 11. Variation of temperature level.

(a)



(b)



(c)

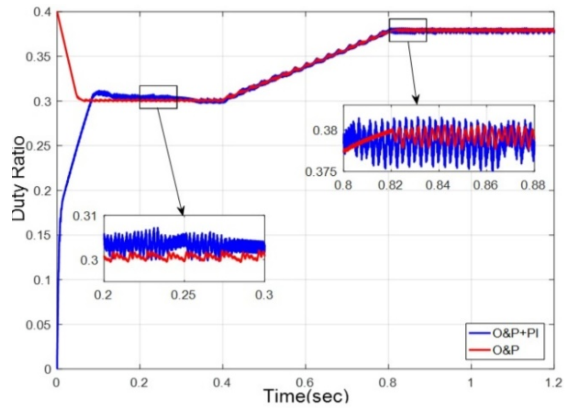


Fig. 12. Dynamic response of the proposed MPPT schemes under variable temperature conditions: (a) power of PV panel, (b) load power, and (c) duty ration.

TABLE II. MPPT SCHEMES EFFICIENCY.

Type of Method	Constant Irradiation and Varying Temperature	Constant Temperature and Varying Irradiation
P&O	95.52%	94.01%
P&O + PI	95.53%	95.14%

The findings reveal that the performance of the dual-loop tracking control system, which combines the P&O algorithm with a PI controller, significantly outperforms the single-loop tracking control system that solely utilizes the P&O technique. The dual-loop control approach achieves higher power output in a shorter timeframe while decreasing oscillations in the PV panel's power generation. Furthermore, under variable irradiation conditions, the dual-loop control scheme demonstrates superior efficiency, reaching 95.14%, compared to the single-loop system's 93.01%. Interestingly, both control schemes maintain the same efficiencies under varying temperature conditions.

Finally, the results demonstrate the dual-loop control approach's capacity to boost energy harvesting and stabilize operation under changing environmental factors, making it appropriate for larger or more intricate PV systems.

VII. CONCLUSION

In this study, two control strategies were developed to enhance the Maximum Power Point Tracking (MPPT) performance of a Photo-Voltaic (PV) system. The first approach was a single-loop tracking control scheme based on the Perturb and Observe (P&O) algorithm, while the second was a dual-loop control scheme combining the P&O algorithm and a Proportional-Integral (PI) controller. Comprehensive simulation analyses were conducted to validate the robustness and efficacy of the proposed schemes. According to the simulation results, the single-loop control scheme offered a more straightforward approach, employing a single control loop to manage the MPPT of the PV system. Conversely, the dual-loop tracking control scheme was more complex but delivered superior tracking performance and excellent robust characteristics against diverse weather conditions. The findings indicated that the dual-loop tracking control scheme converges to the Maximum Power Point (MPP) more rapidly and reduces the risk of oscillations around it. Future research will involve the implementation of a sliding mode controller or a neural PI controller as an alternative to the conventional PI controller to further improve the performance of the PV system.

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