

## An Efficient Hybrid Algorithm for Design and Analysis of MPPT System for PV based Cascaded Half Bridge Multilevel Inverter

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### ABSTRACT

*While the photovoltaic (PV) system demand rises day after day in the context of renewable energy, the system efficiency plays a driving role as it depends on the maximum power point tracking (MPPT) techniques, which continuously adjust the tracking point of the PV array to extract the maximum energy. In this research work, we suggest an efficient hybrid algorithmic strategy for design of a reduced count multilevel inverter (MLI) for MPPT applications in solar PV systems. The proposed hybrid MPPT algorithm integrates the advantages of conventional and advanced control techniques to achieve faster response, higher tracking accuracy and reduced steady state oscillations. The proposed design of the MPPT algorithm integrates the well-known perturb and observe (P&O) technique for fast tracking during quickly changing irradiance with a particle swarm optimization (PSO) to refine the tracking point near the global maximum power point, and effectively reduce the steady state oscillations and raise the efficiency of the PV system during the low irradiance time as well. The designed hybrid algorithm is applied to the proposed reduced count MLI topology. The MATLAB Simulink results validate that the hybrid P&O-PSO MPPT algorithm output has sufficiently a faster tracking efficiency with reduced oscillations as compared to the conventional techniques, making it highly applicable for the PV systems.*

**Keywords:** Photovoltaic; hybrid algorithm; multilevel inverter; maximum power point tracking; metaheuristics

### INTRODUCTION

In order to make solar energy more affordable, researchers are now interested in improving solar panel efficiency. From this perspective, a number of MPPT methods are assessed to maximize the PV systems power. Thus far, numerous traditional MPPT methods have been established. These methods include open circuit voltage (Dorofte et al. 2005), short circuit current (Noguchi et al. 2002), the perturb and observe (P&O) method (Kumar et al. 2018; Bhan et al. 2019), and the incremental Conductance method (Shengqing et al. 2020). The P&O approach is the most straightforward MPPT methodology that has ever been discovered (Azad et al. 2020; Sadanala, Pattnaik & Singh, 2020; Singh & Mandal, 2023). Conventional MPPT techniques differ in terms of tracking speed, sensor count

and system cost. It should be mentioned that the traditional MPPT techniques work well in situations with consistent irradiation. The necessary current and voltage are obtained by connecting a large number of PV panels in parallel series. PV module in such systems will receive varying amount of solar insolation due to partial shade caused by trees, buildings, or moving clouds. The partial shading conditions causes power-voltage curve to have more peaks, making it more complicated. Only one of these peaks the global maximum power point (GMPP) represents the actual MPP; the other MPPs are known as local MPPs (LMPPs). The traditional approaches covered in the previous paragraphs may fit into any of the LMPPs and are unable to track the genuine MPP. This will cause power loss and reduce the PV System's efficiency. Therefore, the system's performance must be undoubtedly improved by updating

or merging algorithms to follow GMPP in the event of shading occurrences (Kakar et al. 2021).

The MPPT techniques are used to optimize solar systems power production while they are in operation. These techniques guarantee that solar panels continuously run at their ideal power point. Enabling effective energy collection even in the face of changing climatic conditions. For solar PV systems' efficient operation and dependably overall, MPPT efficiency is essential (Sadanala et al. 2020). These MPPT algorithms fall into two categories: sophisticated like Fuzzy Logic, Artificial Neural Network (ANN), and the Particle Swarm Optimization (PSO), and traditional approaches like perturb and observe (P&O) and incremental conductance (INC). Power oscillations result from P&O's inefficiency under quickly changing conditions, despite its widespread use due to its simplicity in monitoring power changes and adjusting voltage. However, by mimicking the social behavior of the particles in a search by utilizing PSO, a bio-inspired algorithm, providing faster convergence and more accuracy. It is better suited for dynamic situations since it can handle complex conditions like partial shade and variable irradiance (Sonti et al. 2016).

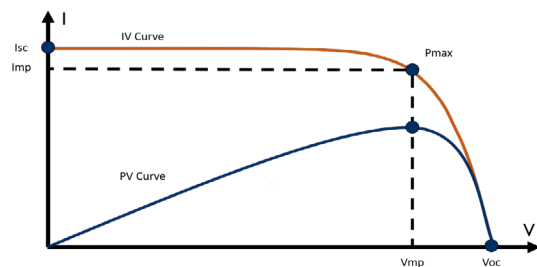


FIGURE 1.  $I/V$  curve of a PV system

As illustrated in Figure 1, the power characteristics of PV systems are nonlinear and heavily impacted by external parameters like temperature and sun irradiation.

Ahmed et al. (2018) critically analyzed the advantages and disadvantages of P&O and PSO methods for MPPT in PV systems using MATLAB simulations. This study highlighted the stable performance of PSO over P&O. Similarly, in (Jiang et al. 2018), encouraging performance of the PSO was highlighted against hill climbing techniques from viewpoint of simulation and practical implementation. A careful selection of algorithm for MPPT necessitates the possibility of hybrid approaches in the solar PV systems (Sandhu & Thakur 2022) due to environmental and cost scenarios. In their comparative work, Bennia et al. (2025), analyzed the MPPT efficiency of P&O against PSO under different shading patterns. Their results show that PSO consistently achieves very high tracking efficiency (above 99%), outperforming P&O under complex shading. But

they also note that PSO's superior performance comes at the price of higher computational complexity, which might be prohibitive in low-cost embedded systems. In recent research, Chtita et al. (2022) have expand their research in hybrid algorithms by integrating memetic computing and hybrid metaheuristic optimization strategies into PSO-based methods. These approaches are aimed to enhance the convergence speed, tracking accuracy, and robustness of conventional PSO algorithms especially under quickly changing environmental conditions and partially shaded operating conditions.

Conventional MPPT techniques frequently lock onto a local maximum power point (MPP) and fail to identify the true global MPP, particularly when partial shading creates multiple peaks in the PV power–voltage characteristics. The process of extracting maximum power is dynamic and difficult due to this fluctuation. Even though traditional MPPT techniques like P&O are popular due to their ease of use, they frequently experience steady state oscillations and decreased accuracy in situations that change quickly. However, at the expense of increased computing complexity, intelligent algorithms like PSO provide better tracking performance. Therefore, due to the nonlinear behavior of PV arrays and alternation in temperature, insulation may change the terminal voltage. Due to this, delivery of maximum possible power from PV module to the load may be differed. The conventional algorithms for MPPT fail to track the MPP, particularly under partially shaded conditions due to generation of multiple peaks in power-voltage characteristics and local/global MPPs. Therefore, developing a hybrid MPPT algorithm is essential to overcome these shortcomings and ensure reliable tracking of the global optimum under all operating conditions.

On the other hand, the inverters are main part of PV systems that converters DC to AC voltage. Two level inverters generate square and quasi-square waveforms as a result harmonics are generated. Furthermore, conventional multilevel inverters (Memon et al. 2023) stabilize the output voltage waveform with reference to the sinusoidal signal with less distortion but increased the number of switches. In previous works, the selective harmonic elimination (SHE) control technique was used for cascaded half-bridge MLI which has limitations such as poor power quality and poor dynamic response under load and line variations. In order to overcome these problems, level-shifted PWM multicarrier technique is used in this study.

This research work suggests a hybrid MPPT strategy that combines the global search capabilities of PSO with the quick reaction of the P&O algorithm to overcome these drawbacks. This study seeks to assess the hybrid method's efficiency in improving tracking efficiency, stability and overall energy extraction in real world PV systems by

comparing it to standalone strategies under various environmental conditions.

The importance of this research originates from its hybrid analysis and efficient use of MPPT algorithms, particularly P&O and PSO, in terms of maximizing solar PV system efficiency. Effective MPPT techniques are very important for improving the performance of PV systems as the world's energy needs grow and the need for sustainable solutions grows simultaneously. This study advances our knowledge of these two popular algorithms operational advantages and disadvantages in a range of environmental circumstances. Furthermore, the results will offer scholars working in the field of metaheuristic algorithms insightful information that will direct the creation of effective and reliable MPPT solutions. The ultimate purpose of this research is to make the use of renewable energy technology more by making sustainable solutions, making the shift to sustainable energy sources easier and supporting international efforts to tackle climate change.

## MATERIAL AND METHODS

In this section, the methodology adopted to achieve the objectives of this research are explained first. The P&O and PSO algorithms are explained for MPPT in PV systems, along with their proposed hybrid implementation. The design of cascaded half bridge multilevel inverter along with adopted PWM method are also explained. Finally, the simulation model is explained for the overall simulation of results.

### ADOPTED METHODOLOGY

In this work, using MATLAB software, a simulation model for PV panels with cascaded half-bridge multilevel inverters is created. At this point, a DC-DC converter and P&O algorithm will also be put into practice. The level shifted PWM approaches are taken into consideration while analyzing the simulation model's performance. The software will be used to build and implement the suggested hybrid MPPT system with cascaded half-bridge inverter using multicarrier control techniques. The proposed hybrid MPPT algorithm design and implementation is achieved by combining the P&O's fine tuning and PSO's fast convergence properties. To evaluate the system performance, tests at different environmental parameter values of temperature and irradiance levels are compared in order to examine factors like total harmonic distortion (THD), output voltage quality and Power Output. These metrics are examined at various irradiances. Ultimately,

simulation and published findings are used to evaluate the outcomes of the hybrid algorithm with traditional P&O method. The methodology general flowchart is shown in Figure 2.

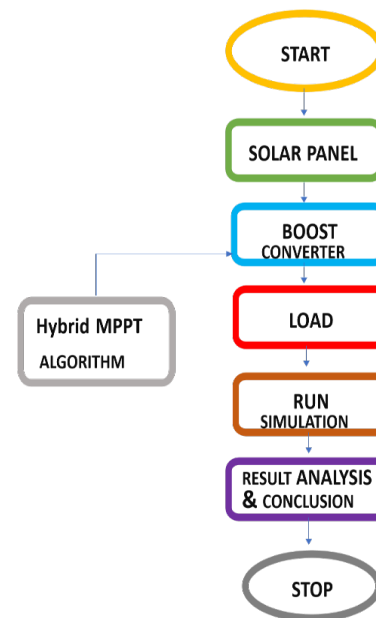


FIGURE 2. General methodology flowchart

### PHOTOVOLTAIC SYSTEM

Figure 3 shows the circuit for the PV as the electrical model of the solar cell depicting the behavior of the solar cell under different operating conditions. It usually comprises of resistive components like series and shunt resistors to limit the internal losses and leakage current, a current source that is representing the light generated current, and a diode forming the p-n junction. This equivalent circuit accurately predicts the solar cells' output under variable conditions of temperature and irradiances by simulating the nonlinear IV relationship of the solar cell. A basic understanding of PV circuit is necessary to design PV Systems and creating control strategies like maximum power point tracking (MPPT) to maximize energy collection.

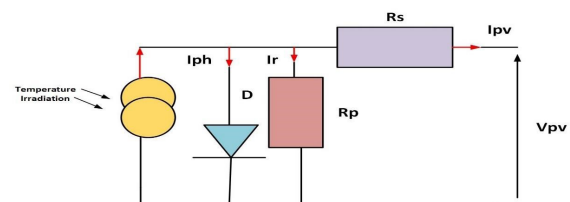


FIGURE 3. Circuit diagram of PV system

## DC-DC BOOST CONVERTER

The main purpose of the boost converter circuit is to raise the input voltage of the circuit to the higher output voltage level by stepping it up. An inductor, controlled switch (usually a transistor), a diode and a filter capacitor are the main parts of the boost converter circuit. The switch is in close position in initial phase of the operation, allowing the current to accumulate energy in the magnetic field of the inductor. When the switch is activated in the second phase, the inductor releases this stored energy into the load and the capacitor via the diode, raising the voltage above the input level. The converter may effectively raise the voltage and at the same time the electricity is supplied to the load by this charging and discharging operation as shown in Figure 4.

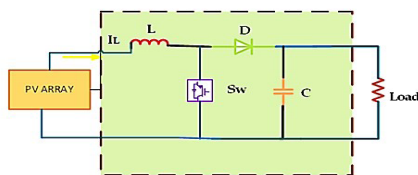


FIGURE 4. DC-DC boost converter system diagram

## PROPOSED HYBRID (P&amp;O-PSO) ALGORITHM

The hybrid (P&O-PSO) algorithm enhances the MPPT performance in photovoltaic system by combining the traditional simplicity approach of P&O algorithm and global search capacity of the PSO algorithm as shown in Figure 5.

In order to make the hybrid MPPT technique efficient in steady state conditions, it starts by applying the P&O algorithm to rapidly approach the proximity of the Maximum Power Point (MPP) through gradual perturbations in voltage or duty cycle. Control is then dynamically moved to the PSO model when the system notices the notable variations in the irradiance or is unable to increase the power output after the predetermined number of repeats. After that, PSO algorithm improves tracking by utilizing a swarm of particles around the estimated point by the P&O algorithm. This allows the MPPT for more accurate power output optimization through iterative updates of the particle position and velocities. Each particle assesses power according to its position, modifies its own best, and advances towards the swarms' global best point. The following flowchart illustrates how the hybrid algorithm structure makes the use of P&O's quick convergence and PSO's power in global optimization. The technique is therefore useful for real time MPPT applications as it provides enhanced tracking speed, decreased state oscillations and stable performance under quickly changing environmental conditions.

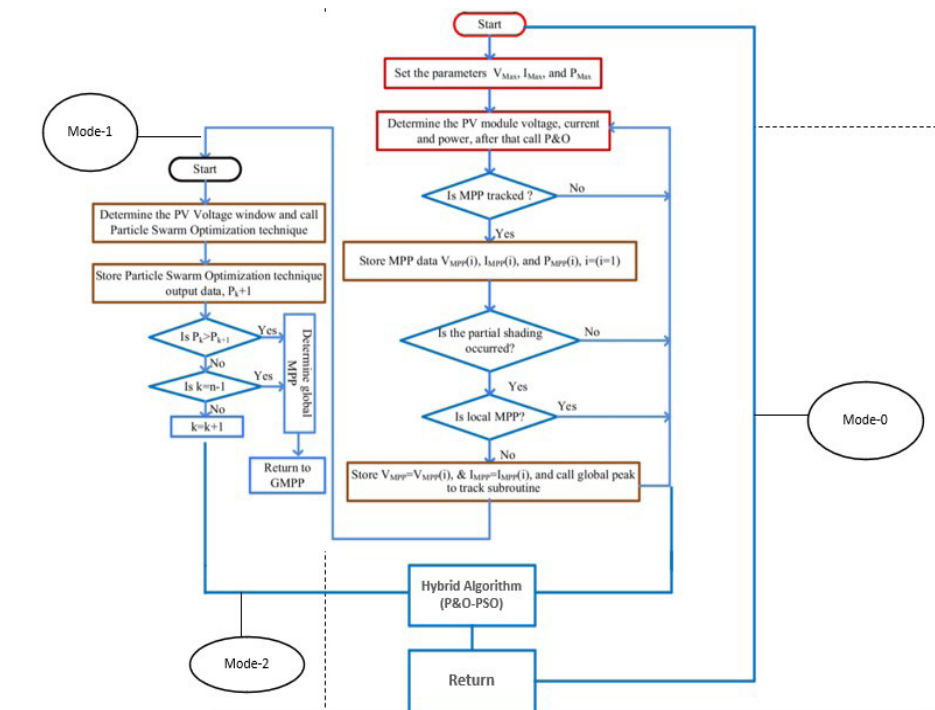


FIGURE 5. Proposed hybrid (P&amp;O-PSO) algorithm

### PROPOSED SYSTEM AND TOPOLOGY

In Figure 6, the block diagram of the proposed system is shown, which consists of four PV arrays, each connected to a hybrid MPPT algorithm incorporated boost converter.

The boosted output is given into a cascaded H-Bridge multilevel inverter (CH-MLI) controlled by a multicarrier PWM technique to supply power to the load circuit diagram.

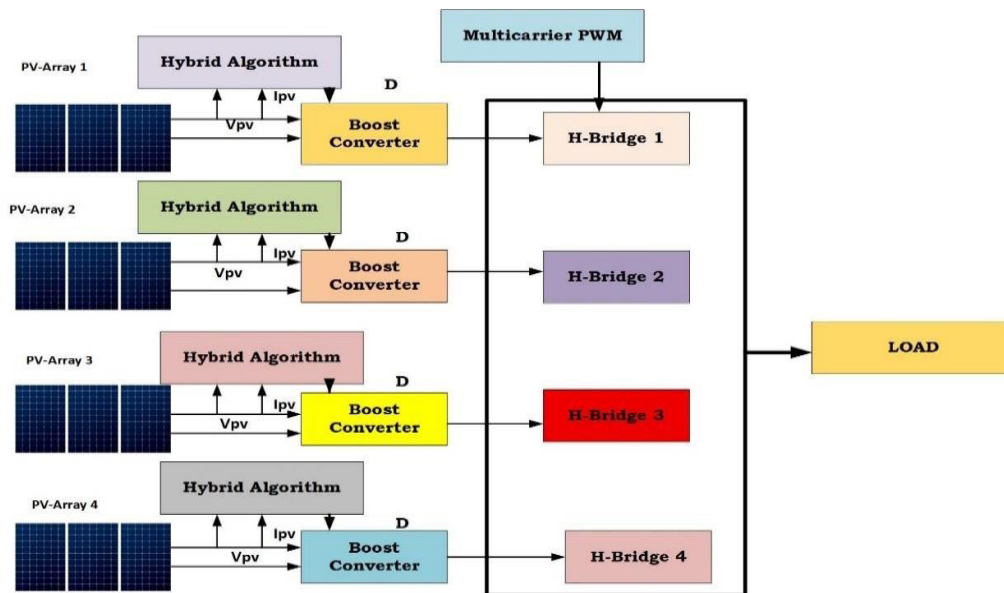


FIGURE 6. Block diagram of proposed system

In Figure 7, the suggested CH-MLI's circuit diagram topology is presented.

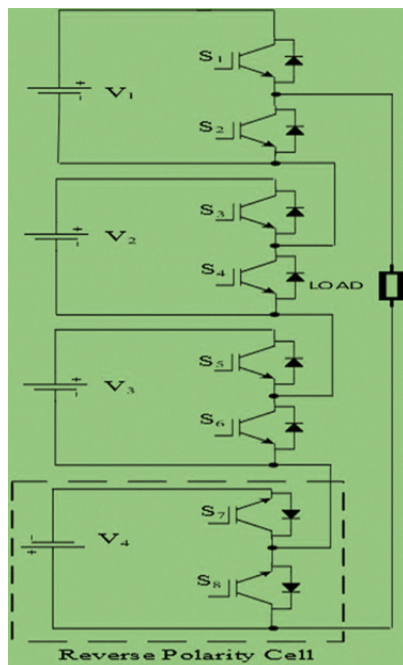


FIGURE 7. Cascaded half-bridge proposed

The suggested inverter design is asymmetric and requires various DC sources, impacting performance. The advantage of employing this asymmetric design is the clear increase in output levels, even if it requires fewer components. The THD likewise reduces in this aspect when compared to symmetric design utilizing the same voltage DC sources. Conversely, asymmetric designs exhibit reduced switching loss and improved system efficiency. It contains  $V_1, V_2, V_3$  and  $V_4$  as voltage sources in reverse polarity (RP); starting  $V_1 = 40V$ , and forthcoming getting doubled of the previous voltage source. Two switch devices along with their anti parallel devices result in a H-bridge inverter, which is connected to each voltage source. In this way, switching devices  $S_1-S_6$  are associated with three normal H-bridges to generate stepped output voltages. On the other hand, the switches  $S_7$  and  $S_8$  form fourth model serving as RP cell to assist raised voltage output levels and enhance quality of waves. The net output to the load side can finally be delivered to guarantee a waveform of multilevel voltage.

The switching states of the proposed CHB-MLI topology are explained in the following matrix.

| State | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $S_7$ | $S_8$ | Out V |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1     | on    | .     | .     | on    | .     | on    | .     | on    | +40   |
| 2     | .     | on    | on    | .     | .     | on    | .     | on    | +80   |
| 3     | .     | on    | .     | on    | on    | .     | .     | on    | +120  |
| 4     | on    | .     | .     | on    | on    | .     | .     | on    | +160  |
| 5     | .     | on    | on    | .     | on    | .     | .     | on    | +200  |
| 6     | on    | .     | on    | .     | on    | .     | .     | on    | +240  |
| 7     | .     | on    | .     | on    | .     | on    | .     | on    | 0     |
| 8     | .     | on    | on    | .     | on    | .     | on    | .     | -40   |
| 9     | on    | .     | .     | on    | on    | .     | on    | .     | -80   |
| 10    | .     | on    | .     | on    | on    | .     | on    | .     | -120  |
| 11    | .     | on    | on    | .     | .     | .     | on    | .     | -160  |
| 12    | on    | .     | .     | on    | .     | on    | on    | .     | -200  |
| 13    | on    | on    | .     | on    | .     | on    | on    | .     | -240  |

This matrix acts as a practical guide showing exactly which switches need to be turned ON or OFF (.) to obtain the required voltage at the load. First column represents state, second through to ninth columns represent switching patterns for switches  $S_1$ – $S_8$ , respectively, whereas the last column shows output voltage in volts (V) in both directions of the generated wave. Each entry in the table represents a specific voltage state, allowing the flow of power from the DC sources to the load to be controlled in a clear and structured manner. By following this defined sequence of switch operations, the inverter can generate stepped voltage levels in an orderly way. This makes the control process easier to understand and implement, while also ensuring that the output voltage levels are produced accurately.

Additionally, the switching sequence is synchronized with the modulation technique applies to the system to ensure the accurate timing and smooth level transitions. Proper timing is required to be maintained between the switches to prevent short circuit conditions and to enhance the reliability of the power electronic components. The controlled switching strategy also contributes to reduced switching stress, lower power losses and overall performance as the design has reduced number of switches.

This sequence of switching operations during both positive and negative cycles enables the multilevel inverter to generate a multilevel stepped waveform that is more closely resembles to the sinusoidal signal. As due to the increased number of levels such a waveform reduces the harmonic distortion and improves the power quality compared to the conventional two-level inverters. So, the proposed design gives the desired output waveform with reduced switches and making the proposed configuration suitable for the medium and high-power applications.

## MATLAB SIMULINK MODELS

The standard electrical parameters used in the simulation model are shown in Table 1.

TABLE 1. Electrical parameters used in simulation model

| No | Electrical parameters | Count / values                                                              |
|----|-----------------------|-----------------------------------------------------------------------------|
| 1  | DC Sources            | 4                                                                           |
| 2  | Rating of DC Sources  | $V_1=40\text{V}$ , $V_2=80\text{V}$ , $V_3=120\text{V}$ , $V_4=240\text{V}$ |
| 3  | Switches              | 8 IGBTs                                                                     |
| 4  | Levels                | 13-levels                                                                   |
| 5  | Resistance            | 24ohms                                                                      |
| 6  | Inductance            | 20mH                                                                        |

The proposed hybrid MPPT technique is intended to effectively track the MPP of a solar PV system under the variable irradiances and temperature conditions. The proposed hybrid algorithm is simulated in the MATLAB/Simulink as shown in Figure 8.

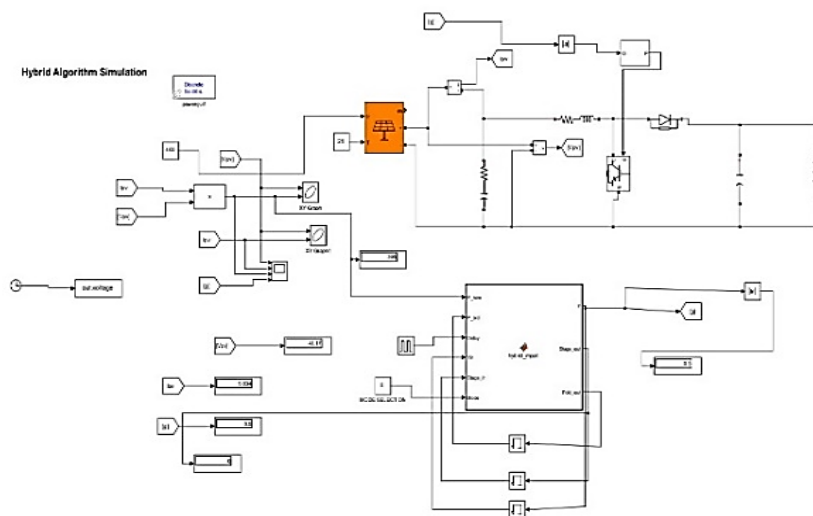


FIGURE 8. Simulation model of hybrid MPPT algorithm

One of the models' primary parts is the PV module that is providing power to the load by producing voltage and current in response to environmental inputs. A MATLAB function block is used to create the Hybrid MPPT controller which variably modifies the operating point by processing inputs including voltage, step size, current, power, and mode selector. Three modes are available for the function: 0 mode for the (P&O), which is used for the fine tuning and mode 1 for the (PSO), which is used for the quick initial tracking and 2 for the Hybrid mode, which blends both algorithms for better tracking performance. A boost converter is used to apply a voltage reference, created by the MPPT, to the system is also included in the simulation. The irradiance block in the simulation gives the variable irradiance values to test the MPPT's algorithm durability and efficiency, scope blocks

are used to provide real time graphs of voltage, power and tracking mode.

The following PV based cascaded half-bridge multilevel inverter (CHB-MLI) systems simulation model is displayed in Figure 9. To simulate nonlinear, I-V and PV behavior under variable irradiance and temperature, the model consists of the four independent PV subsystems, each subsystem represents a single diode equivalent circuit. To maximize the power extraction from each PV source, a hybrid Perturb and Observe (P&O) -Particle Swarm Optimization (PSO) MPPT controller controls the duty cycle of a DC-DC converter. Four cascaded half bridge inverter cells each consisting of two IGBT switches (S1-S8) are fed by the regulated DC outputs. An output waveform of 13 levels is generated by connecting these cells in series.

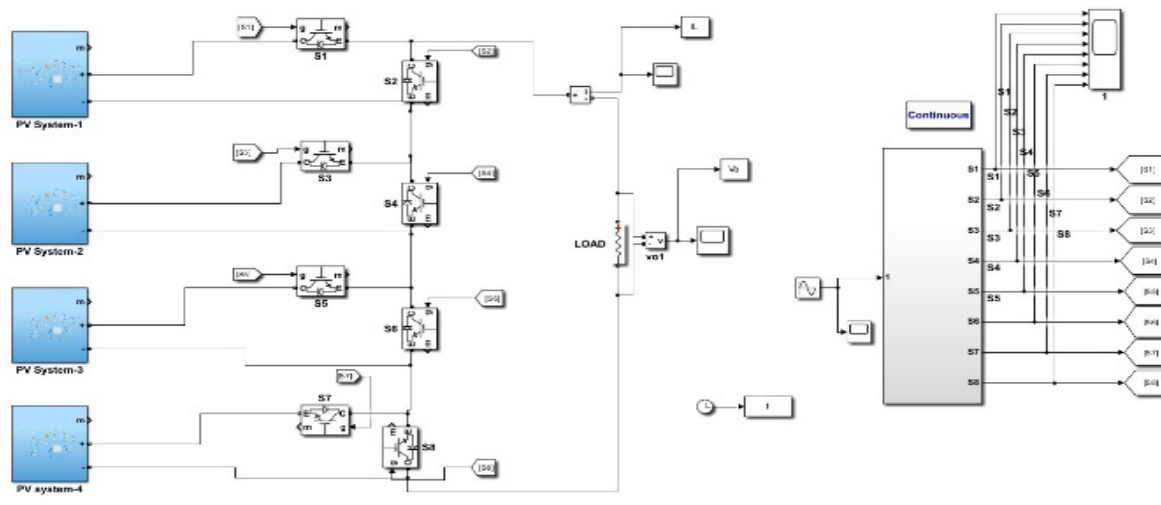


FIGURE 9. Simulation model of CHB PV connected system

## RESULTS AND DISCUSSION

In this section, the MATLAB/Simulink simulations of the proposed hybrid MPPT system combined with the cascaded half-bridge multilevel inverter (CHBMLI) are presented with discussion and validation. The overall performance of P&O-PSO algorithm is examined under variable irradiances and temperature and compared with the conventional P&O approach. Important output parameters are considered such as output voltage waveform, Total Harmonic Distortion (THD), maximum power tracking accuracy and system efficiency.

A PV array, a DC-DC boost converter, a hybrid MPPT controller, and a load make up the simulation model of a photovoltaic (PV) system using the hybrid PSO-P&O MPPT algorithm. The output voltage and current of the PV array, which transforms solar energy into DC electricity, change in response to temperature and solar irradiation.

The hybrid MPPT algorithm dynamically controls the duty cycle of a boost converter, which is used to regulate and step up the voltage to fulfill load needs. The iterative P&O approach and the quick global search capacity of PSO are combined in the hybrid P&O-PSO algorithm. While the P&O approach fine-tunes the operating point to track the precise maximum power point (MPP), PSO first predicts an estimated MPP by investigating the power-voltage characteristics. While reducing steady-state oscillations, this synergy allows for quick convergence to the MPP.

Based on the hybrid algorithm, the MPPT controller creates a duty cycle signal that is transformed into a PWM signal to regulate the boost converter's switching. In order to show how the system dynamically adapts to variations in irradiance or temperature, guaranteeing maximum power tracking from the PV array, the simulation tracks important parameters like PV voltage, current, power, and duty cycle. The hybrid P&O-PSO controller effectively directed the

PV system in the simulation model to converge to the MPP, which corresponds to a goal PV voltage of roughly 40V, under low irradiance conditions ( $400 \text{ W/m}^2$ ). The P&O approach adjusted the DC–DC boost converter's duty cycle, whereas PSO quickly assessed the MPP's nearby. The system continued to operate steadily with few oscillations despite the decreased irradiance, and the power output stabilized at the highest level possible for that irradiance, confirming the hybrid algorithm's efficacy in obtaining accurate MPP tracking in low light confirming the hybrid algorithm's ability achieve accurate MPP tracking in low light, as shown in Figure 10.

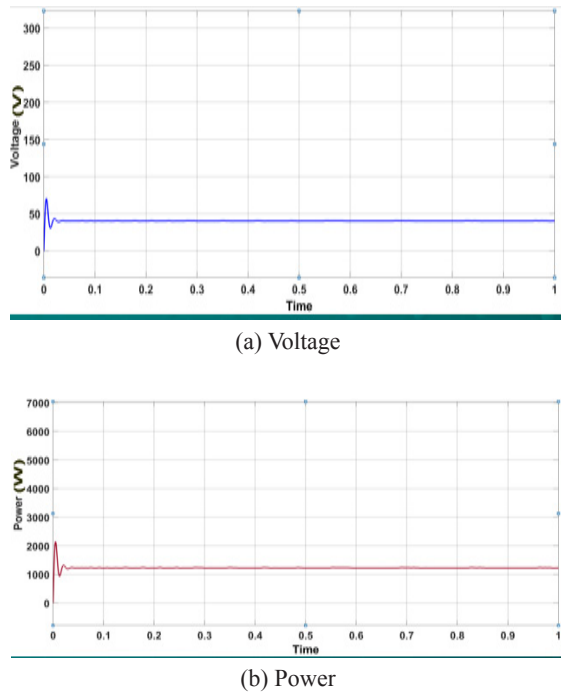


FIGURE 10. Hybrid algorithm results at  $400 \text{ W/m}^2$

Similarly, the hybrid P&O-PSO algorithm dynamically changed the duty cycle to converge the MPP, which corresponds to a higher PV voltage of about 80V, under the normal irradiation condition of ( $800 \text{ W/m}^2$ ), see Figure 11. In comparison to P&O alone, the combined action of P&O and PSO algorithm makes the convergence faster while reducing the oscillations and making the steady operation. The hybrid controller capacity to track the MPPT and optimal energy extraction under variable irradiances was demonstrated by the PV power output increasing correspondingly. The results of Figure 11, demonstrate that the P&O-PSO approach output waveform in comparison to the conventional P&O and PSO algorithms' variable environmental conditions by improving tracking speed and steady state stability.

The operation of the inverter and phase disposition strategy is confirmed by the switching signals shown in

Figure 12. The gate pulses of the eight switches ( $S_1$  to  $S_8$ ) were created exactly in accordance with the triangle carrier signals and the reference sinusoidal modulation. In order to prevent the overlap situation or shoot through situations, each H-bridge functions in the proper order, with the gate signals displaying the various and steady alteration between complementary switches. The expected logic produced from PD-PWM approach is matched by the timing of the ON and OFF transitions. The successful application of the PWM control technique and the proper operation of the inverter system are confirmed by the figure shown, which clearly shows how each switch reacts to the modulation pattern.

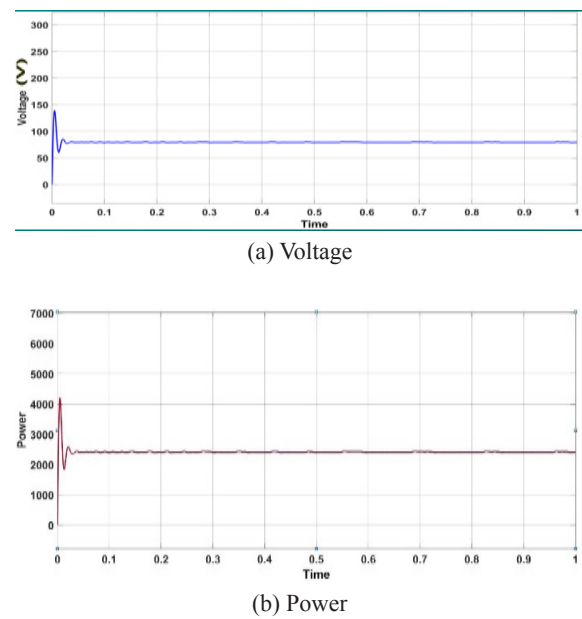


FIGURE 11. Hybrid algorithm results at  $800 \text{ W/m}^2$

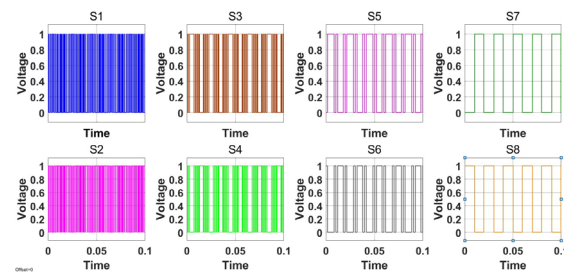


FIGURE 12. Switching pattern of proposed CHB-MLI PV connected

The inverter generates the 13-level stepped output voltage waveform as shown in Figure 13. The waveform clearly shows 13 different levels on each cycle, approximately a sine wave in the shape of a staircase. The output voltage of various cascaded H-bridge switches, each of which adds gradually to the total output, are combined

to create the output waveform. Each step corresponds to precise voltage increment, and the levels are uniformly divided over the positive and negative half cycles, ranging from -6Vdc to +6Vdc.

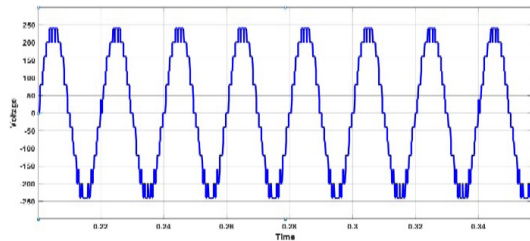


FIGURE 13. Output voltage of proposed CHB-MLI PV connected

Figure 14 shows the Fast Fourier Transform (FFT) study, the inverter output waveform total harmonic distortion (THD) is 7.22%. Because the output waveform is 13 level stepped, this THD number indicated the existence of harmonic components in the output voltage. The observed THD of 10.93% shows that there is still noticeable presence of high frequency harmonics. The suggested hybrid PSO-P&O MPPT-controlled cascaded half-bridge multilevel inverter performs effective DC-AC conversion with increased voltage quality, decreased harmonic distortion, and enhanced overall system performance, according to the simulation results.

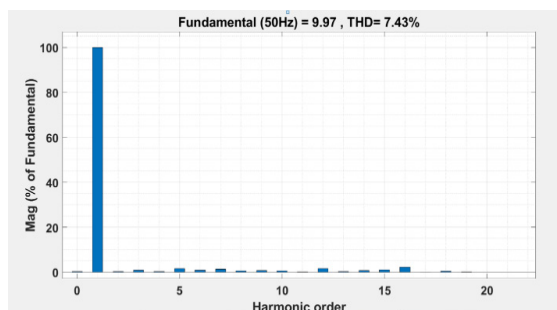


FIGURE 14. THD in proposed CHB-MLI PV connected

The results of the proposed hybrid P&O-PSO MPPT algorithm are compared with the conventional P&O algorithm method under various irradiance conditions to verify its performance. Key parameters such as PV Voltage, current, power output, convergence speed, and steady state oscillations were examined after both algorithms were applied to the identical PV system model with a conventional DC-DC boost converter. Under constant irradiance, the traditional P&O algorithm shows dependable tracking of the maximum power point (MPP); but under quickly changing environmental conditions, its performance disturbs. Slow convergence to the (MPPT) and steady state

oscillations which can decrease the total energy harvesting efficiency and that is the primary drawback of the P&O algorithm.

On the other hand, hybrid P&O-PSO algorithm combines the fine-tuning capability of P&O algorithm with the global Particle Swarm Optimization (PSO), the fast convergence, less oscillations and the better tracking accuracy are the results of PSO quick estimation of the approximate MPP and P&Os accurate local adjustments.

The voltage and power waveforms were observed for the irradiances of 400-1200 W/m<sup>2</sup>. Table 2 presents the comparison of output, overshoot and settling times (in seconds) of voltage V (in V) and power P (in W) in these cases.

The hybrid (P&O-PSO) algorithm approach converges to the maximum power point faster and maintains steady state voltage and power output even under low irradiance (400 W/m<sup>2</sup>), while the traditional P&O method exhibits observable oscillations in both voltage and power around the MPP. In contrast to the P&O, which still shows some oscillations, the hybrid algorithm effectively calculates the MPP at moderate irradiance (800 W/m<sup>2</sup>), generating higher and more stable voltage and power waveforms.

TABLE 2. Comparison of simulation results

| Irrad.<br>(W/m <sup>2</sup> ) | Algor. | Output |      | Peak overshoot |      | Settling time |      |
|-------------------------------|--------|--------|------|----------------|------|---------------|------|
|                               |        | V      | P    | V              | P    | V             | P    |
| 400                           | P&O    | 40     | 970  | 90             | 1600 | 0.08          | 0.06 |
|                               | Hybrid | 40     | 1200 | 40             | 1000 | 0.05          | 0.03 |
| 800                           | P&O    | 80     | 1950 | 170            | 2700 | 0.05          | 0.06 |
|                               | Hybrid | 80     | 2480 | 70             | 1700 | 0.03          | 0.04 |
| 1200                          | P&O    | 120    | 3000 | 160            | 5200 | 0.06          | 0.05 |
|                               | Hybrid | 120    | 3450 | 90             | 2700 | 0.04          | 0.03 |

The MPP is tracked by the conventional method at different irradiances but there are discernible amounts of oscillation around the steady state MPP. Higher voltage and power overshoot are the result, especially in dynamic conditions when irradiance fluctuates quickly. Additionally, oscillations cause slower stabilization and small power losses. The results of the Hybrid P&O-PSO method, which combines the fast-tracking capability of P&O with the global optimization quality of PSO algorithm. The hybrid method greatly lowers voltage and power overshoot and increases the tracking accuracy. The hybrid algorithm achieves the MPP more smoothly and sustains the steady voltage and power outputs with few oscillations under different irradiances. Lastly, the settling time of the hybrid algorithm and P&O algorithm outperforms the individual P&O algorithm as shown in the last of Table 2. This suggests improved dynamic performance and higher

flexibility in response to variations in temperature and irradiation, resulting in more effective maximum power tracking from PV system.

The comparison clearly shows that the hybrid P&O-PSO algorithm is more efficient than the conventional P&O and PSO approach in terms of. Higher steady state power output Faster MPP convergence Reduced voltage and power oscillation. These results verify the hybrid P&O-PSO technique enhances the steady state efficiency and dynamic response of the PV system under various irradiation conditions. The simulation results and performance of the Hybrid P&O-PSO algorithm and the Perturb and Observe (P&O) method under different irradiance values were compared in form of output, overshoot and settling times (in seconds) of voltage  $V$  (in V) and power  $P$  (in W) in Table 2.

The hybrid P&O-PSO algorithm is tracking MPP faster in voltage settling time than the conventional P&O method, as shown in Figure 15. The figure shows that this hybrid algorithm has an efficient tracking capability and stability, which enables it to reach the MPP more quickly. The faster stabilization shows that the hybrid algorithm can effectively adjust to changing environmental conditions, improving the PV system tracking speed and energy tracking efficiency.

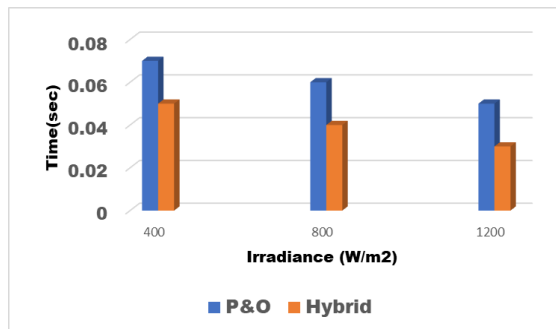


FIGURE 15. Comparison of voltage settling time

The Hybrid P&O-PSO algorithm has a comparatively faster settling time and reaches the MPP more quickly than the conventional P&O algorithm, as shown in Figure 16. The Figure shows that the hybrid algorithm enhances tracking efficiency and transient response. The hybrid algorithm is more successfully adjustable to the variations in irradiance and tracking the maximum energy extraction and improved steady state performance of the PV system, as shown by the decreased power oscillations and faster stability.

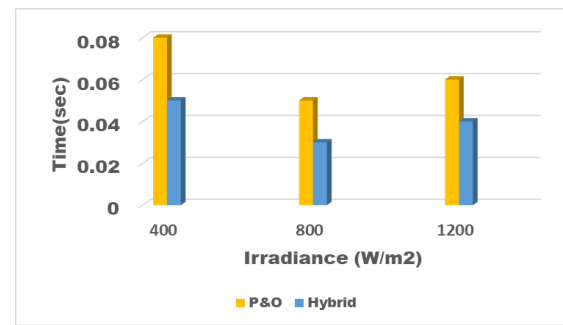


FIGURE 16. Comparison of power settling time

A comparative analysis was done in Table 3 to observe the effect of odd harmonics on the total harmonic distortion (THD) of the proposed inverter output. In the first scenario, the THD was calculated as 10.92% through FFT analyzer, and it indicates a significant number of odd harmonics that adversely affect the waveform quality and efficiency of inverter. On the other hand, through the proposed hybrid MPPT algorithm the THD is reduced to 7.43%, which is significantly an improvement in harmonic suppression. As the odd harmonics are reduced, it basically shows the effectiveness of the proposed design of hybrid MPPT algorithm based MLI in enhancing the voltage quality and overall performance of the PV system.

TABLE 3. Odd harmonics comparison

| Odd Harmonics | Conventional THD = 10.93% | Proposed THD = 7.43% |
|---------------|---------------------------|----------------------|
| H3            | 0.24%                     | 0.80%                |
| H5            | 0.64%                     | 1.59%                |
| H7            | 3.63%                     | 1.27%                |
| H9            | 1.19%                     | 0.70%                |

Table 4 shows the comparison between the THD% of the conventional methods with the proposed topology. It clearly shows that from all the three cases the proposed hybrid MPPT algorithm with reduced count switches has the lowest THD% of 7.3% for the same level of output 13 levels.

TABLE 4. THD comparison of conventional and proposed hybrid topology

| Levels | THD% (Conventional)                  | THD% (Proposed) |
|--------|--------------------------------------|-----------------|
| 13     | 10.83<br>(Raiker & Loganathan, 2021) | 7.43            |
| 13     | 9.45<br>(Hamidi et al. 2021)         | 7.43            |
| 13     | 8.59<br>(Macaulay & Zhou, 2018)      | 7.43            |

The proposed CHB-MLI is inherently adaptable with the ability to scale to higher voltage levels; however, careful consideration must be given to the modular design's operation. In the suggested CHB-MLI that employs an efficient modulation technique and features an asymmetric design, many common issues have been circumvented, such as modularity challenges, voltage stress, output quality trade-offs, and fault intolerance. Conversely, prototype creation, managing complexity, and upkeep are clear factors in the practical execution of the suggested system.

## CONCLUSION

This research study was conducted to improve overall efficiency and the performance of PV system. The cascaded half bridge multilevel inverter (CHB-MLI) was modified to enhance the output voltage waveform quality. The simulation results obtained using MATLAB show the total harmonic distortion (THD) of 7.9%, showing the effectiveness of the proposed inverter design as it produces stable output. A boost converter was used to apply the Perturb and Observe (P&O) algorithm for maximum power point (MPP) under various values of irradiances. The tracking efficiency and dynamic reactivity of the algorithm were accessed separately. The results illustrate that although P&O algorithm is simple and popular, it has several drawbacks, including oscillations around the (MPP) during steady state operation and slower convergence under quickly changing irradiance. Finally, the main contribution lies in the design of hybrid MPPT algorithm that combines (P&O) with (PSO) to overcome these limitations. This hybrid algorithm method reduces steady state oscillations and improves the tracking speed by combining the simple perturb mechanism of P&O with quick global search capacity of PSO. The hybrid P&O-PSO algorithm delivers the higher MPPT performance under variable irradiance conditions, offering smoother power output and faster convergence to the MPP, according to the simulation data. In conclusion the hybrid MPPT algorithm effectively improves PV system performance when combined with an enhanced CHB-MLI inverter design. High quality voltage output, quicker and more precise maximum power point tracking and enhanced stability in a variable environmental condition. The results of this research show how well modern inverter design can be integrated with sophisticated MPPT method, highlighting its potential for real world PV applications and further research in renewable energy systems.

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## DECLARATION OF COMPETING INTEREST

None.

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