

Improved MPPT Control Strategy for PV Connected to Grid Using IncCond-PSO-MPC Approach

Nora Kacimi, Abdelhakim Idir[✉], Said Grouni, and Mohamed Seghir Boucherit

Abstract—This paper proposes a new hybrid maximum power point tracking (MPPT) control strategy for grid-connected solar systems based on Incremental conductance—Particle Swarm Optimization and Model Predictive Controller (IncCond-PSO-MPC). The purpose of the suggested method is to create as much power as feasible from a PV system during environmental changes, then transfer it to the power grid. To accomplish this, a hybrid combination of incremental conductance (IncCond) and particle swarm optimization (PSO) is proposed to locate maximum power, followed by model predictive control (MPC) to track maximum power and control the boost converter to achieve high performance regardless of parameter variations. A two-level inverter, likewise, controlled by Model Predictive Control, is employed to inject the PV power generated. In this application, the MPC is based on minimizing the difference between the reference and prediction powers, which is computed to select the switching state of the inverter. The proposed system is simulated and evaluated in a variety of dynamic conditions using Matlab/Simulink. Results reveal that the proposed control mechanism is effective at tracking the maximum power point (MPP) with fewer power oscillations.

Index Terms—DC/DC boost converter, grid-connected PV, incremental conductance particle swarm optimization and model predictive controller (IncCond-PSO-MPC), maximum power point tracking (MPPT), photovoltaic (PV).

I. INTRODUCTION

ENERGY has become a critical factor in economic and social development in our society over the last few decades, and solar energy has gotten a lot of attention as a way to overcome increased energy consumption and environmental problems [1]. It is one of the most prominent sources for power generation. A solar photovoltaic module converts solar energy directly into electricity [2]. Solar photovoltaic power generating systems are gaining popularity because they are more abundant, efficient, and ecologically benign than conventional power generation systems such as fossil fuel, nuclear, or coal [3].

Different topologies and control methodologies can be used to implement these systems. However, they can be classified into two types: stand-alone systems and grid-connected systems [4]. Standalone application produces very little electrical energy, it is only appropriate for low-power applications. PV energy sources must be connected to the grid system in order to be used at medium and high-power levels, and a DC-AC inverter is typically used to regulate the DC-link voltage and manage active and reactive power flow between the PV generator and the grid [5]. Furthermore, in order to be fully operational, PV systems must deliver the maximum amount of energy. However, because PV systems have nonlinear (P–V) characteristics, a maximum power point tracking technique is utilized to extract maximum output power regardless of environmental changes.

Several MPPT techniques have been proposed in literature for better extraction of maximum power [6]–[14]. Under uniform conditions, most MPPT techniques perform well. However, literature contains a multitude of other state-of-the-art partial shading MPPT methods. In [15], the authors provide a comprehensive overview of 62 global MPPT methods. The memetic salp swarm algorithm-based MPPT control for partial shading conditions is discussed in [16], which is an extension of the salp swarm algorithm. The authors of [17] described a partial shading MPPT approach based on collective intelligence that employs five sub-optimizers. The authors in [18] proposed a modified Fibonacci search technique for tracking the GMPP. In contrast, the authors in [19] discussed a systematic modification of the P & O algorithm for tracing the GMPP. The strategy based on the merging of P&O with a genetic algorithm is described in [20].

The Particle Swarm Optimization (PSO) method is the most commonly used. The PSO method's main drawbacks are its slow operation and large oscillations. Several modifications were made to the PSO method in order to overcome large oscillation problems. Some changes were also made to the reinitiating of the PSO algorithm, and others used a hybrid of the PSO algorithm.

Furthermore, tracking delays occur with optimization-based MPPT approaches due to the ultimate operating point, which is calculated by comparing all population findings. Additionally, when Partial Shading Conditions (PSC) are not present, it is tracking performance dips behind that of standard methods. Incremental conductance (IncCond), on the other hand, is a well-known technique with relatively good performance. However, it has some drawbacks, such as not guaranteeing convergence to the true maximum power point in some conditions, such as

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in (PSC), and it is relatively slow, which reduces the efficiency of photovoltaic work.

To address this issue, the authors proposed a Hybrid MPPT control strategy based on the IncCond-PSO-MPC approach. Under uniform conditions, the IncCond is used with the step size selected, which significantly reduces tracking time. In order to detect MPP quickly under partial shading, the PSO is used where the initial population is used by the last reference current. To increase tracking speed, a model predictive control (MPC) is also employed to identify optimal switching of the DC/DC converter.

An MPC was employed at each sampling instant to solve a finite-horizon optimal control problem and get control actions for both the present and the future [21]–[24]. A predictive control strategy has numerous advantages, including ease of implementation and high performance in terms of time response. In this paper, a predictive current controller is used to replace the delay control. The control methodology consists of two steps. The first step is to calculate the reference current I_{mpp} using a hybrid (IncCond-PSO) that is related to the MPP working current. The second step is a developed MPC regulator for the boost converter.

A two-level voltage source inverter controls the PV grid-connected inverter (2L-VSI). In literature, various control techniques for grid-connected inverters have been presented, including hysteresis and linear control with pulse width modulation, voltage-oriented control, direct power control (DPC), and so on. The most common controller for power converters is the classical proportional-integral (PI) controller. However, due to consideration of fixed gains, they are unable to handle dynamic operating conditions [25].

Because of its high accuracy and simple approach, as well as the ease with which system nonlinearities and constraints can be integrated in the cost function, the predictive control model MPC has shown good performance [26]. This latter component is crucial when building an MPC since it enables the selection of control objectives, which results in higher performance for the PV grid-connected system in terms of operational efficiency, improved power quality, remote operations control, and environmental efficiency. MPC is recommended for grid-connected inverters due to the benefits mentioned previously.

Our paper's main contribution is that it proposes a novel hybrid IncCond-PSO-MPC method for improving the quality of the PV panel and extracting maximum power. The rest of this paper is divided into two sections:

1) In the first stage, a novel method is used to extract the greatest amount of power. This method uses a hybrid IncCond-PSO to determine the optimal current of a PV system. This is then used in the MPC cost function to select the optimal switching of the DC/DC converter.

2) For the second stage, a predictive control coupled with two-level three-phase voltage source inverter is proposed to validate the control method. A PI controller collects reference power from the DC link voltage loop, which is dedicated to maintaining the DC link voltage at the goal value, and a cost function is used to select an ideal switching state.

To evaluate the robustness of the suggested method in a specified setup, simulation results are obtained in a Matlab/Simulink environment. According to the findings, the proposed IncCond-PSO-MPC technique optimizes efficiency and extracts the ideal power that follows the power of the PV panel.

The remainder of this work is structured as follows: Section II includes the researched system's synoptic schematic, as well as a mathematical model of the PV source and boost converter. Section III goes through the framework of the proposed hybrid MPPT approach in detail. Section IV addresses the performance of the suggested technique and offers simulation results. Section V concludes with appropriate conclusions.

II. PV SYSTEM DESCRIPTION AND MODELING

Figure 1 depicts overall system topology. It is made up of a PV system, a DC/DC boost converter output, and R_g , L_g filters to decrease the ripple components induced by switching, as well as a voltage source inverter (VSI).

The system is adapting in two steps. First, the MPPT-controlled boost converter harvests the maximum power from the PV array and tracks it regardless of environmental fluctuations. The DC-DC boost power is subsequently fed into the grid by the two-level inverter. The PI controller additionally maintains DC-link voltage to ensure it is at the proper level.

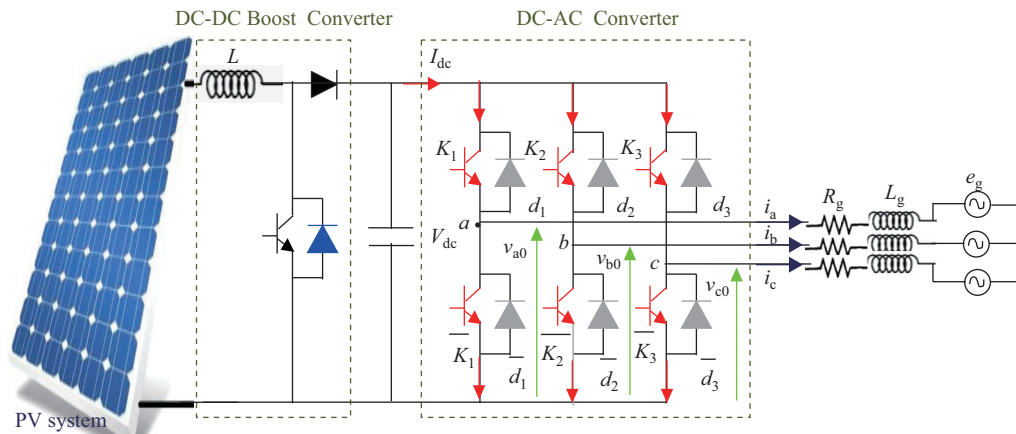


Fig. 1. Topology of the overall system under consideration.

Mathematical representations for all system components are generated and supplied in the following sub-sections for control design considerations.

A. Array Model

A photovoltaic cell is an electrical device that converts solar energy directly into electricity using the photovoltaic effect [27]. The most recent modeling technique, seen in Fig. 2, consists of a current source comprised of a single diode and resistors [28], [29].

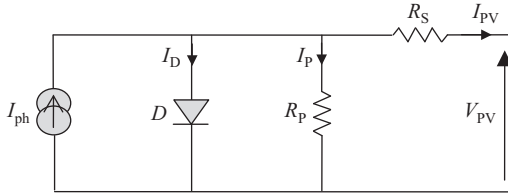


Fig. 2. The equivalent electrical circuit of one diode.

The solar cell model is a P-N semiconductor junction, similar to a diode; when exposed to light, it generates a DC current.

As is generally known, solar irradiance, temperature, and load current all have an effect on the current generated by a solar cell. The following is the relationship between output current (I_{PV}) and output voltage (V_{PV}) [30].

$$I_{PV} = I_{ph} - I_0 \left(e^{\frac{q(V_{PV} + R_s I_{PV})}{N_s T K a}} - 1 \right) - \frac{V_{PV} + R_s I_{PV}}{R_p} \quad (1)$$

where I_{PV} is the current supplied by the cell (A); I_0 is the diode saturation current; q is the Electron charge; K is the Boltzmann constant; T is the cell temperature in Kelvin, a is the PV cell's ideality coefficient; I_{ph} the photocurrent generated by the PV cell in the presence of a particular amount of light (A); R_s is the cell's series resistance (Ω); R_p is the cell's parallel resistance (Ω); N_s is number of cells connected in series.

B. DC-DC Boost Converter Model

Electronic devices that convert one level of DC electrical power to another are known as DC-DC converters [31]. The boost converter architecture is utilized to provide high voltage gain to the MPPT algorithm in order for it to attain maximum power. Fig. 3 depicts the basic circuit of a boost converter.

The converter's dynamic model can be expressed as follows:

$$\begin{cases} L \frac{di_L}{dt}(t) = -(1-s)V_c(t) + V_{pv}(t) \\ C \frac{dV_c}{dt}(t) = (1-s)I_L(t) + \frac{1}{R} V_c(t) \end{cases} \quad (2)$$

where s is the switching state, which can be taken to 1 or 0; I_L is the current inductor; V_c is the voltage capacitor; V_{pv} is the PV array voltage.

C. DC-AC Voltage Source Inverter

In a grid-connected PV system, a three-phase two-level power converter is used. A three-phase two-level inverter's conventional structure consists of three arms (a, b, c), each

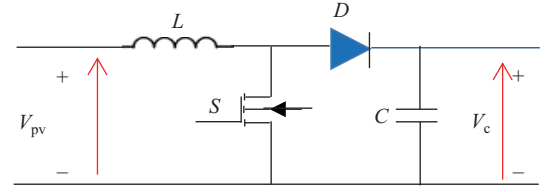


Fig. 3. Equivalent circuits of boost converter.

of which consists of two parallel diode/transistor assemblies. There are eight alternative switching voltage vectors that can be obtained.

The following equations represent the mathematical model of grid currents in the natural frame (abc):

$$\begin{cases} L_g \frac{di_a}{dt} = -R_g I_a - e_a + V_{an} \\ L_g \frac{di_b}{dt} = -R_g I_b - e_b + V_{bn} \\ L_g \frac{di_c}{dt} = -R_g I_c - e_c + V_{cn} \end{cases} \quad (3)$$

where L_g and R_g are the output filters' inductance and resistance, respectively, e_a is the grid voltage, and V_{an} is the output voltage of the two-level inverter.

The Clarke transformation is used to transfer grid voltage and phase current components from the natural (a, b, c) reference frame to the stationary (α, β) frame, which is defined as [32]:

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (4)$$

The converter's input current dynamic can therefore be expressed as:

$$\begin{cases} L_g \frac{di_\alpha}{dt} = -R_g I_\alpha - e_\alpha + V_\alpha \\ L_g \frac{di_\beta}{dt} = -R_g I_\beta - e_\beta + V_\beta \end{cases} \quad (5)$$

III. PROPOSED CONTROL DESIGN

The MPPT method is used to generate the switching signal that maintains the PV system's operation at the MPP for the boost converter. This study considers a new combination to extract maximum power. The Incremental Conduction-Particle Swarm Optimization technique is used to estimate current I_{ref}^* at MPP, and then the latter is used to predict switching state by minimizing a cost function of predictive control as shown in Fig. 4.

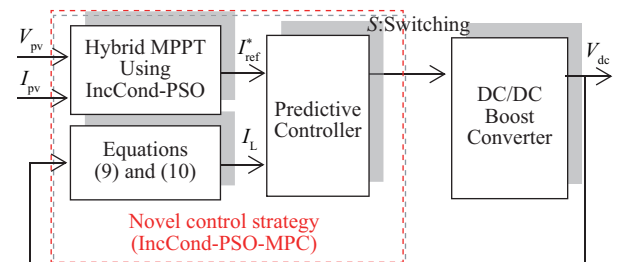


Fig. 4. The proposed MPPT using hybrid IncCond-PSO-MPC approach.

A. Design Principle for a Conventional IncCond Technique.

When the PV array is subjected to rapid changes in external circumstances, the incremental conductance (IncCond) technique outperforms other methods by tracking the MPP more quickly [33]. The MPP is typically calculated by taking a derivative of the PV power output with respect to voltage output. The photovoltaic panel's output current and voltage are utilized to compute conductance and incremental conductance. This method's fundamental equations are as follows:

- Operation point is at (MPP) $\frac{dV_{pv}}{dI_{pv}} = -\frac{V_{pv}}{I_{pv}}$
- Operation point is at left side of MPP $\frac{dV_{pv}}{dI_{pv}} < -\frac{V_{pv}}{I_{pv}}$
- Operation point is at right side of MPP $\frac{dV_{pv}}{dI_{pv}} > -\frac{V_{pv}}{I_{pv}}$

Figure 5 depicts the incremental algorithm's flowchart. As shown, the method generates a reference current I_{ref} , which increases when the slope is positive and reduces when it is negative [34]. This reference current will be fed into the predictive control block, which will be explained in the following sections.

Under partial shading, PV systems have multiple peaks, and IncCond can get stuck in a local peak instead of a global peak. To overcome this problem, a PSO is proposed in this paper. The block diagram of the hybrid technique is depicted in Fig. 5.

B. PSO Algorithm

PSO is a robust searching algorithm created in 1995 [35] by Eberhart and Kennedy based on patterns seen in bird flocking and fish schooling. A group of unique agents known as a swarm of particles is used in this procedure. The algorithm discovers the fitness value corresponding to each particle in the search space of the optimization problem, and the algorithm selects the optimal solution from among those. The most effective solution will attract the other particles. This searching criterion will be repeated until the particles have converged on the global optimal solution [36]. The next movement of the particles will then be determined by information obtained in the swarm. The particle position can be calculated as follows:

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad i = 1, 2, \dots, N \quad (6)$$

where $V_i(k)$ denotes the particle's velocity, k is the number of perturbation iterations, and N denotes the total number of particles. Speed is determined by:

$$V_i(k+1) = \omega V_i(k) + c_1 r_1 (P_{best,i} - x_i(k)) + c_2 r_2 (G_{best} - x_i(k)) \quad (7)$$

where ω is inertia weight, c_1 is the cognitive coefficient, c_2 is the social coefficient, $P_{best,i}$ is the best solution of particle i , and G_{best} is the best solution of the entire swarm (global best), and $r_1, r_2 \in (0, 1)$. The following are the PSO steps:

Step 1: Set the PSO parameters W_{min} and W_{max} , as well as c_1 and c_2 ;

Step 2: Generate a population of particles with locations x and velocities V ;

Step 3: Put iteration $k = 1$;

Step 4: Calculate particle fitness $F_i^k = f(x_i^k)$, $\forall i$ and determine the best particle index P_{best} ;

Step 5: Select $P_{best_i}^k = x_i^k$ and $G_{best}^k = x_i^k$;

Step 6: Updates velocity and position of particles;

Step 7: Evaluates fitness $F_i^{k+1} = f(x_i^{k+1})$, $\forall i$ and determines the best particle index.

When PSC is present, the PV system has numerous local peaks (LP), one of which is the global peak (GP). A change in irradiance causes the position of the GP to shift to another peak location, which the IncCond MPPT may not detect. As illustrated in Fig. 5, the proposed MPPT method employs hybrid MPPT algorithms. Under uniform conditions, anIncCond approach is used, while under partial conditions, the PSO technique is used.

To shorten search time and avoid particle convergence failure, the PSO is re-initialized with the beginning values of the latest reference current, and MPP is identified promptly. The shading pattern (SP) change can be easily checked using (8).

$$\frac{P_{pv,new} - P_{pv,old}}{P_{pv,old}} > \Delta P(\%) \quad (8)$$

A predictive control is used to optimize power and generate a switching signal for the DC/DC converter. Using a first order approximation for the derivative in (2), the predicted current and voltage in discrete time are given by:

$$I_L(k+1) = I_L(k) - (1-S)\frac{T_s}{L_f}V_c(k) + \frac{T_s}{L_f}V_{pv}(k) \quad (9)$$

$$V_c(k+1) = V_c(k) + (1-S)\frac{T_s}{C}I_L(k) + \frac{T_s}{RC}V_c(k) \quad (10)$$

where T_s is sample time.

By minimizing a cost function, the anticipated variables will be used to find the ideal switching state.

In this research, a cost function is evaluated for each conceivable switching state and will be chosen to track the current I_{ref} given by the hybrid (IncCond-PSO) controller, as illustrated in Fig. 5.

C. DC-DC Link Voltage Regulation

This controller regulates DC link voltage, which is critical for power transfer and overall system stability. The goal of this control algorithm is to keep the value of V_{dc} close to the reference value.

A basic PI controller is implemented to avoid variations and instability in DC link voltage. The controller works by using a proportional gain to boost dynamics and an integrator quantity via the gain to improve steady-state tracking. The transfer function of the system must first be specified in order to identify controller gains.

The following is the dynamic equation for DC link voltage:

$$C \frac{dV_{dc}}{dt} = -i_{inv} \quad (11)$$

where i_{inv} is the inverter current.

The voltage transfer function for a closed loop DC connection is represented as follows:

$$\frac{V_{dc}}{V_{dc_ref}} = \frac{K_p/C(K_i/K_p)}{S^2 + K_p/CS + K_i/C} \quad (12)$$

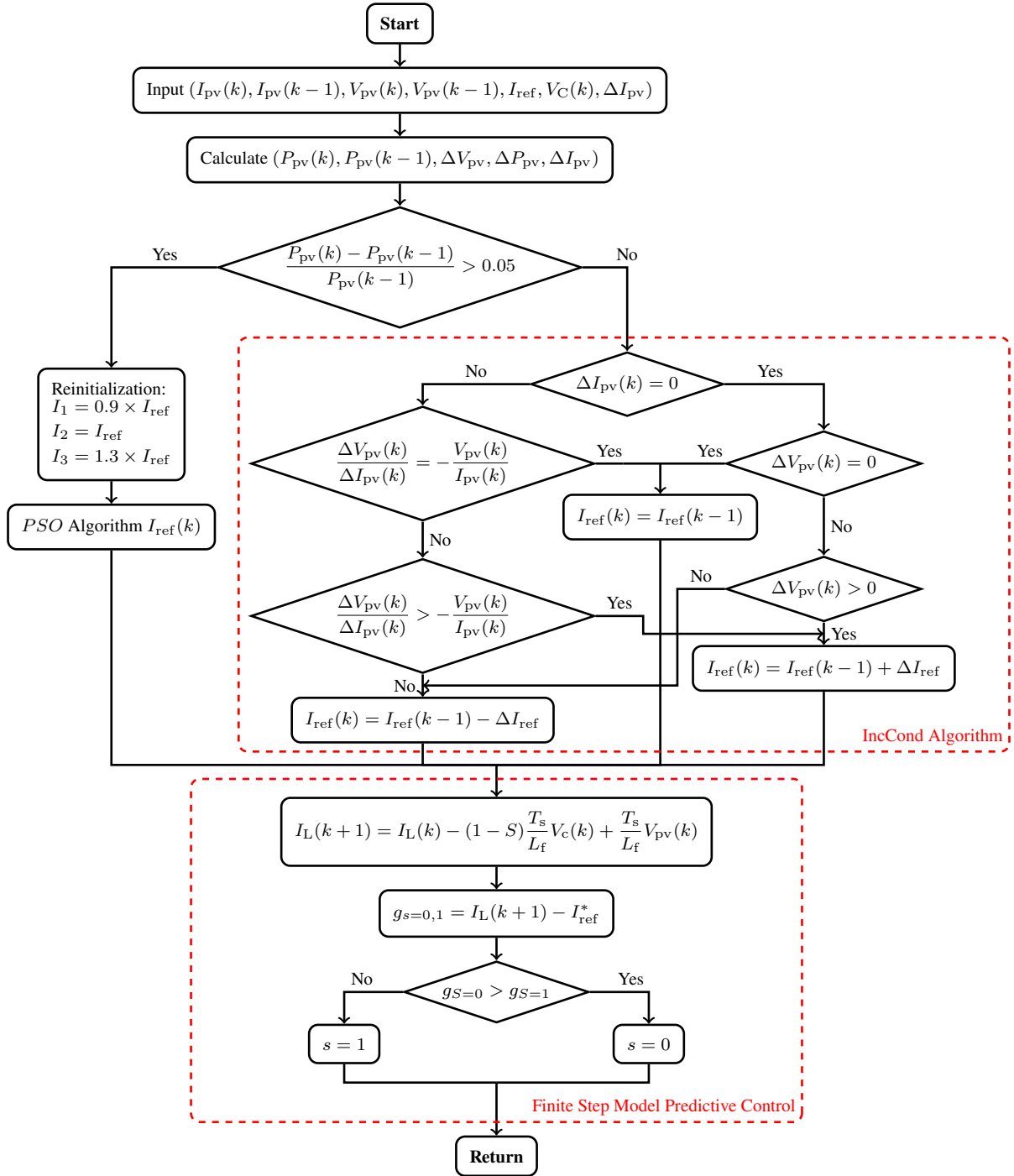


Fig. 5. The proposed flowchart (IncCond-PSO-MPC).

From (12), the relation between V_{dc} and V_{dc_ref} is the transfer function of the second order

$$\frac{V_{dc}}{V_{dc_ref}} = \frac{\omega_n^2}{S^2 + 2\zeta\omega_n S + \omega_n^2} \quad (13)$$

By equaling (12) and (13). The PI parameters are chosen as follows: $K_p = 2C\zeta\omega_n$ and $K_i = C\omega_n^2$

D. DC-AC Control With MPC

The PV array is connected to the grid via a three-phase converter controlled by a conventional MPC, as shown in

Fig. 6. Model predictive control is based on a discrete-time system model that predicts behavior of all voltage source inverter switching states. By applying Euler forward to the equation (5), the equations (14) and (15) below are obtained:

$$i_\alpha(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_\alpha(k) + \frac{T_s}{L_f} (v_\alpha(k) - e_\alpha(k)) \quad (14)$$

$$i_\beta(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_\beta(k) + \frac{T_s}{L_f} (v_\beta(k) - e_\beta(k)) \quad (15)$$

The grid's active and reactive power at the next sampling instant can be estimated in coordinates as follows:

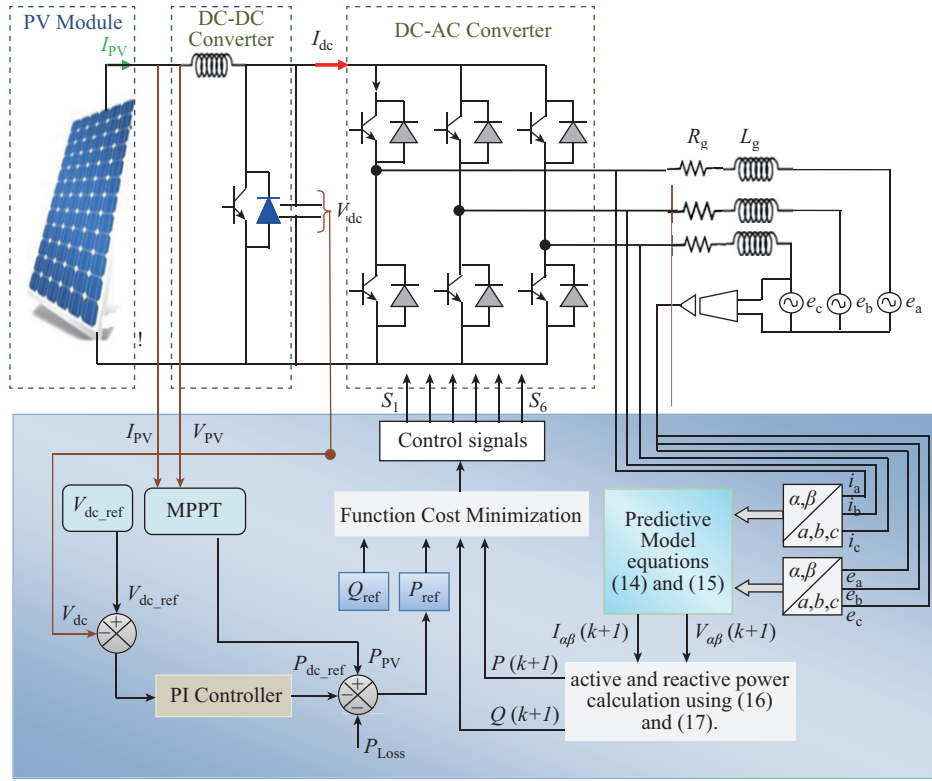


Fig. 6. The block diagram control of DC/AC of PV system connected to grid.

$$P(k+1) = e_\alpha(k+1)i_\alpha(k+1) + e_\beta(k+1)i_\beta(k+1) \quad (16)$$

$$Q(k+1) = e_\alpha(k+1)i_\alpha(k+1) - e_\beta(k+1)i_\beta(k+1) \quad (17)$$

The required quantity of active and reactive power can be fed into the grid by selecting the optimal voltage space vector. A cost function that should be defined in accordance with the system's control requirements.

The following is the definition of a cost function:

$$g(k+1) = |P_{\text{ref}}(k+1) - P(k+1)| + |Q_{\text{ref}}(k+1) - Q(k+1)| \quad (18)$$

The grid reference injected active power is computed as follows:

$$P_{g_{\text{ref}}} \simeq P_{\text{PV}} - P_{\text{dc_ref}} - P_{\text{Loss}} \quad (19)$$

$$P_{\text{Loss}} = P_J = 3R_g I_g^* I_g^* \quad (20)$$

where P_{PV} is PV array power, $P_{\text{dc_ref}}$ is the reference active power required to compensate for inaccuracy in the DC link voltage described earlier. P_{Loss} is the amount of power dissipated as a result of output filter resistance.

At time k , grid voltage and current $v_g(k)$ and $i_g(k)$ are measured. Predicted variables voltage and current are then calculated at time $(k+1)$ using equations (14) and (15).

Predicted active and reactive powers, as well as their references, are then used to evaluate the cost function as follows.

$$g(k+1)$$

As shown in the flowchart in Fig. 7, the switching state that minimizes the cost function will be chosen to be applied to the voltage source inverter at the next sampling period.

IV. SIMULATION RESULTS

Figure 1 is implemented in MATLAB/Simulink to validate performance of the suggested system. The PV array's effectiveness has been proven in a variety of atmospheric situations. Every PV generator has a maximum power point that is affected by solar irradiance and temperature. To achieve the desired PV power, the modules can be connected in series or in parallel to form a string, resulting in a PV array of the desired capacity. The PV array in this study is composed of three panels (two SM110 modules connected in series and two connected in parallel). Table I shows the electrical specifications of the system.

Figure 8(b) shows the (P-V) output characteristic of a solar panel under uniform changing irradiance and a temperature of 25 °C. The red circles represent the maximum power point positions at the corresponding irradiance. The (P-V) output characteristic of a PV array under partial shadowing is depicted in Fig. 8(b). It can detect several peaks caused by partial shading and a single MPP caused by uniform solar irradiation.

To investigate the suggested controller's performance and dynamic response, we proposed using a resistance as load in the first part and a PV system connected to the grid in the second part. The proposed MPPT is tested in a variety of weather conditions. Table II lists the parameters for the PSO.

A. Performance of PV Array Under Standard Test Conditions

We tested the proposed algorithm under uniform irradiation to validate its performance. As shown in Table III, three PVs are subjected to 1000 W/m² (STC Case).

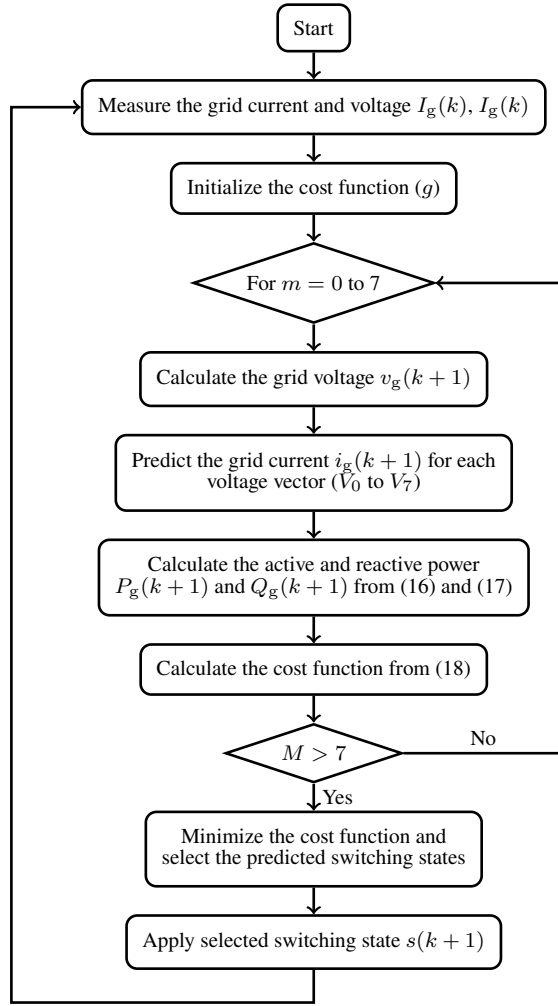


Fig. 7. Flowchart diagram of the implemented MPC.

TABLE I
STUDY SYSTEM PARAMETERS

Electrical characteristics	Value
Maximum power	110 W
Open circuit voltage	43.5 V
Short circuit current	3.45 A
PV output voltage at MPP	35 V
PV output current at MPP	3.15 A
Number of cells connected in series	72
Electrical parameters of Boost converter	Value
Inductance (L)	45 mH
Capacitance (C)	1110 μ F
Load resistive (R)	80 Ω

TABLE II
PSO PARAMETERS

Electrical characteristics	Value
Particle numbers	03
Maximum Number of iterations	50
Weight (w)	0.9
C1	1.6
C2	1.2

The results of the tracking voltage and current and power outputs are depicted in Fig. 9. The PV operated at 1320 W, which corresponds to $V = 213.4$ V and $I = 6.21$ A. Analyzing

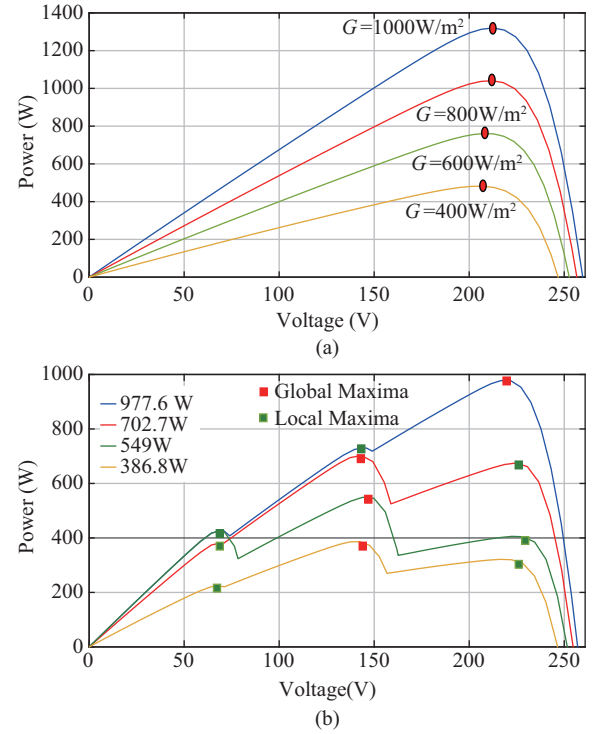


Fig. 8. Characteristic of the PV. (a) Under different irradiance level. (b) Under Partial shading.

TABLE III
SHADING PATTERNS TAKEN FOR THIS STUDY

Cases	V_{MPP} (V)	I_{MPP} (A)	G_{MPP} (W)
STC [1000, 1000, 1000]	212.4	6.21	1320
PSC1 [900, 780, 480]	143.3	4.90	702
PSC2 [1000, 600, 300]	143.9	3.81	549

the power curve reveals the suggested MPPT can track MPP effectively under standard conditions. The maximum power point has been tracked before 0.05 s with minimal power oscillation.

Figure 10 shows the proposed output power for the four different MPPT techniques (Perturb and Observe (P&O), incremental conductance (IncCond), hybrid IncCond-PSO and IncCond-PSO-MPC).

From Fig. 10, it can be seen that all techniques track the GMPP. Amplitude of oscillation is very small with respect to the MPP for the proposed technique. On the other hand, the P&O exhibits large oscillations, as shown by the zoomed portion (see Fig. 10).

B. Performance of PV Array Under Step Change of Irradiance

We tested the proposed algorithm's performance under varying irradiance conditions to validate its performance. The irradiance level for all PV is initially set to 600 W/m², then gradually increased to 1000 W/m² at 0.6 s, then decreased at 1.2 s to 800 W/m², and the temperature is kept constant at 25°C.

Figure 11 depicts the simulation outcome. As seen in Fig. 11, a step drop or increase in irradiance causes a change in PV power. As irradiance increases, the hybrid MPPT method

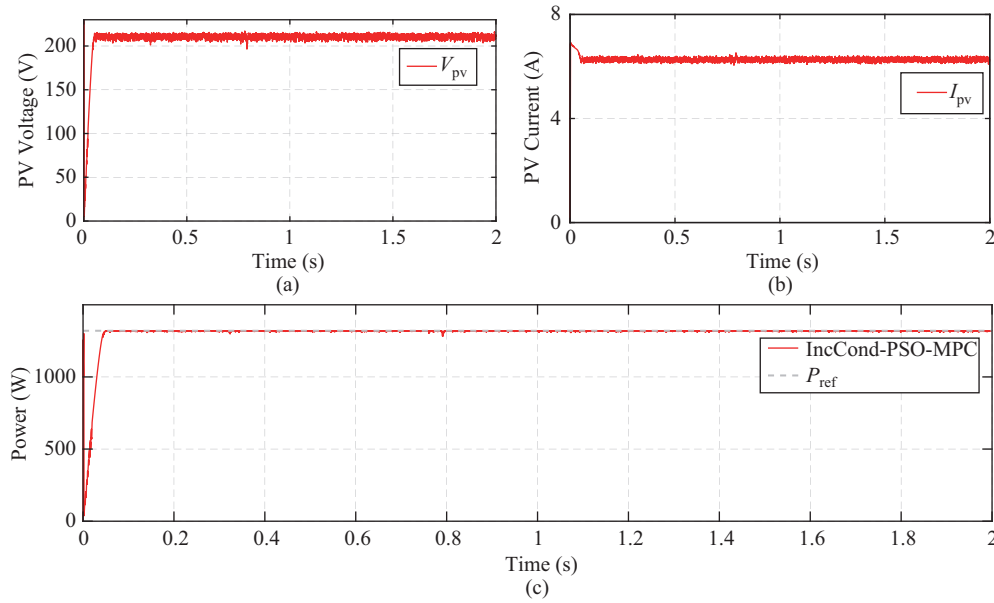


Fig. 9. MPPT tracking under STC. (a) PV Voltage. (b) PV Current. (c) PV Power output.

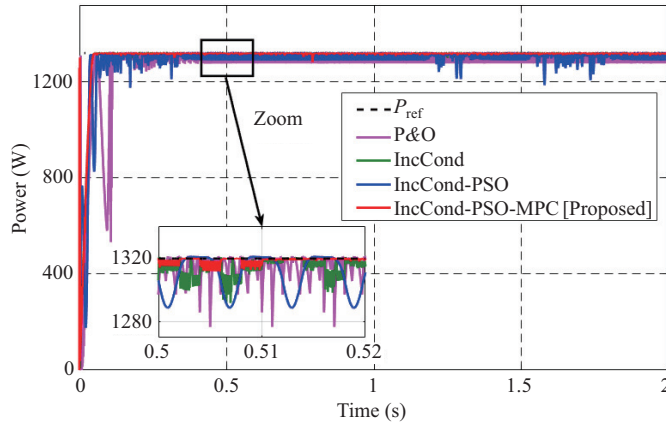


Fig. 10. PV array power output results under Standard condition.

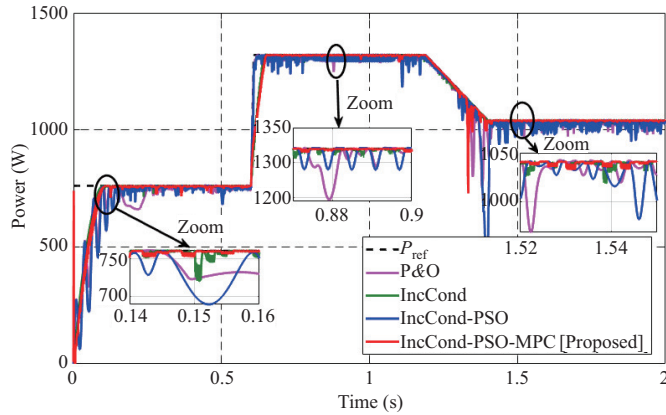


Fig. 11. PV array power output results under step change irradiance.

C. Performance of PV Array Under Partial Shading

The suggested MPPT is evaluated first in STC, then under step changes in irradiance, and as shown in Figs. 10 and 11, it converges to the MPP.

To evaluate the performance of the proposed IncCond-PSO-PC technique, a 2 s simulation is run, including two partial shade pattern tests, P1 and P2.

Table III shows the various irradiance patterns, as well as the corresponding MPP.

The partial shading pattern exposes the three PVs panels to values of (900, 780, 480) W/m² in the first test. The highest output power is 702 W. The proposed MPPT, as shown in Fig. 12, tracks the maximum power point with minimal oscillations.

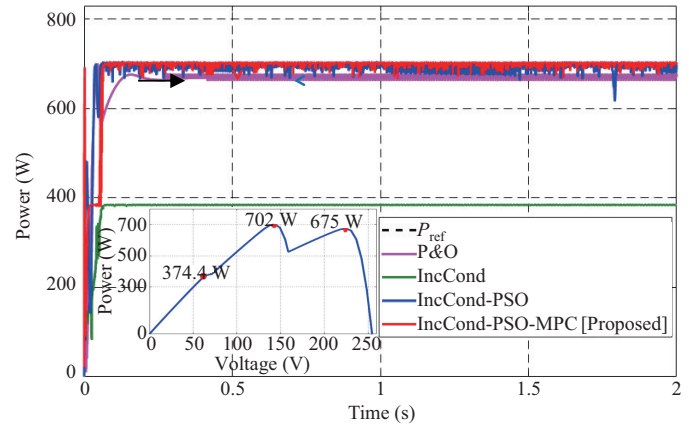


Fig. 12. PV power output under Partial shading P1.

quickly converges to its new operating point. Under uniform change situations, it is found the suggested MPPT can track MPP efficiently and with reduced power oscillation. Table IV displays the outcome of the proposed algorithm.

The PV characteristics corresponding to shading condition P1 are depicted in Fig. 12.

The proposed algorithm's tracking result is represented in the image above. Traditional IncCond is discovered to be stuck

in LMPP at 374.4 W, while P&O are also found to be stuck in LMPP at 675 W.

However, as shown in Fig. 12, the proposed MPPT approach accurately follows the corresponding 702 W. The tracking outcome obtained by the suggested algorithm is depicted in Fig. 12. Classical IncCond is found to be stuck in LMPP at 374.4 W, also P&O stuck in LMPP at 675 W.

However, as shown in Fig. 12, the suggested MPPT approach accurately follows the P_{ref} corresponding to 702 W.

Similarly, adopting the proposed MPPT, a second test, P2, was performed. The partial shade arrangement exposes the three PVs panels to values of (1000, 600, 300) W/m², with a maximum power of 549 W. Results are depicted in Fig. 13. The proposed MPPT approach (see Fig. 13), has clearly proved its usefulness and accuracy in tracking the GMPP. But IncCond and P&O are stuck at 628.6 W. The suggested MPPT strategy is compared to existing techniques in Table IV.

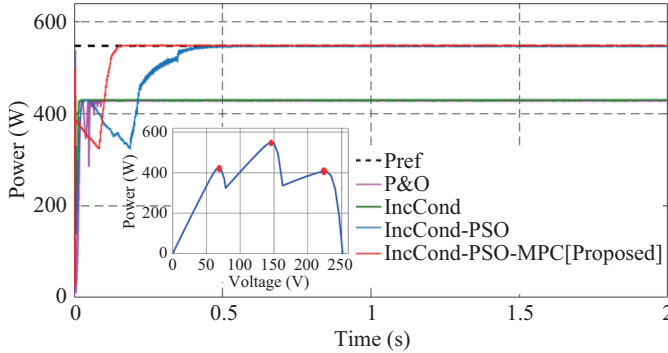


Fig. 13. PV power output under Partial shading P2.

The proposed MPPT outperforms the IncCond-PSO and normal IncCond approaches, as shown in Table IV. It can be concluded the proposed method improved convergence speed significantly, and its total efficiency is over 99%, which is greater than existing methods. When using the proposed method, tracking speed can also display higher precision tracking.

As can be observed, simulation results validate the suggested method's improved performance in terms of tracking speed and efficiency when compared to other existing approaches. As shown in Fig. 14(a), the suggested method has an overall efficiency of almost 99 %, which is greater than other approaches by more than 2 %.

Tracking Speed is depicted in Fig. 14(b).

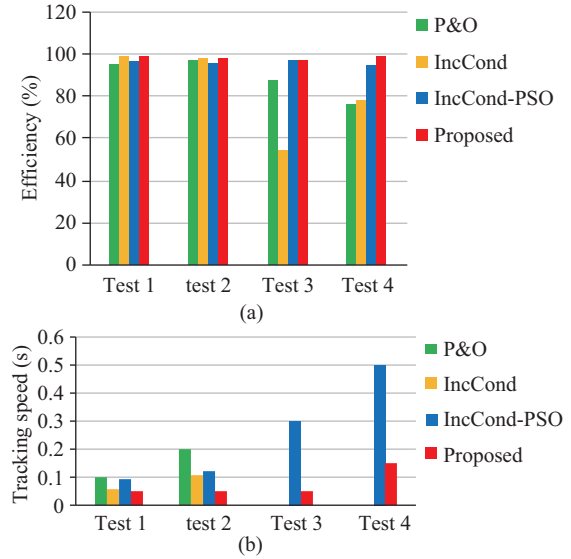


Fig. 14. Comparison various MPPT techniques. (a) Efficiency. (b) Tracking.

D. Dynamic Response of the Overall PV System With Hybrid MPPT

This section includes the injected PV power from PV systems into the grid under various irradiation changes and illustrates the efficiency of the approach used. The MPC-controlled two-level voltage source inverter is used. The PI controller is employed to keep the DC link voltage steady enough to be referenced. Table V depicts the DC/AC converter characteristics used in simulation studies.

First, the global system's performance is evaluated under uniform irradiation, as shown in Fig. 15. The irradiance level for all PV is initially set at 600 W/m².

PV array output oscillates around the MPP, as seen in Fig. 15(a), but is completely maintained at its reference value (700 V). Then, as shown in Fig. 15(c), a 0.6 s change in irradiation from 600 to 1000 W/m² leads to an increase in PV power production and a slight divergence in V_{dc} from its reference.

TABLE V
ELECTRICAL PARAMETERS OF DC/AC CONVERTER

Electrical characteristics	Value	PI controller	Value
Grid voltage (e)	50 V	Proportional gain (K_p)	5
Voltage frequency (f)	50 Hz	Integral gain (K_i)	40
Filter resistance (R_f)	0.5 Ω		
Filter inductance (L_f)	10 mH		
DC source voltage (V_{dc})	700 V		

TABLE IV
COMPARATIVE RESPONSE PERFORMANCE ANALYSIS RESULTS

Tests	Performances	P&O	IncCond	IncCond-PSO	IncCond-PSO-MPC[Proposed]
Test 1: STC	Tracking speed (s)	0.1	0.06	0.09	0.05
	Efficiency (%)	95	99	97	99
Test 2: Variable	Tracking speed (s)	0.2	0.11	0.12	0.05
	Efficiency (%)	97	98	96	98
Test 3 PSC 1	Tracking speed (s)	—	—	0.3	0.05
	Efficiency (%)	88	54	97	97
Test 4 PSC 2	Tracking speed (s)	—	—	0.5	0.15
	Efficiency (%)	76	78	95	99

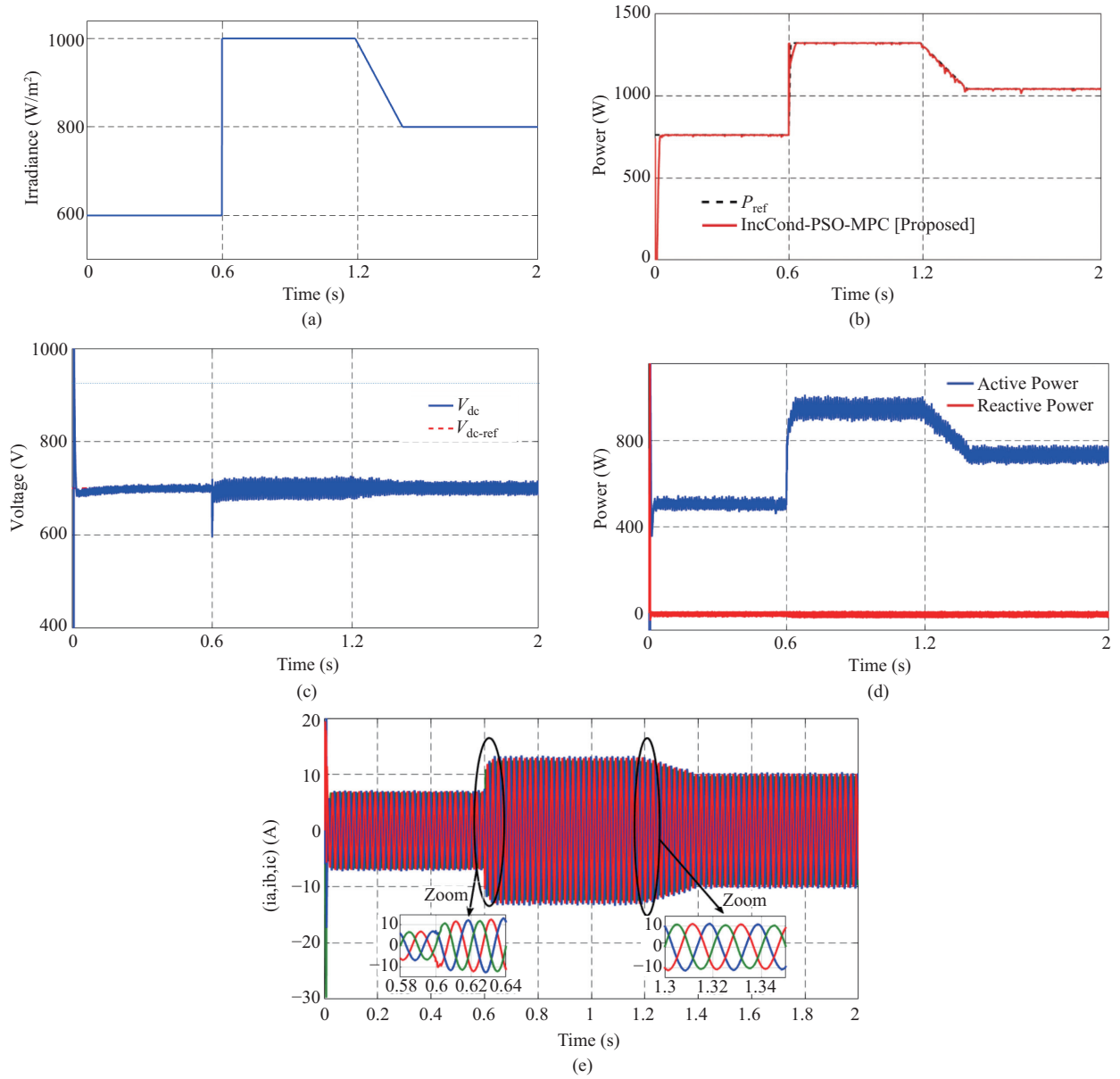


Fig. 15. Performance of global system under uniform irradiation changes. (a) Solar irradiance profile; (b) PV power; (c) DC-link voltage; (d) Grid-injected active and reactive power; and (e) Grid current of the three-phase system.

Increases in grid current are caused by increases in PV power, as seen in Fig. 15(e), where the amplitude of the grid current is proportional to PV power despite a modest overshoot from its reference (700 V). The MPC's ability to inject maximum available power is in response to irradiation variations.

As can be seen, the grid's instantaneous active and reactive power has a low ripple in the injected power. It can also be seen that active power behaves similarly to the power, and the reactive power stabilizes at zero and is unaffected by variations in irradiation. Furthermore, despite the alteration, the grid current maintained its sinusoidal structure. There is a shift in irradiance; there is a slight difference in current. The proposed control mechanism, as shown in Fig. 15, ensures rapid regulation of this variance.

Figure 16 depicts the second test. Initially, the partial

shading pattern exposes the three PV panels to values of ($G1 = 900$, $G2 = 780$, $G3 = 480$) W/m², with a maximum power of 702 W. The irradiance will then be increased to 1000 W/m² at 0.6 s for all three PV panels, and then lowered to 600 W/m² at 1.2 s, as illustrated in Fig. 16(a).

The proposed MPPT tracks maximum power for all irradiation conditions. V_{dc} is maintained with little deviation to its reference, as seen in Fig. 16(c). Reactive power is nearly 0 V, and grid current has preserved its sinusoidal shape, as illustrated in Fig. 16(e).

V. CONCLUSION AND FUTURE WORK

In this paper, a new hybrid MPPT controller for grid-connected solar systems combining Incremental conductance — Particle Swarm Optimization and Model Predictive Control (IncCond-PSO-MPC) is presented. The proposed solution

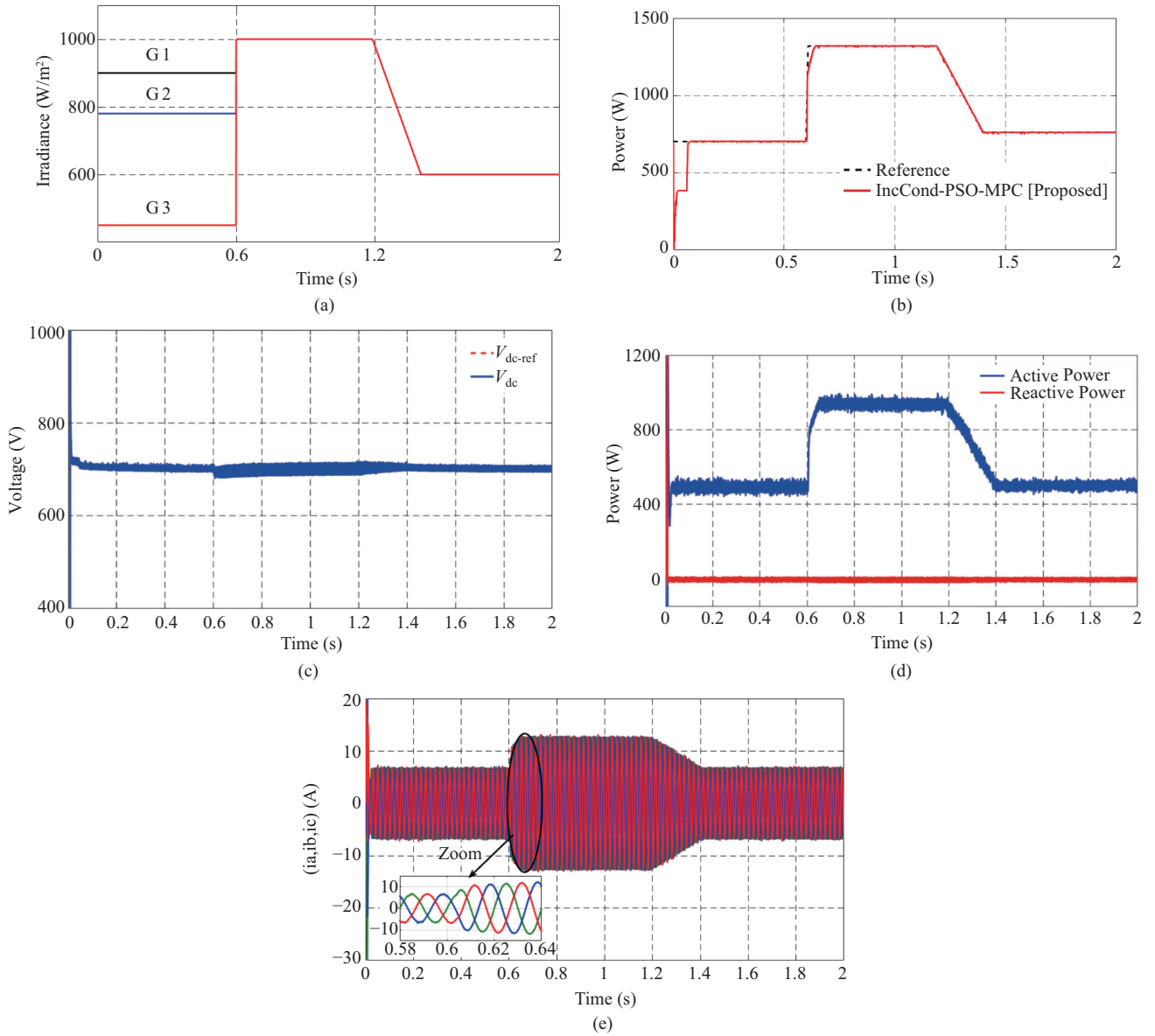


Fig. 16. Performance of global system under irradiation changes. (a) Solar irradiance profile; (b) PV power; (c) DC-link voltage; (d) Grid-injected active and reactive power; and (e) Grid current of the three-phase system.

involves producing as much power as possible from a PV system under changing environmental conditions and then transferring it to the power grid. Maximum power is located using a hybrid combination of Incremental conductance (IncCond) and Particle Swarm Optimization (PSO), and the Model Predictive Control (MPC) then records maximum power and controls the boost converter to achieve high performance regardless of parameter variations. A two-level inverter, which is likewise controlled by MPC, is utilized to inject the PV power generated. The proposed MPPT was tested using factors such as power tracking speed and efficiency. A number of experimental simulations on a variety of instances (tests) have demonstrated the proposed approach is highly effective.

In tracking time and power conversion efficiency in PV output power, the suggested method greatly outperforms traditional P&O, conventional IncCond and Incremental conductance – Particle Swarm Optimization (IncCond-PSO). Integra-

tion of the MPC controller with the IncCond-PSO not only helped dramatically reduce steady-state oscillations in output power, but also reduced total maximum power point tracking time when compared to the IncCond-PSO and traditional IncCond. We can conclude the new proposed MPPT is a viable technique for boosting efficiency of a PV system in partial shade.

As future work, further research could focus on experiments comparing these techniques for mismatched situations such as partial shading, non-uniformity of PV panel temperatures, damage to panel glass, and dust or shadow impacts for specific applications.

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