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Advanced Maximum Power Point Tracking and DC-DC Converter Design for Enhanced Efficiency in Standalone PV Systems

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Abstract: To maximize the efficiency of solar energy conversion into electricity, photovoltaic (PV) system optimization is crucial. This is especially true for off-grid solar installations in remote areas lacking grid access. In order to maximize energy extraction from freestanding PV systems, regardless of fluctuating external conditions, this research provides a modified DC-DC converter and a novel Maximum Power Point Tracking (MPPT) technique. To ensure the photovoltaic (PV) system operates at full capacity despite rapid changes in weather conditions, the proposed solution utilizes the Modified Incremental Conductance MPPT algorithm that dynamically adjusts the system's operational parameters. Extensive simulations run in the MATLAB/Simulink platform confirm that the MPPT technique is efficient and effective. The proposed method outperforms traditional MPPT approaches in both convergence speed and output power stability. This research also develops a novel DC-DC converter to address the challenges given by the fluctuating solar irradiation. The modified DC-DC converter exhibits high gain and shorter settling time, and the improved MPPT method enhances the feasibility of deploying solar energy systems in off-grid and remote regions by enhancing the autonomy of standalone PV systems.

Keywords: MPPT, PV Systems, Solar Systems, MATLAB, Renewable Energy, Zeta converter

1 Introduction

PHOTOVOLTAIC (PV) energy has become a prominent renewable energy source due to its low environmental impact, lack of moving parts, and minimal maintenance requirements [1]. However, PV panels exhibit nonlinear V-I (voltage-current) characteristics that are highly sensitive to variations in temperature and irradiance. To optimize power generation, maximum power point tracking (MPPT) algorithms are employed. These algorithms continuously adjust the operating parameters of the PV system to track the maximum power point on the V-I and P-V (power-voltage) curves, thereby ensuring maximum power output under dynamic environmental conditions [2].

An essential component in this process is the MPPT controller, which controls the converter interfacing the PV panels and the load. Despite fluctuations in temperature and irradiance, the MPPT controller ensures that the system consistently operates at its maximum power point (MPP), thereby delivering consistently optimal power output. MPPT has demonstrated its effectiveness in various research applications and has been widely adopted across diverse practical applications [16].

A recent advancement in photovoltaic (PV) system control is the development of a novel MPPT technique designed for single-phase grid-connected voltage source inverters (VSIs). This method eliminates the need for a current sensor by using only voltage-based parameters

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[8, 9]. By incorporating a power angle-based variable, this sensor-less MPPT approach not only simplifies the system design but also reduces hardware costs. Furthermore, another MPPT technique involving a DC-DC converter for grid-connected PV systems has been proposed [15, 17]. This method improves efficiency by deriving the maximum power point from an extremum determined using a signal induced by DC-link voltage ripple, thereby eliminating the need for an intermediary DC-DC conversion stage.

Several studies have explored the impact of MPPT on energy storage applications. A comparative analysis of PV panels with and without MPPT for charging energy storage devices, such as batteries and ultracapacitors, indicated that MPPT significantly enhances charging efficiency [19, 20]. Several MPPT techniques, including Hill-Climbing, Incremental Conductance (InCon), and Perturb and Observe (P&O), have been evaluated in [7]. Although all these methods aim to maximize power extraction, they differ in methodology: some directly track the maximum power point (MPP), while others rely on indirect responses to environmental variations. Trade-offs in complexity, cost, and efficiency among various MPPT algorithms are analyzed in [11], offering deeper insights into their influence on PV system performance and overall cost.

Reference [10] investigates the performance of various inverter topologies integrated with MPPT techniques and offers insights into overcoming challenges associated with multi-stage inverter systems. In this context, a newly developed MPPT algorithm for single-phase, two-stage photovoltaic converters eliminates the need for DC sensors, thereby simplifying the system architecture while preserving high tracking accuracy and dynamic response. This streamlined design contributes to improved reliability and reduced costs without compromising precision or efficiency in maximum power point tracking.

Advancements in MPPT technology have significantly enhanced the efficiency of photovoltaic systems, especially in grid-connected systems and energy storage applications. Ongoing refinement of MPPT algorithms has the potential to improve the reliability and operational performance of PV systems, thus supporting the broader adoption of renewable energy technologies.

2 Maximum Power Point Tracking Methods:

Photovoltaic (PV) energy is increasingly recognized as a key renewable power source due to its environmental sustainability and minimal operational demands. PV systems operate without fuel consumption, mechanical components, or noise, rendering them both environmentally benign and low-maintenance. However, PV panels exhibit a nonlinear current–voltage (I–V) characteristic that is influenced by environmental factors such as temperature and irradiance. At a specific point on the I–V curve referred to as the maximum power point (MPP) the panel delivers its highest output power under given conditions. Maintaining operation at the MPP is challenging due to the dynamic nature of these environmental variables, thereby necessitating the use of maximum power point tracking (MPPT) techniques. These algorithms dynamically adjust voltage and current levels to ensure that the PV panel consistently operates at its MPP. Figure 1 presents the block diagram of a standard MPPT system, illustrating how the algorithm aligns the PV output with the load requirements.

Numerous digital and analog MPPT techniques have been developed to improve the power extraction efficiency of photovoltaic (PV) systems. Commonly employed methods include Perturb and Observe (P&O) [3], Incremental Conductance (IC) [4,5], artificial neural network (ANN)-based approaches [6,7], and fractional open-circuit voltage and short-circuit current techniques [8,9]. Hybrid methods, which combine multiple strategies to leverage their respective advantages, have also been proposed [11,12]. Detailed descriptions of these MPPT algorithms are available in [13,14]. These algorithms continuously identify the maximum power point (MPP) by monitoring real-time PV output parameters such as voltage, current, and power. They require computational resources typically provided by specialized processors, including digital signal processors (DSPs), digital signal controllers (DSCs), or microcontrollers (μCs), which are capable of executing complex mathematical operations such as multiplication and differentiation, ensuring precise and efficient MPPT operation [18,19].

Although high-performance processors facilitate effective MPPT implementation, their use may not be appropriate for all application scenarios. In low-power PV applications—including wireless sensor networks, standalone LED lighting, and traffic signage—the use of such processors may be economically unfeasible. Moreover, in energy-constrained systems, the inclusion of MPPT circuits based on DSPs, DSCs, or microcontrollers (μCs) may undermine overall efficiency due to their relatively high power consumption. In such contexts, analog-based MPPT solutions provide a cost-effective and power-efficient alternative, reducing energy overhead while still ensuring reliable maximum power point tracking.

2.1 Incremental-Conductance Method

As its name implies, the IC technique aims to achieve the P-V curve's peak by meeting

$$\frac{dP}{dV} = \frac{d(V*I)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = 0 \tag{1}$$

where DC power (P), voltage (V), and current (I) are the three variables being monitored. We get: by multiplying (3.7) by 1/V:

$$\frac{1}{V}\frac{dP}{dV} = \frac{I}{V} + \frac{dI}{dV} = G + dG \tag{2}$$

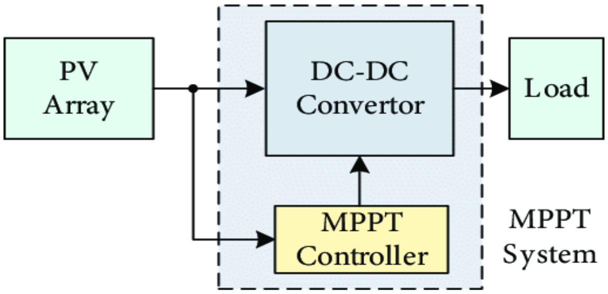

Fig 1. Common model of MPPT-based solar PV system

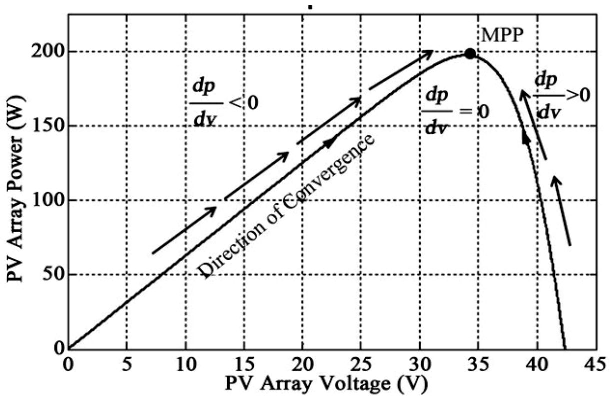

Fig 2. An Illustration of the Incremental Conductance Method Using a P-V Curve

3 Modified Incremental Conductance MPPT

The Maximum Power Point Tracking (MPPT) technique is used to optimize the performance of a photovoltaic (PV) system. By connecting the PV modules to the load via a Zeta converter, this approach ensures that the PV system operates at its maximum power point (MPP). To track the MPP, the converter's duty cycle is continuously adjusted. Under steady irradiance conditions, the standard Incremental Conductance (INC) method (Figure 3) performs effectively. The INC algorithm enhances power extraction by monitoring the slope of the power–voltage (P–V) curve and adjusting the converter's duty cycle to maintain operation at the MPP.

MPP is reached when $\frac{dP}{dV} = 0$

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

$$\frac{dP}{dV} > 0 \text{, then } V_{pv} < V_{mpp} \tag{4}$$

$$\frac{dP}{dV} = 0 \text{, then } V_{pv} = V_{mpp} \tag{5}$$

$$\frac{dP}{dV} < 0 \text{, then } V_{pv} > V_{mpp} \tag{6}$$

The relationship between the rate of change of current with respect to voltage (dI/dV) and the negative ratio of current to voltage (−I/V) is fundamental in determining the maximum power point voltage (VMPP). If the module voltage is reduced and the power–voltage slope (dP/dV) is negative, the operating point lies to the left of the MPP. Conversely, a positive slope indicates that the operating point is to the right of the MPP, corresponding to an increased module voltage. The MPPT algorithm continuously adjusts the voltage until the slope dP/dV becomes zero, indicating that the system has reached the MPP. Once this condition is met, voltage adjustments are ceased, as the system is now operating at its peak power output.

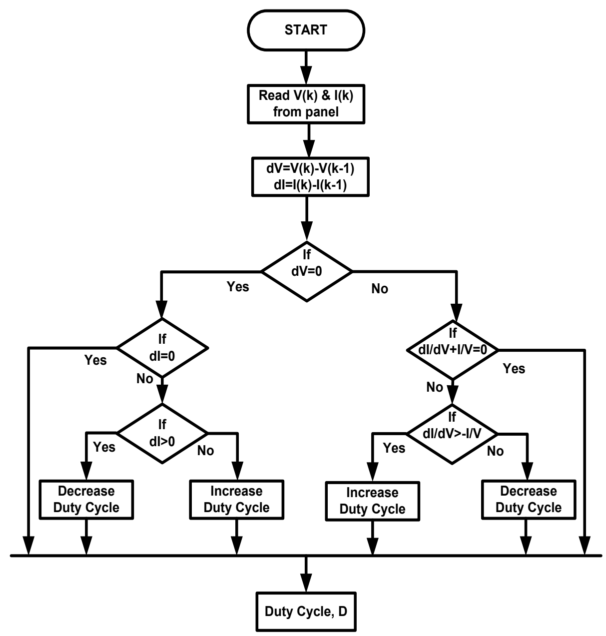

Fig 3. The Incremental Conductance MPPT Method

The response with a fixed step size is sluggish under varying irradiance conditions. Thus, a variable step size is proposed, which reduces the step size near the P-V curve peak to improve the convergence accuracy of the MPP, though this may reduce the convergence speed. To accelerate convergence under rapidly fluctuating irradiance, a revised INC method is introduced. Figure 4 shows the proposed block diagram.

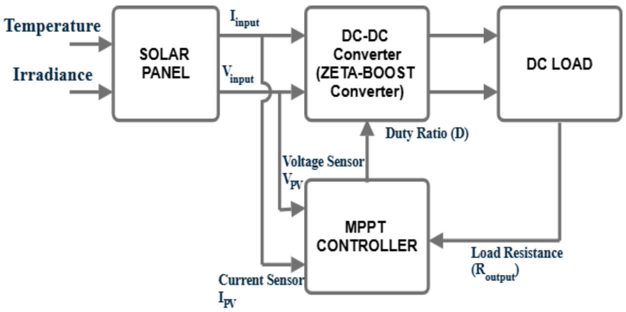

Fig 4. Schematic of the DC/DC converter that has been suggested, using an updated INC algorithm

Nearly all photovoltaic modules exhibit a straight line connecting their MPPs, referred to as the MPP line. Figure 5 shows the I-V curve of the PV module under various levels of solar irradiance. The I-V curve can be overlaid with a load line to illustrate how the PV module supplies power to a load. The intersection of the load line and the I-V curve indicates the module's operating voltage and current. The module's power output at this operating point is calculated by multiplying the voltage and current. The I-V curve illustrates how the power output of the PV module varies with the load line and the incident sunlight intensity.

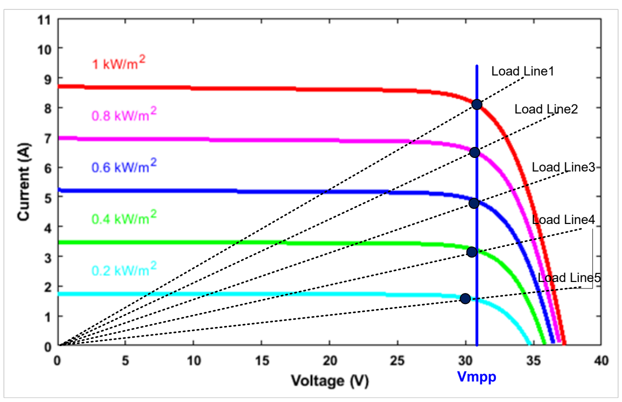

Fig 5. Load line and MPP curves.

Representing the relationship between the input voltage, output voltage, and currents for a DC-DC converter is

$$V_{input} = \frac{1-D}{D} V_{output} \tag{7}$$

$$I_{input} = \frac{D}{1-D} I_{output} \tag{8}$$

Divide equation (7) with (8) we get

$$R_{input} = \frac{(1-D)^2}{D^2} R_{output} \tag{9}$$

Here, D stands for the duty cycle (or duty ratio), Vinput for the converter's input voltage (Vpv), and Iinput for the converter's input current (Ipv), all of which are identical to the PV module's voltage and current, respectively. The PV module's input resistance, or Rinput, is the converter's input resistance, and the load resistance, or Rload, is the converter's output resistance.

The gain of the converter is adjusted by varying the duty cycle (D). The input resistance can be adjusted in this way until the load line meets the I-V curve at the MPP marking the point at which the PV system is operating at its most efficient.

Equation (9) can be written as

$$\frac{D^2}{(1-D)^2} = \frac{R_{output}}{R_{input}} \tag{10}$$

Load resistance calculated from MPP by substituting the duty cycle, PV voltage and PV current in (10)

$$D = \frac{\sqrt{\frac{I_{input}}{V_{input}} R_{load}}}{1 + \sqrt{\frac{I_{input}}{V_{input}} R_{load}}} \tag{11}$$

In real-world systems, achieving the zero-slope condition requires several iterations. Allowing a predefined tolerance in determining the MPP improves accuracy. To determine the MPP, this thesis modifies the zero-slope criterion by introducing a minimal allowable error. Upon reaching the MPP, the proposed technique eliminates steady-state oscillations by applying an acceptable error limit of 0.06, as defined in equation (12). An allowed error margin greater than the MPPT step size of 0.05 is selected.

$$\frac{dI}{dV} + \frac{I}{V} < 0.06 \tag{12}$$

Figure 6 shows the flow chart for the proposed algorithm

The MPP for a PV module under 1000 W/m² irradiance is located at point A (VMPP1, IMPP1) on load line 1, as shown in Figure 6. When irradiance decreases from 1000 to 400 W/m², the MPP shifts to point B. This occurs because the DC-DC converter duty cycle remains constant during the change. Equation (12) is used to adjust the operating point according to the new MPP values (VMPP and IMPP). Since these values are uncertain, the equation employs estimates to track the new MPP. Figure 7 shows the MPP I-V curve. From this curve, the new IMPP is estimated as 0.8 × ISC. The previous VMPP value is used to estimate the new VMPP, as it remains relatively stable across different irradiance levels. By substituting IMPP ≈ IB, IB = IPV, and VB = VMPP = VPV into equation (12), the new MPP is approximated along load line 2, approaching the actual new MPP at point C.

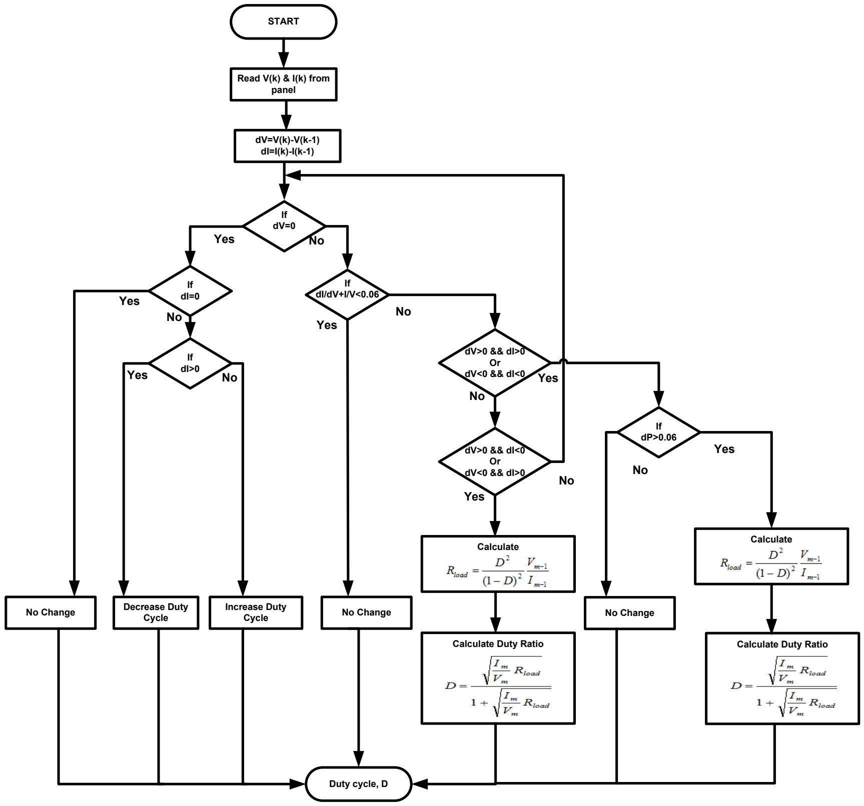

Fig 6. Proposed modified INC MPPT method under fast varying irradiance

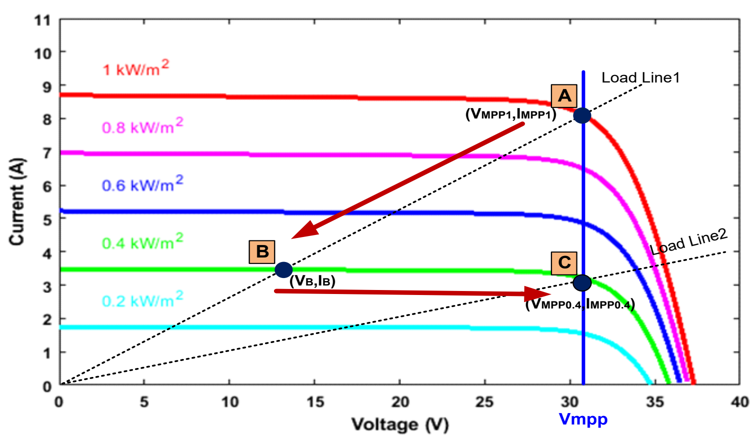

Fig 7. MPP on I-V curves for 1.0 to 0.4 kW/m2 solar irradiation drop

4 Bidirectional Zeta Boost Converter

Energy can flow bidirectionally between the input and output of the converter due to two bidirectional switches (such as MOSFETs). These switches, labeled S1 and S2 in Figure 8, can be turned on and off to control power flow. A capacitor, denoted as CC, is connected between the source and load sides, along with two inductors, L1 and L2. This configuration forms a Zeta converter, a type of boost converter capable of both stepping up and stepping down power bidirectionally

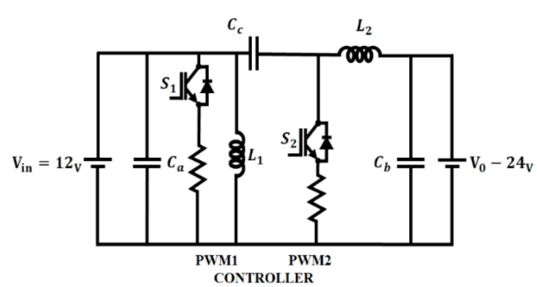

Fig 8. Bidirectional Zeta Boost Converter Circuit

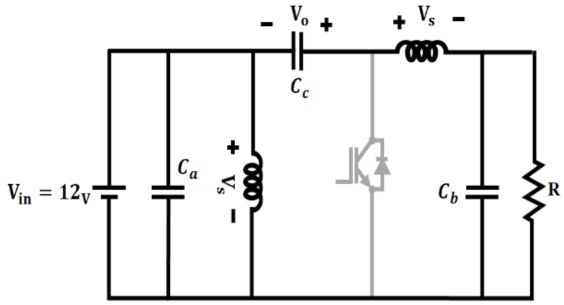

Fig 9. Mode-1 operation of the ZBC

Mode 1: If S_1 is ON and S_2 is OFF, inductance L_1 collects power from the source of voltage, and inductance L_2 saves energy both the voltage coming from the source and capacitor. Because of the inverse development of the IL_1 and IL_2 , the capacitor charging to V_{batt}, and the Capacitor being linked in series with L_2, the voltage across L_2 is VS. Figs. 2 and 3 depict the Zeta converter's operating modes. The voltage between L_1 and L_2 in the circuit seen in Fig. 6 may be expressed by utilizing KVL:

$$L_1 \frac{dL_1}{dt} = V_S \tag{13}$$

$$L_2 \frac{dL_2}{dt} = V_S \tag{14}$$

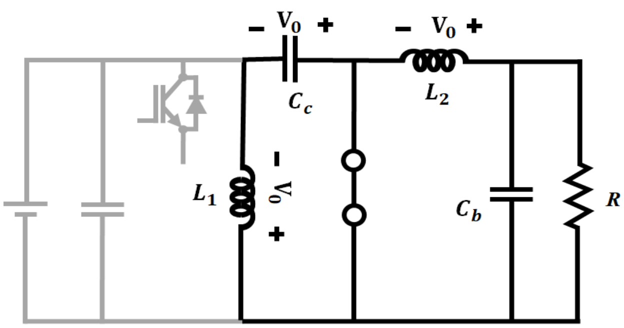

Fig 10. Mode-2 operation of ZBC

Mode 2: Switch S_2 is used to facilitate the discharging of inductors L_1 and L_2 when switch S_1 is turned ON and off. As the capacitor charge to voltage V_{batt}, inductor L_2 is connected parallel to the battery. The current that flows between L_1 and L_2 is described in the sections that follow.

$$L_1 \frac{dL_1}{dt} = -V_0 \tag{15}$$

$$L_2 \frac{dL_2}{dt} = -V_0 \tag{16}$$

Average output voltage

$$V_0 = V_S(\frac{D}{1-D}) \tag{17}$$

Where D represents duty period of S_1.

Table 1. Parameters of Bi directional Zeta Boost converter

Parameter	Numerical Value
DC link Voltage Vdc	60 V
Output Voltage Vo	240 V
Switching frequency fs	10 kHz
Output Power Po	4 kW
Inductor L1 L2	420 µH
Capacitor Ca Cb	220 µF
Capacitor Cc	1000 µF

5 Simulation Results

In this study, the STH-250WH solar panel is used, and as outlined in Table 1, the photovoltaic panel specifications provide only limited parameters. As a result, several crucial parameters required for accurately modeling the photovoltaic panel are not included in the manufacturer's data. These missing parameters include the diode saturation current, photocurrent, diode ideality factor, and the series and shunt resistances.

Table 2. Specifications of Soltech 1STH-250 WH PV panel at Standard Testing Conditions (STC) of 1000 W/m2 and 250 C

Characteristics	Value
Pmax	250 Watts
Vmp	30.7 Volts
Imp	8.15 Amps
Isc	8.66 Amps
Vco	37.3 Volts
Temperature coefficient Voc, kV	-369.0 mV/0C
Temperature-coefficient of Isc, Ki	86.9 mA/0C

Simulations were performed for both the conventional Incremental Conductance (INC) algorithm and the proposed method under constant and variable irradiance conditions to compare their performance. The MPPT controller was configured with a sampling time of 0.05 seconds. Under constant irradiance, the simulation was run for 1 second, whereas under variable irradiance, it was extended to 4 seconds. During the variable irradiance scenario, the irradiance level increased from 0.4 kW/m² to 1.0 kW/m² and then decreased back to 0.4 kW/m². This test setup enables a comprehensive evaluation of the system's performance under rapidly changing irradiance conditions.

5.1 Simulation results at variable solar-irradiance

In this work, the solar irradiance is increased from 500 W/m² to 1000 W/m² over a one-second interval. It then decreases to 800 W/m² at the 2-second mark and further drops to 600 W/m² at 3 seconds. This varying irradiance profile challenges the system's maximum power point tracking (MPPT) capability and overall performance in a dynamic operating environment. The results demonstrate the system's responsiveness and effectiveness in adapting to rapid fluctuations in irradiance.

5.1.1 with INC MPPT Method

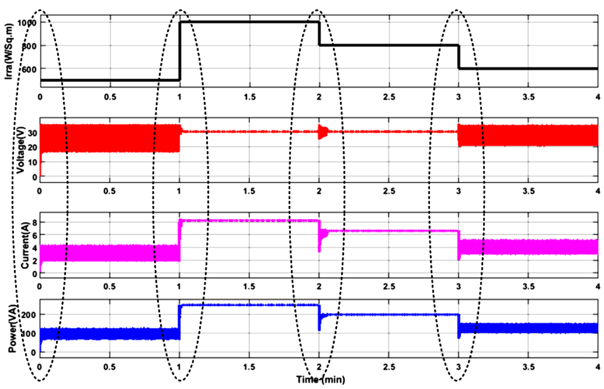

Fig 11. The following are the outcomes of the INC MPPT system simulations run under varying irradiation conditions: (i) irradiance; (ii) PV voltage; (iii) PV current; and (iv) PV power.

Simulation analysis of the Incremental Conductance (INC) method reveals that it struggles to accurately track the MPP under sudden changes in irradiance, particularly at lower intensity levels. However, it performs better in tracking the MPP when irradiance levels are higher.

Table 3 presents a detailed analysis of the voltage and current responses of a photovoltaic (PV) system employing the Incremental Conductance (INC) method under varying irradiance conditions. In the first period (0–1 s) at an irradiance level of 500 W/m², the voltage fluctuates between 17 V and 34 V, and the current ranges from 2 A to 4 A. However, the system does not achieve steady state, although it exhibits satisfactory dynamic behavior. During the second period (1–2 s) at 1000 W/m², the system reaches steady state at 30.7 V and 8.15 A within 0.02 seconds, demonstrating excellent transient performance. In the third period (2–3 s) at 800 W/m², a voltage of 32 V and a current between 6 A and 7 A are observed, with steady-state achieved in 0.05 seconds, again indicating stable dynamic response. In the final period (3–4 s) at 600 W/m², the voltage varies between 20 V and 32 V and the current between 3 A and 5 A. Although steady state is not attained during this interval, the system maintains acceptable dynamic stability.

Table 3. Voltage and Current Measurements Under INC method

Time in Sec	Irradiance in W/m2	V in Volts	I in Amps	Reaches to steady state in sec
0 – 1	500	17-34 V	2-4 A	Never Reaches
1 – 2	1000	30.7 V	8.15 A	0.02
2 – 3	800	32 V	6-7 A	0.05
3 – 4	600	20-32 V	3-5 A	Never Reaches
3 – 4	600	20-32 V	3-5 A	Never Reaches

5.1.2 with Proposed MPPT Method

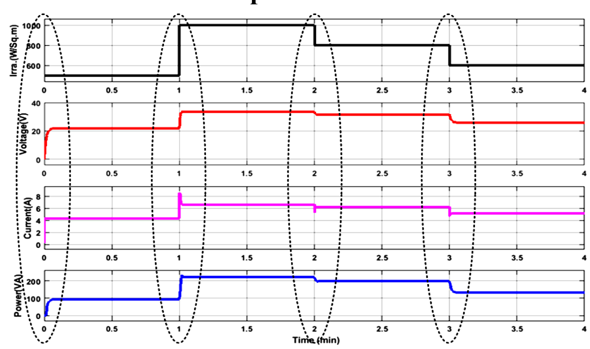

Fig 12. The Simulation Results of the Proposed MPPT System's Irradiance-Variable Simulation at 1000 W/m2; (i) Light intensity; (ii) Grid voltage; (iii) Grid current; (iv) Grid power

The proposed MPPT controller considers the I–V characteristics of both the solar panel and the DC–DC converter to determine the initial duty cycle. Subsequently, the duty cycle is incrementally adjusted using a small step size, ensuring that the operating point remains close to the maximum power point (MPP), thereby enhancing efficiency. Table 4 presents the measured voltage and current values, along with the overall performance of the photovoltaic (PV) system employing this MPPT strategy. This method improves system efficiency by optimizing power output under varying operating conditions.

To illustrate the system’s dynamic and steady-state performance, Table 3 presents detailed voltage and current values for the PV system under various irradiance conditions, as calculated using the proposed method. The system reaches steady state within 0.0055 seconds during the first second (0–1 s) at 500 W/m² irradiance, stabilizing at 24 volts and 4 amps. Maintaining strong dynamic performance, the system stabilizes at 30.7 volts and 8 amps during the second (1–2 s) at 1000 W/m², achieving steady state in 0.03 seconds. These results demonstrate that the method can effectively track the maximum power point (MPP) even under high irradiance conditions. Operating at 32 volts and 6 amps, the system reaches steady state in 0.03 seconds and consistently sustains robust dynamic performance during the third second (2–3 s) at 800 W/m².

The PV system is able to effectively follow the MPP and provide constant dynamic performance across all irradiance levels because to the suggested method's quick reaction and stable operation. Optimizing PV system performance has never been easier than with this technology, which outperforms traditional MPPT techniques in stability and reaction time.

Table 4. Voltage and Current at different irradiance values

Time Period (in sec)	Irradiance (in W/m2)	V (volts)	I (amps)	Reaches to Steady state (in sec)	Dynamic Performance
0 – 1	500	24 V	4:00 AM	0.0055	Very Good
1 – 2	1000	30.7 V	8:00 AM	0.03	Very Good
2 – 3	800	32 V	6:00 AM	0.03	Very Good
3 – 4	600	33 V	5A	0.03	Very Good
Time Period (in sec)	Irradiance (in W/m²)	V (volts)	I (amps)	Reaches to Steady state (in sec)	Dynamic Performance

Table 5. Comparison of the MPPT Methods

Parameter	P&O Method	INC Method	Fuzzy MPPT	Neural Network MPPT	Proposed Method
Efficiency (%)	83.47	91.51	92.85	93.6	94.25
Tracking Power Loss (%)	24.6	17.05	10.42	7.89	5.76
Tracking Time (s)	1.42	1.16	0.95	0.72	0.28
Steady-State Oscillations	Large	Small	Small	Very Small	Negligible

Focusing on key performance metrics under varying solar irradiance conditions, Table 4 compares the proposed MPPT method with two widely adopted techniques: the Incremental Conductance (INC) method and the Perturb and Observe (P&O) method. Considering efficiency, power loss, tracking time, and steady-state behavior, the comparison demonstrates that the proposed method outperforms the others. The proposed method achieves the highest efficiency of 94.25%, compared to 91.51% for the INC method and 83.47% for the P&O technique. This indicates that the proposed method can extract more power from the solar panel system, enhancing maximum power point tracking under varying irradiance conditions.

Power loss is a critical performance metric, and the proposed approach significantly outperforms the Incremental Conductance (INC) and Perturb & Observe (P&O) methods, exhibiting power losses of 5.76% and 17.05%, respectively. The reduced power loss indicates improved system efficiency and energy output. The proposed method also achieves a substantially shorter tracking time of 0.28 seconds compared to 1.16 seconds for INC and 1.42 seconds for P&O. This rapid response enables more accurate power extraction and minimizes energy loss under rapidly changing irradiance conditions. Furthermore, the approach demonstrates superior stability with negligible steady-state oscillations, unlike the minor oscillations observed with INC and the significant oscillations with P&O. Reduced oscillations ensure stable output power and prolong component lifespan by minimizing harmful fluctuations. Overall, the proposed MPPT method offers enhanced efficiency, speed, and stability, making it especially suitable for photovoltaic systems operating under dynamic irradiance conditions.

5.2 BLDC Motor Load Integration

The BLDC Motor load is connected to system shown in the figure 4. The following observations are found in the MATLAB/Simulink.

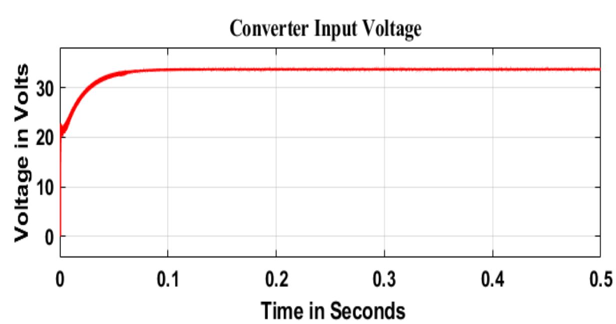

Fig 13. Converter input Voltage

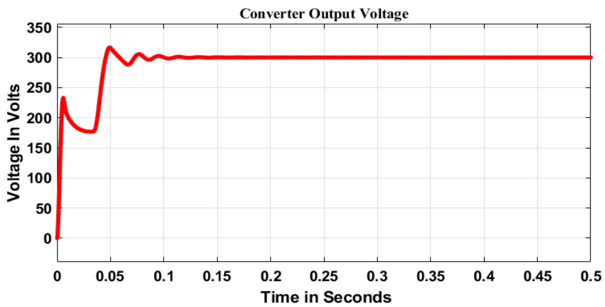

Fig 14. Converter output voltage

Figures 13 and 14 illustrate the input and output voltage waveforms of the Zeta boost converter. The converter operates with an input voltage of 33.3 V and achieves an output voltage of 300 V, resulting in a calculated voltage gain of 9.09. The system exhibits a settling time of 0.1 seconds.

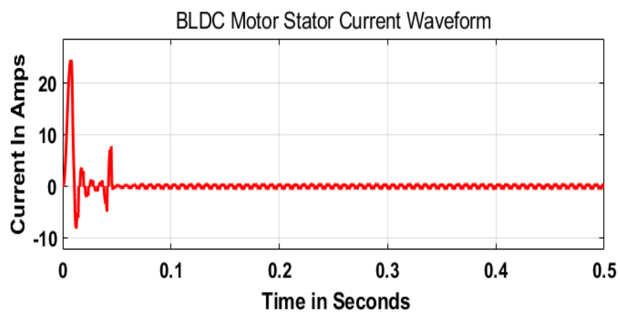

Fig 15. BLDC Motor Current waveform

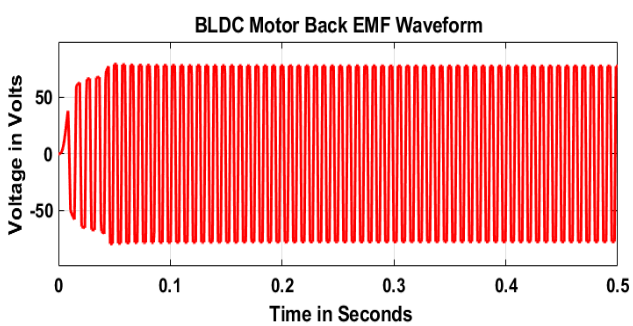

Fig 16. BLDC Motor Back EMF waveform

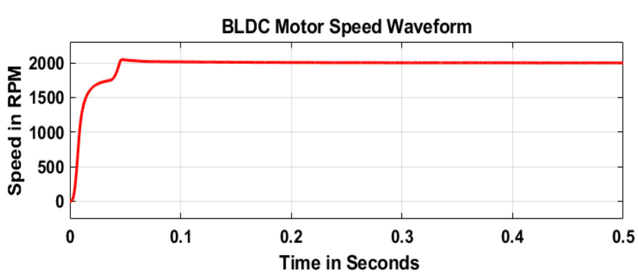

Fig 17. BLDC Motor Speed waveform

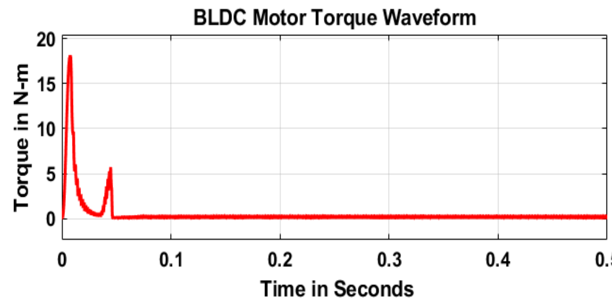

Fig 18. BLDC Motor Torque waveform

Figures 15 to 18 shows the current, back EMF, speed, and torque waveforms of the BLDC motor. The motor operates steadily at a constant speed of 2000 rpm.

Integrating the Zeta boost converter properly is essential for good results from the proposed MPPT method. High efficiency is provided and the panel is less stressed since the converter keeps the current steady, benefiting the regulation of step-up and step-down voltages. A good microcontroller or DSP adds speed and accuracy to the switching and duty cycle calculations with the MPPT algorithm. The use of great electrical components and strong filters helps to support high-frequency switching and lower noise. In addition, impacts from temperature changes and low light need to be managed by jointly tuning the MPPT algorithm and converter settings.

6 Conclusion

This research presents a novel Maximum Power Point Tracking (MPPT) method designed to efficiently respond to rapid fluctuations in solar irradiance and load. Unlike conventional iterative techniques, the proposed approach calculates the duty cycle directly from load characteristics, enabling faster and more accurate tracking of the Maximum Power Point (MPP). Simulation results demonstrate significant improvements, including an 11.29% reduction in power losses and tracking speeds 3.8 and 5.6 times faster than the Incremental Conductance (INC) and Perturb & Observe (P&O) methods, respectively. The reduction of steady-state oscillations further enhances overall system efficiency. Additionally, integrating a high-efficiency DC-DC converter optimizes power transfer and, together with the fast dynamic response of the MPPT algorithm, substantially improves system performance under varying irradiance conditions.

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