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Investigating Impact of Boost Converter on Efficient MPPT Based Solar PV Array for MicroGrid System

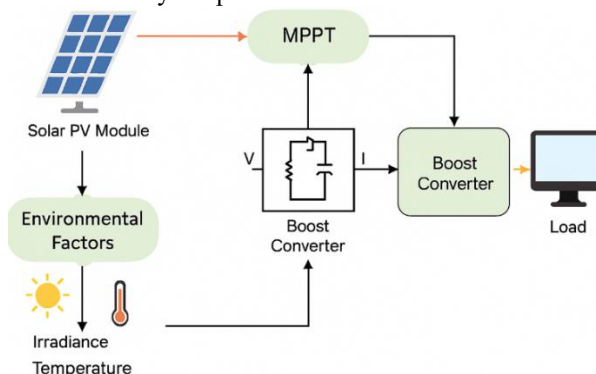


Abstract: This study presents an optimized design of a Maximum Power Point Tracking (MPPT)-based solar photovoltaic (PV) system, aimed at enhancing overall performance through refined MPPT control and boost converter optimization. The investigation focuses on the influence of boost converter operation and MPPT control signals on Total Harmonic Distortion (THD) at the inverter output. A detailed model is developed for a 100-kW PV array interfaced with a 25-kV grid via a DC-DC boost converter and a three-phase, three-level Voltage Source Converter (VSC). The MPPT functionality is implemented using the Incremental Conductance algorithm with an integral regulator. Harmonic mitigation is addressed through a sequence of measures, including modelling of two independent PV arrays under varying irradiance and temperature conditions, application of the Perturb and Observe (P&O) algorithm for optimal power extraction, and the design of a modified boost converter topology with enhanced filtering. Comparative simulations demonstrate the effectiveness of the proposed system relative to conventional MPPT-boost converter configurations. Analysis shows that the initial system exhibits a THD of 44.83%. Introducing an RC shunt filter in the boost converter and reducing the sampling time lowers the THD to 3.08% at a 60 Hz fundamental frequency. Further optimization, achieved by reducing the sampling size and aligning the switching instant with the waveform, decreases THD to 0.43%. These results highlight the critical role of sampling strategies and filter integration in improving power quality, confirming the proposed approach as a significant advancement in the design of grid-connected solar PV systems.

Key Words: Solar photovoltaic Array, THD, MPPT Tracker, P&O, Boost Converter, Shunt Filter, VSC Inverter, FFT Analysis,

1. Introduction

The increasing global demand for sustainable and environmentally friendly energy has driven the widespread adoption of solar photovoltaic (PV) systems. The efficiency of these systems, however, is highly sensitive to environmental factors such as solar irradiance and temperature, which fluctuate continuously and may cause Total harmonic Distortion (THD) in the system resulting in variable power output. To maximize energy extraction under such varying conditions, Maximum Power Point Tracking (MPPT) techniques are commonly employed. Power electronic converters, particularly boost converters, play a crucial role in regulating voltage and current to the load while facilitating effective MPPT operation. Despite their importance, the influence of boost converter characteristics, such as duty cycle response, switching frequency, and overall efficiency on MPPT performance has not been thoroughly explored. Inefficient converter design or control can lead to significant power losses, reduced energy harvesting, and diminished system efficiency. Consequently, investigating the impact of boost converters on MPPT-based solar PV systems is essential to optimize energy extraction, enhance converter operation, and ensure reliable system performance under dynamic environmental conditions. The abbreviations used in study are presented in Table 1 below.



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Figure 1 Architecture diagram of MPPT trackers and Bost converter based Solar PV micro grid system

Table 1 Abbreviation and Nomenclature of design parameters

Abbreviations		Abbreviations	
PV	Photo Voltaic	ANFC	Adaptive Neuro-Fuzzy control
BCon	Boost Converter	PWM	Pulse Width Modulation
VSC	Voltage Source Converter	kV	Kilo Volt
P&O	Perturb and Observe	AC	Alternating Current
MPP	Maximum Power Point	MPPT	Maximum Power Point Tracking
INC	Incremental Conductance	DC	Direct Current
THD	Total Harmonic Distortion	kW	Kilo Watt

Figure 1 depicts the architectural framework of a solar PV system integrated with MPPT tracking and a boost converter ($B_{Converter}$) to achieve efficient energy regulation. The system operation begins with the solar PV module, which converts incident solar irradiance into electrical power. Environmental factors, primarily irradiance and temperature, directly influence the PV module’s electrical output, causing dynamic variations or distortion in voltage and current. This generated power is then supplied to a boost converter (B_{Con}), which elevates the voltage to meet the load requirements. The MPPT controller continuously monitors the PV output and dynamically adjusts the duty cycle of the boost converter to maintain operation at the maximum power point. The regulated energy is subsequently delivered to the load, completing the power flow. Bidirectional arrows between the MPPT controller and the boost converter illustrate the real-time control and feedback mechanisms, emphasizing the system’s adaptive capability under fluctuating environmental conditions.

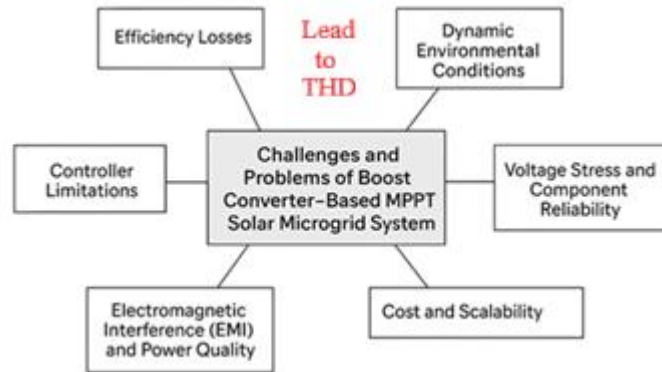


Figure 2 Challenges and problems of the MPPT and Boost Converter based PV system

Despite the widespread use of boost converters and MPPT algorithms in solar photovoltaic (PV) systems, Figure 2 illustrates several persistent challenges continue to limit optimal energy extraction and affect system reliability. One major concern is the efficiency loss associated with inherent conduction and switching losses in boost converters, particularly at high switching frequencies used to enhance MPPT responsiveness. These losses not only reduce overall energy conversion efficiency but also generate additional thermal stress, increasing heat dissipation and potentially impacting the long-term performance of the system.

Environmental variability further complicates the operation of PV systems. Rapid fluctuations in solar irradiance, changes in ambient temperature, and sudden shading events lead to dynamic variations in PV output voltage and current. Such conditions challenge the MPPT algorithm’s capacity to accurately and consistently identify the true maximum power point, often resulting in transient instability and diminished tracking accuracy. Conventional MPPT techniques, including Perturb and Observe (P&O) and Incremental Conductance, often struggle under partial shading or rapidly changing conditions, where balancing tracking speed with system stability becomes particularly difficult.

The step-up voltage function of the boost converter also imposes additional stress on power electronic components, such as switches, capacitors, and the PV modules themselves. Over time, this stress, combined with voltage and current ripple, can compromise component reliability and reduce system lifespan. Furthermore, integrating real-time control and feedback mechanisms between the MPPT controller and the boost converter introduces considerable architectural complexity. Advanced strategies, such as adaptive or predictive MPPT, require substantial computational resources and precise sensing capabilities, which may be impractical for cost-sensitive applications.

Integrating multiple solar photovoltaic (PV) systems into a common framework is inherently a complex and challenging task due to the nonlinear characteristics of PV modules and the variability of solar irradiance. When multiple PV units are connected, issues such as synchronization, power quality, and system stability become

significant concerns. One of the critical challenges in such integration is the presence of harmonic distortions at the inverter output, which can adversely affect the efficiency and reliability of the overall system. Therefore, it becomes essential to conduct a thorough investigation of these interconnected PV systems with a particular focus on minimizing harmonic distortions. By addressing this issue, the performance of the inverter can be enhanced, ensuring that the generated power is of higher quality, complies with grid standards, and contributes to the stable operation of the microgrid or utility network.

Contribution of Work

The key contributions of this work are:

- The proposed work makes several significant contributions to the design and optimization of grid-connected solar PV systems.
- A comprehensive model of a 200 kW system, comprising two independent 100 kW PV arrays interfaced through DC-DC boost converters and a three-phase, three-level Voltage Source Converter (VSC), has been developed.
- MPPT strategies, using Perturb & Observe (P&O) algorithms, are implemented to maximize power extraction under varying irradiance conditions.
- A modified boost converter topology with shunt RC filtering for Boost converter is introduced to mitigate harmonics and enhance power quality. The system’s performance is rigorously evaluated in terms of efficiency, dynamic response, stability measured in terms of THD. Comparative analyses of different MPPT algorithms highlight their impact on overall system behaviour.
- The modified boost converter with shunt RC filter is integrated with the optimized sampling strategies to achieve a significant decrease in THD further down to 0.43% with optimized switching alignment.

Overall, the study demonstrates substantial improvements in power quality, harmonic suppression, and operational efficiency, positioning the proposed methodology as a robust enhancement over existing approaches in the literature. In rest of this paper section 2 presented the classification of MPPT and Solar PV system designs, followed by the literature review of related works in section 3. The proposed methodology including mathematical modeling architecture diagram and flow chart is presented in the Section 4. The expected results and evaluation of THD performance are presented in Section 5. and finally section 6 concluded the discussion.

2.0 Classifications of MPPT based Solar PV Systems

Figure 3 illustrates the classification of MPPT techniques applied to solar photovoltaic (PV) arrays when integrated with boost converters. The diagram is structured hierarchically, beginning with the overall focus on MPPT-based solar PV systems, followed by the categorization of commonly used algorithms such as Perturb and Observe (P&O), Incremental Conductance (INC), and advanced hybrid methods like Adaptive Neuro-Fuzzy control (ANFC). Each technique is evaluated against critical performance indicators, including efficiency, total harmonic distortion (THD), dynamic response time, and implementation complexity.

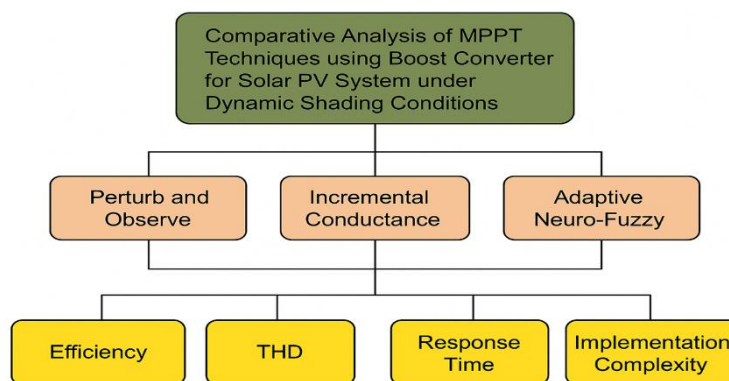


Figure 3 Classification of MPPT based solar Array using Boost Converter

This classification framework highlights the trade-offs between conventional and intelligent MPPT approaches, showing that while traditional methods such as P&O and INC are simpler to implement, they may suffer from slower response and higher distortion under rapidly changing environmental conditions. Overall, the classification in Figure 3 provides a clear comparative perspective on how different MPPT strategies interact with boost converter-based PV systems to optimize energy harvesting under varying operating conditions.

3. Review of Litterature

In recent time development of MPPT-based solar PV array systems based on boost converters has progressed significantly in the last decade, with research focusing on improving dynamic performanc, thee efficiency, and

harmonic quality of THD. Ahmed and Mohonta [1] carried out a comprehensive comparison of MPPT techniques integrated with boost converters, establishing baseline performance in terms of efficiency and response time. However, the study did not explicitly evaluate harmonic distortion (THD), which remains an essential parameter for inverter-connected PV systems. Building on this, Shaikh et al. [2] investigated PV systems under dynamic shading conditions, comparing multiple MPPT algorithms. Their work highlighted that while classical methods like P&O and INC perform adequately under uniform irradiance, they show significant performance degradation under shading, often leading to power oscillations and reduced efficiency. Still, their work lacked THD analysis, which could have provided additional insight into power quality issues. Chewale et al. [3] presented an MPPT-boost converter design for PV systems, demonstrating effective energy extraction. However, the research was mostly conceptual and lacked detailed experimental validation on THD and inverter-side harmonics, limiting its practical relevance. In contrast, Gaherwar et al. [4] introduced a high-efficiency boost converter with P&O MPPT, showing improvements in steady-state tracking. The limitation here was that the study primarily considered converter efficiency and did not provide a detailed evaluation of harmonic distortion, which is critical for grid-connected systems.

Koca et al. [5] emphasized the design parameters of boost converters, highlighting the importance of inductor sizing and switching frequency for achieving stable MPPT. While informative for converter designers, the study again did not measure THD performance, making it difficult to assess power quality implications. Siddique et al. [6] reviewed emerging MPPT algorithms, including machine learning and soft computing methods, and identified limitations such as high computational cost, slow convergence in real-time, and challenges in scalability. Importantly, they stressed the need for harmonic quality evaluation in future works. Similarly, Krishnaram et al. [7] proposed a hybrid MPPT with interleaved boost converters that enhanced tracking under partial shading. Their approach improved efficiency but was limited by increased design complexity and higher switching losses, which indirectly affect THD performance. Nagthane et al. [8] compared P&O and INC methods in a grid-connected PV-battery hybrid system, highlighting trade-offs: P&O exhibited oscillations, while INC achieved better steady-state accuracy. However, both showed vulnerability to rapid irradiance fluctuations, leading to degraded THD performance at the inverter side. Rana et al. [9] proposed a high-gain buck-boost converter to address voltage mismatch issues in PV systems. Although the design improved voltage conversion, limitations included component stress and a lack of harmonic distortion analysis. Similarly, Ali et al. [10] explored P&O-based systems under varying conditions, concluding that while simple, the algorithm is prone to steady oscillations that could raise THD.

Hashim et al. [11] optimized boost converter design for faster MPPT convergence, which improved tracking under varying conditions. However, their approach still suffered from switching-induced harmonics, and the work did not include explicit THD measurements. Choudhary and Gupta [12] extended converter-based studies for battery charging applications, showing dynamic benefits, but lacked harmonic evaluation. Balasubrahmanyam and Gupta [13] introduced a new MPPT technique, demonstrating better efficiency, yet limitations included increased algorithmic complexity and no analysis of harmonics.

Prakash et al. [14] shifted focus to adaptive control for active power filters, directly targeting harmonic mitigation in PV-based systems. Their results showed effective THD reduction under variable solar input, although challenges remained in terms of controller tuning and computational burden. Nadia and Mouna [15] examined boost converters with MPPT for green energy applications, contributing to converter design knowledge, but without detailed harmonic assessment. Babaa et al. [16] provided a broad overview of boost converters, establishing fundamental design insights, but their study was mostly qualitative, lacking quantitative results on THD or dynamic MPPT performance.

Jain and Bhullar [17] focused on PV-battery-grid integration, highlighting energy storage benefits for grid reliability. However, limitations included system complexity and potential harmonic interactions between storage and inverter operation. Mimoun et al. [18] specifically addressed THD performance of MPPT algorithms under partial shading, finding that conventional algorithms often increase THD due to oscillations in operating points, whereas advanced methods provide better current quality. This study stands out as one of the few that directly quantifies harmonic behavior. Similarly, Endiz et al. [19] provided a detailed review of tracking speed, identifying the limitation that harmonic distortion and power quality are often overlooked in algorithm development.

Sumalatha and Muneender [20] explored THD analysis in hybrid PV-wind systems, demonstrating that converter design and switching frequency strongly influence distortion levels. Salman et al. [21] introduced ML and metaheuristic MPPT algorithms, which improved dynamic accuracy but carried the limitation of higher computation and THD performance in practical conditions. Kathe et al. [22] presented a comprehensive review of MPPT methods, identifying that while hybrid methods enhance performance, they remain constrained by complex hardware implementation and lack of THD-focused studies. Finally, Sarang et al. [23] compared digital as well as conventional MPPT techniques, showing that digital strategies significantly improve stability, tracking speed, and primarily the harmonic performance, although real-time implementation remains a limitation due to

hardware based requirements and their computational demand. The summary of BCon based MPPT solar PV systems is given in the Table 2 including limitations.

Table 2 Summary of MPPT and Boost converter based solar PV Array methods

Reference	Methodology	Performance Parameters	Limitations
Ahmed et al. [1]	Comparative analysis of MPPT with boost converter	Efficiency, tracking response	No THD evaluation; lacks dynamic shading analysis
Shaikh et al. [2]	Comparative MPPT under dynamic shading	Energy yield, stability	Poor performance of classical MPPT; THD not assessed
Chewale et al. [3]	MPPT-based boost converter design	Output power, stability	Lacks experimental validation; no THD study
Gaherwar et al. [4]	High-efficiency boost with P&O MPPT	Efficiency, steady-state accuracy	THD not considered; focus limited to converter
Koca et al. [5]	Boost converter design for PV	Stability, voltage gain	No THD measurement; limited to design aspects
Siddique et al. [6]	Review of emerging MPPT algorithms	Efficiency trends, convergence	High computational cost; THD rarely analysed
Krishnaram et al. [7]	Hybrid MPPT with interleaved boost	Efficiency, shading adaptability	Complex design; increased switching losses affect THD
Nagthane et al. [8]	P&O vs. INC in PV-battery grid system	Tracking speed, accuracy	Oscillations in P&O; THD performance degraded
Rana et al. [9]	High-gain buck-boost converter	Voltage conversion, gain	High component stress; no THD data
Ali et al. [10]	P&O under varying conditions	Adaptability, energy output	Steady oscillations → THD risk; no THD analysis
Hashim et al. [11]	Boost converter for fast MPPT	Convergence time, accuracy	Switching harmonics increase THD; not quantified
Choudhary et al [12]	PV-powered buck-boost for battery charging	Dynamic response, charging profile	No THD or power quality assessment
Balasubrahman yam et al [13]	New MPPT technique with boost converter	Efficiency improvement	Higher complexity; THD not considered
Prakash et al. [14]	Adaptive control for shunt filter in PV	Harmonic reduction, stability	Computationally heavy; tuning challenges
Nadia et al. [15]	Boost converter with MPPT	Converter efficiency	No harmonic study; lacks grid-side evaluation
Babaa et al. [16]	Overview of boost converter design	Converter operation principles	Lacks quantitative analysis; no THD discussion
Jain & Bhullar [17]	PV-battery integration with grid	Energy storage impact, reliability	Complex integration; harmonic interaction not studied
Mimoun et al. [18]	Comparative MPPT focusing on THD	THD, current quality, shading performance	Limited scope; algorithm-specific analysis only
Endiz et al. [19]	Review of traditional & advanced MPPT	Efficiency, adaptability	THD overlooked in most methods; practical gaps
Sumalatha & Muneender [20]	THD analysis in PV-wind hybrid	THD, simulation validation	Specific to hybrid systems; not generalizable
Salman et al. [21]	ML & metaheuristic MPPT evaluation	Efficiency, accuracy	Computational complexity; THD not benchmarked

Katche et al. [22]	Review of MPPT techniques	Classification of methods	Implementation complexity; no detailed THD analysis
Sarang et al. [23]	Digital vs. conventional MPPT	Efficiency, stability, THD	requires high resources; real-time challenge

The literature review in Table 2 highlights that, although extensive research has been conducted on Maximum Power Point Tracking (MPPT) algorithms and their integration with boost converters in solar PV systems, a consistent gap persists in the systematic assessment of Total Harmonic Distortion (THD). Only a limited number of studies, such as those by Mimoun et al. [18], Prakash et al. [14], and Sumalatha and Muneender [20], have directly examined harmonic distortion, showing that inverter output quality is strongly affected by MPPT-induced oscillations and converter switching strategies. The majority of existing works have concentrated on improving efficiency, convergence speed, and operational stability, while largely overlooking essential power quality indicators like THD, which are crucial for maintaining compliance with grid standards such as IEEE-519. Moreover, advanced techniques involving artificial intelligence and hybrid optimization methods [6, 7, 21, 22, 23] demonstrate promising gains in adaptability and tracking accuracy, yet they also pose significant challenges in terms of computational demands, real-time deployment, and harmonic regulation. Therefore, future research efforts should aim to establish a balanced framework that simultaneously enhances efficiency, reduces THD, and ensures practical real-time implementation of MPPT-boost converter systems. Therefore, this research is aimed to design and investigate the performance of two MPPT solar PV system array of based on modified Boost converter filters for improving the THD efficiency.

4. Proposed MPPT based Solar PV System Design

This research proposed designing and examining the performance of an efficient MPPT-based solar PV arrays-based system. The basic architecture diagram for the proposed solar PV system with microgrid is suggested in Figure 4.

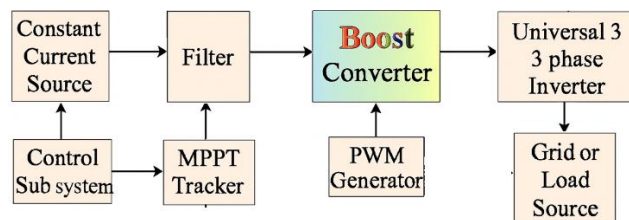


Figure 4 The proposed architecture diagram of the MPPT based solar PV system

The proposed research is independently try to investigate the MPPT and boost converter designs (as highlighted in Figure 4) for the performance improvement. The THD is proposed to evaluate based on the impact of boost converter and MPPT control signals and inverter output. In practice the MPPT system provides the modulated wave with peak power points controls.

$$THD = \sum_{n=2}^k V_n^2 / V_1^2 \tag{1}$$

The MPPT operates the solar panels to offer the greatest output to a demand and change the power. The present research is aimed at designing and investigating the performance of dual solar PV array configurations integrated with MPPT techniques, where the power regulation is achieved through a modified boost converter equipped with RC filtering mechanisms. The primary objective of the proposed methodology is to enhance the overall efficiency of the PV system while significantly reducing harmonic distortion (THD) at the inverter output. A comprehensive model has been developed for a 100-kW photovoltaic (PV) array interfaced with a 25-kV grid through a DC–DC boost converter and a three-phase, three-level Voltage Source Converter (VSC). The Maximum Power Point Tracking (MPPT) function within the boost converter is realized using a Simulink-based implementation of the Incremental Conductance (Inc_{Cond}) algorithm combined with an integral regulator to ensure stable and efficient power extraction. To achieve THD immunization the work involves several sequential stages: first, the modeling of two independent solar PV arrays under varying irradiance and temperature conditions as shown in Figure 5.

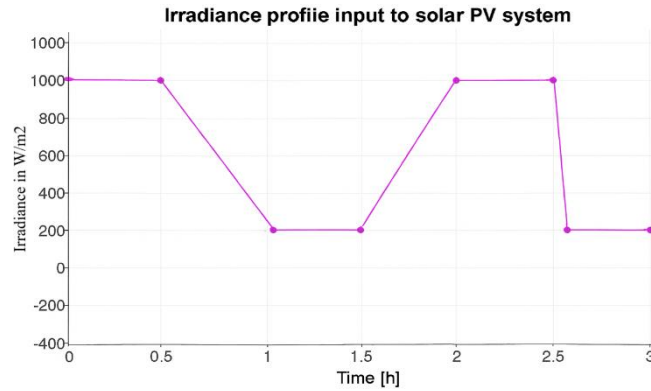


Figure 5 Varying irradiance profile as input to solar PV system

It is clear from the Figure 5 that the irradiance profile begins at a high-level of 1000 W/m², drops to 200 W/m², and then rises again, forming a symmetrical dip followed by a sharp recovery. This pattern reflects intermittent shading or cloud cover effects typical in dynamic solar environments.

The MPPT implementation Perturb and Observe (P&O) algorithms to ensure optimal power extraction; third, the design and integration of a modified boost converter topology incorporating modified filters within the converter structure to mitigate harmonics and improve power quality. The P&O algorithm is as follows;

1. **Initialization:** At the beginning, if the persistent variables are empty, they are initialized. The duty cycle D_{old} is set to an initial value D_{init} , and the previous voltage V_{old} and previous power P_{old} are set to 0.
2. **Power and Voltage Change Calculation:** The mathematical modeling of current power P is calculated by multiplying the current voltage V and current I can be derived as;

$$P = V \times I \tag{2}$$

The change in voltage dV and change in power dP are then calculated by comparing the current values with the previously stored values.

$$dV = V - V_{old} \tag{3}$$

$$\text{and } dP = P - P_{old} \tag{4}$$

3. **Duty Cycle Adjustment Logic:** The core logic for adjusting the duty cycle D is executed if the controller is enabled (Enabled ≈ 0) and there is a change in power ($dP \approx 0$). The adjustment depends on the signs of dP and dV are presented in the Table 3 as follows:

Table 3 Power Conditions for P&O MPPT method

Condition	$\Delta P < 0$	$\Delta P > 0$
$\Delta V < 0$	$D = D_{old} - \delta D$	$D = D_{old} + \delta D$
$\Delta V > 0$	$D = D_{old} + \delta D$	$D = D_{old} - \delta D$

The flow chart of the P&O based MPPT tracker algorithm is shown in the Figure 6. The performance of the proposed system is evaluated in terms of efficiency, dynamic response, stability, and THD compliance with grid standards (such as IEEE-519).

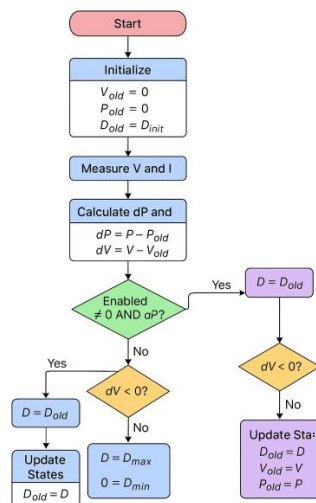


Figure 6 Flow chart of P&O based MPPT tracker

Comparative simulations are carried out against conventional MPPT-boost converter systems to validate the effectiveness of the proposed approach in achieving both high efficiency and superior harmonic performance.

4.1 Simulink Model with Dual Solar PV system and Boost Converter

The proposed design is hybrid combination of two individual solar PV systems based on MPPT design with individual capacity of 100KW and overall capacity of the 200-kW Grid-Connected PV array. the proposed Simulink model is shown in Figure 7. The Solar PV system is investigated with modified Boost converter unit with shunt RC filter as highlighted in red color box. The aim is to investigate the FFT analysis for minimizing the THD performance of the system. The powerGUI block is aided for the performance investigation.

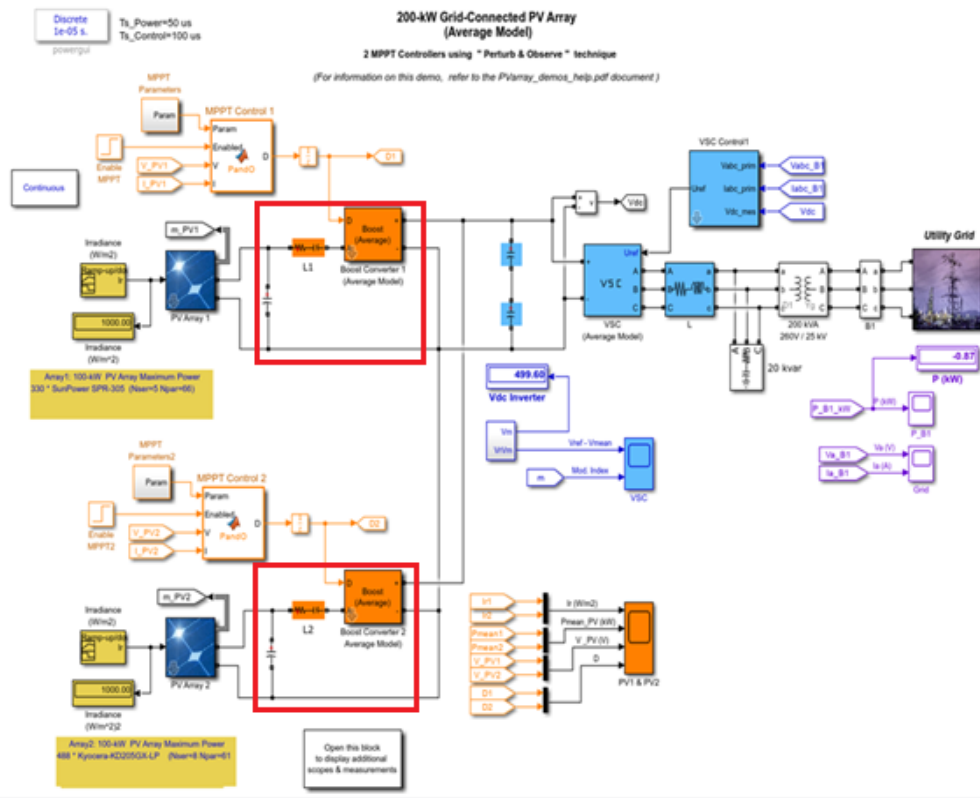


Figure 7 Proposed Solar PV Model Design with P&O MPPT and modified Boost Converter testing

The solar PV system is modeled to represent a grid-connected configuration, incorporating power conversion and control stages to achieve efficient energy transfer. The system consists of two PV arrays, each rated at 100 kW under standard solar irradiance of 1000 W/m². The direct current (DC) generated by each array is processed through an average model of a boost converter, which steps up the PV voltage to a stable 500 V DC. Each converter is equipped with a MPPT controller employing the P&O method, ensuring optimal energy extraction under varying environmental conditions. The DC link feeds an average model of a three-phase, three-level VSC, which converts the 500 V DC to a 260 V AC output while maintaining a unity power factor. A 20 kVAR capacitor bank is included to filter harmonics generated by the VSC. Furthermore, a 200 kVA, 260 V/25 kV step-up coupling transformer facilitates interconnection with the utility grid. The grid is modeled as a 25 kV distribution feeder coupled with a 120 kV equivalent transmission system, providing a detailed and realistic representation for analyzing the performance of the grid-integrated PV system as shown on Figure 7 model.

5. Expected Results

The results section has sequentially performed the various experiments and presented the results in three pas. the first pass has validated the impact of sinusoidal irradiance profile on various MPPT modes.

5.1 Experiment 1: Validation of sinusoidal Irradiance model for MPPT methods

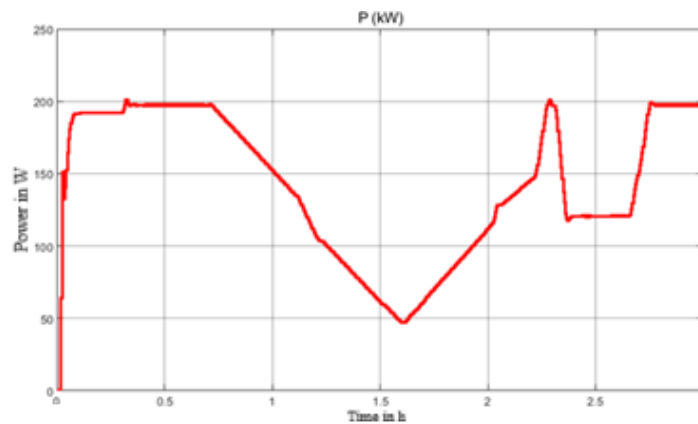
This work focuses on the simulation and comparative analysis of various MPPT algorithms for solar photovoltaic (PV) systems, aimed at improving energy harvesting under fluctuating irradiance conditions. Figure 8(a) illustrates the dynamic power output response of a proposed model of solar PV system over a three-hour interval under varying irradiance conditions. The system initially exhibits a rapid increase in power generation, reaching approximately 200 kW within the first 0.25 hours, followed by a stable output until 0.75 hours. A gradual decline is observed thereafter, with power dropping to a minimum of nearly 50 kW around 1.5

hours, likely due to transient shading or reduced solar input. The system demonstrates effective recovery, regaining peak output within 0.7 hours and maintaining near-optimal performance through the remainder of the interval. These fluctuations highlight the responsiveness of the PV system and its control mechanisms to environmental variability.

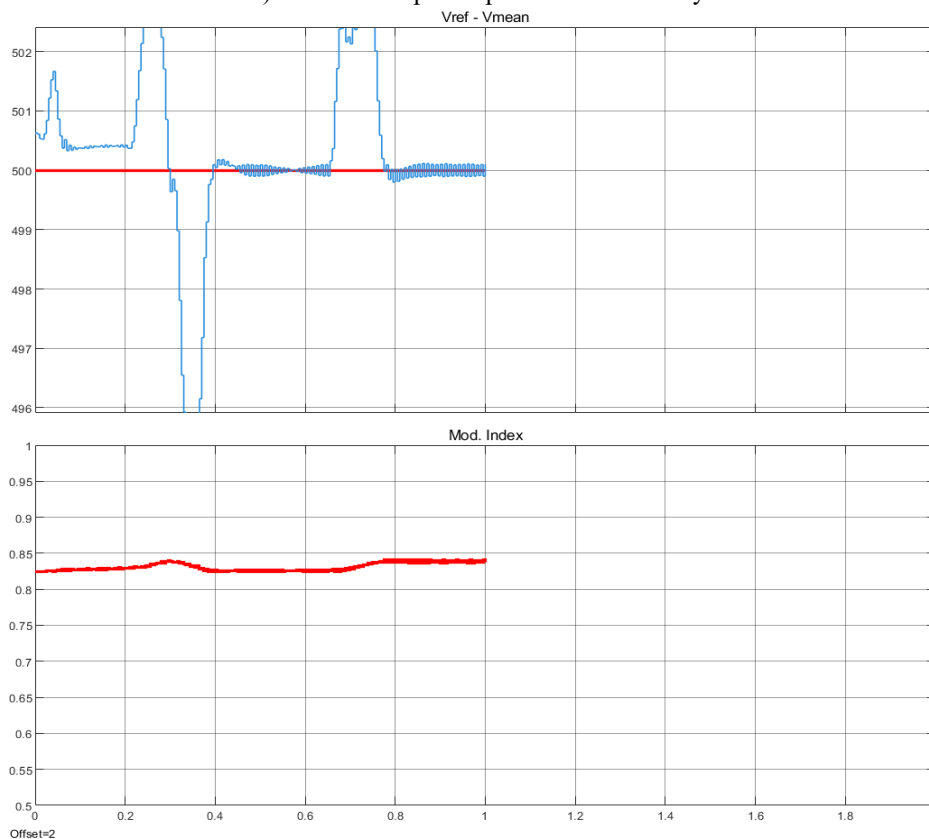
Figure 8(b) presents the modulation index response of the solar PV inverter system over a 2-second interval, highlighting its dynamic stability under varying operating conditions. The modulation index begins at approximately 0.88 and exhibits only a minor transient dip near 0.3 seconds, briefly reaching around 0.85 before recovering. For the remainder of the interval, the index remains consistently close to its initial value, indicating effective control and minimal deviation. This stable behaviour confirms the robustness of the inverter’s modulation strategy, ensuring reliable power conversion and grid compatibility throughout the observed period.

Figure 8(b) also presents modulation index response of solar PV inverter system over a 2 s interval, highlighting its high dynamic stability under varying operating conditions sing mis nearly constant.

Figure 9 presents a comprehensive analysis of the dynamic behaviour of a Solar PV array under varying solar irradiance conditions. The irradiance profile exhibits sharp declines around time intervals 1.5 and 2.5, simulating transient shading or cloud cover. Correspondingly, the mean PV output power demonstrates a strong correlation with irradiance, dropping from peak values of approximately 120 kW to near-zero during low irradiance periods.



a) Power Output response of solar PV system



b) Voltage and modulation index for Solar PV system design

Figure 8 Experimental results of Voltage and Power output response of Proposed solar PV system

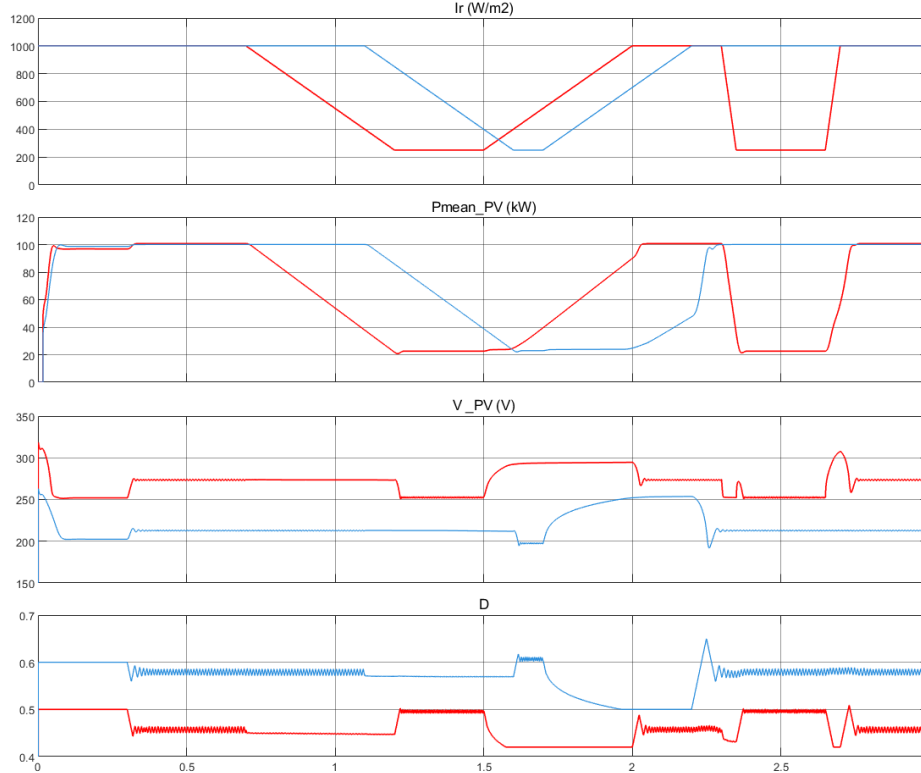


Figure 9 Results of dynamic behaviour of a Solar PV array under varying solar irradiances

The PV system voltage as in Figure 9 fluctuates between 200 V and 350 V, with the red trace indicating more pronounced instability, suggesting a less regulated or more aggressively tuned control strategy. The duty cycle response further highlights the system’s control dynamics, where the red trace shows significant modulation, peaking near 0.7, while the blue trace remains comparatively stable. These observations underscore the importance of robust voltage regulation and responsive control algorithms, such as MPP, to ensure optimal energy harvesting and system stability. The results also suggest that incorporating energy buffering or adaptive converter design may enhance performance under rapidly changing environmental conditions.

5.2 Experiment 2: Validation of THD for Proposed Solar PV system

This section has presented the ideal THD validation based on FFT analysis as shown in the Figure 10. The harmonic analysis presented in Figure 9 validates the presence of significant distortion in the signal, characterized by a fundamental frequency of 50 Hz with a magnitude of 17,000 units and a Total Harmonic Distortion (THD) of 44.83%.

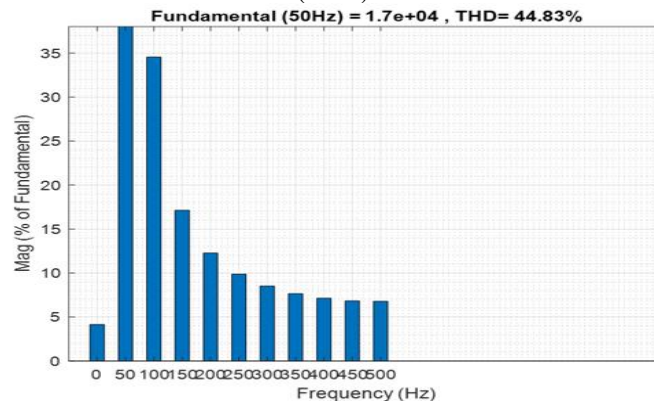


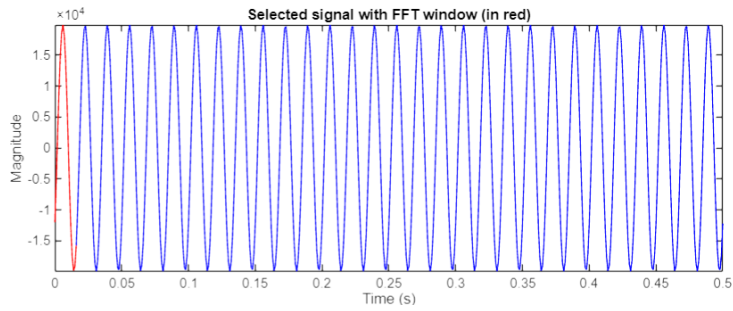
Figure 10 Validation of the THD for the Dual Solar PV system with boost converter

The harmonic spectrum in Figure 10 reveals pronounced components at integer multiples of the fundamental frequency, with amplitudes expressed as percentages relative to the fundamental. Although the magnitude of higher-order harmonics diminishes progressively beyond 300 Hz, their cumulative contribution to the THD remains substantial. This elevated THD level indicates considerable nonlinearity in the system, which may adversely affect signal fidelity and operational efficiency, particularly in power electronic applications or grid-

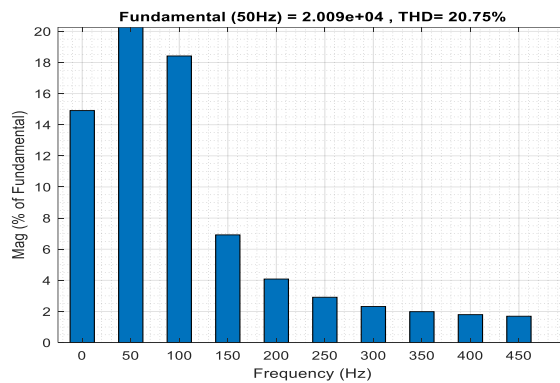
connected photovoltaic inverters. The results underscore the necessity for enhanced filtering techniques, refined modulation strategies, or adaptive control mechanisms to mitigate harmonic distortion and ensure compliance with power quality standards.

5.3 Result of THD with Modified BC Shunt filter

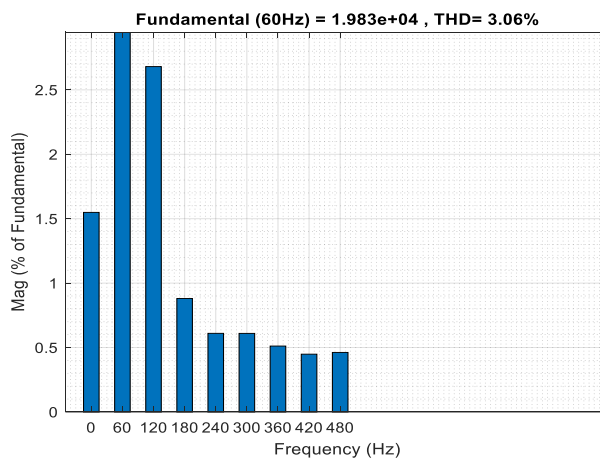
The pre shunt filter of B_{Con} is modified as RC filter and also the sampling or switching time is minimized for THD impact analysis. results are investigated for the modified B_{Con} architecture and the THD is evaluated using FFT analysis. Figure 11(a) depicts the output voltage waveform of the system over a 0.5-second duration. The waveform exhibits a periodic sinusoidal pattern, indicating a stable and continuous alternating voltage output. The magnitude of the waveform oscillates symmetrically between approximately $\pm 1.5 \times 10^4$, demonstrating consistent amplitude and frequency characteristics.



a) Output Voltage wave form



b) with proposed modified filter-based Boost converter and MPPT at 50 Hz at 0 sec starting time



c) for 60 Hz fundamental frequency and starting at 0.03 sec

Figure 11 Results of THD for the two Solar PV system based MPPT models with modified filter-based Boost converter

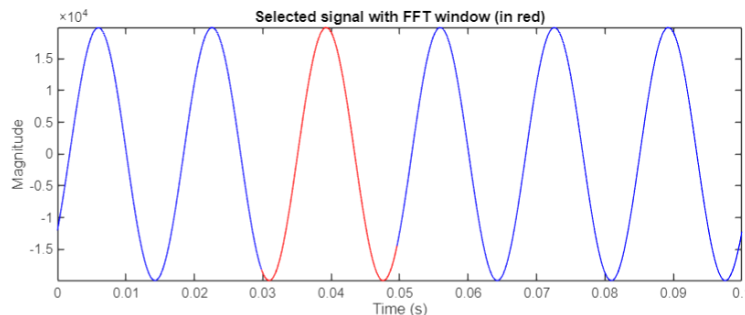
Figure 11(b) illustrates the frequency spectrum of the output voltage waveform, depicting the harmonic components as a percentage of the fundamental frequency. The spectrum clearly shows that the fundamental frequency, approximately 50 Hz, possesses the highest THD magnitude of about 20%, signifying its dominance in the output waveform. A few lower-order harmonics, particularly at 100 Hz, 150 Hz, and 200 Hz, are observed with progressively lower amplitudes, while the higher-order harmonics beyond 250 Hz exhibit magnitudes

below 3%. This distribution indicates that the output voltage retains a predominantly sinusoidal nature with minimal harmonic distortion. The low presence of higher-order harmonics further reflects the efficiency of the filtering mechanism, ensuring high power quality and making the system well-suited for applications requiring stable and clean sinusoidal voltage, such as grid-connected or sensitive load operations.

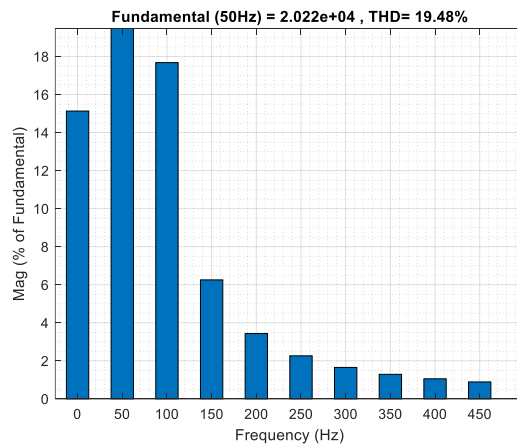
Now the modifying the sampling time 0.03 sec and restricting time steps the further THD analyses is carried out. Figure 11(c) shows the harmonic spectrum of the output voltage waveform corresponding to a fundamental frequency of 60 Hz, analysed from the time interval beginning at 0.03 seconds. The spectrum indicates that the 60 Hz fundamental frequency has the highest THD=3.08% only which is well within the limit of IEEE-519. With lower-order harmonics at 120 Hz, 180 Hz, and 240 Hz appearing at considerably reduced magnitudes. Higher-order harmonics beyond 300 Hz are almost negligible, each contributing less than 1% of the fundamental. This confirms that the output voltage is predominantly sinusoidal with minimal total harmonic distortion (THD). The low harmonic content reflects the system’s effective filtering capability and high-power quality, ensuring a clean, stable voltage output suitable for grid integration and sensitive electrical loads.

5.2 Impact of Reduced sampling size on THD

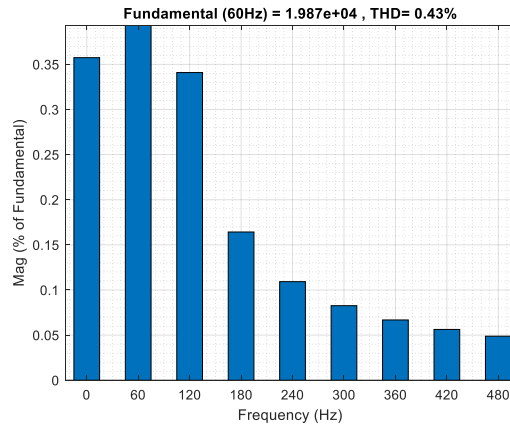
Evaluating THD over a short time span is valuable for analysing steady-state or switching interval behaviour, where the system operates under almost constant conditions. This approach aids in assessing converter performance, the quality of PWM switching, and the effectiveness of filter designs. Therefore, as another experiment the sampling time of time steps are reduced and THD is investigated for only 0.1 sec total span instead of 1 or 10 sec. The respective results are shown in Figure 12.



a) reduced sample size voltage wave for FFT evaluation



a) for 60 Hz fundamental and modified Boost converter sampling at 0. sec starting time



b) for 60 Hz fundamental and modified Boost converter sampling 0.03 sec

Figure 12 Results of the predicted output THD for the different reduced timings

Figure 12(b) illustrates the harmonic spectrum of a modified Boost converter operating at a 50 Hz fundamental frequency, starting time (of wave as in Figure 12 a) at 0 seconds. The bar graph reveals a dominant fundamental component at 50 Hz, with progressively diminishing harmonic at THD of 19.48. The second harmonic (100 Hz) exhibits a noticeable but reduced amplitude, while subsequent harmonics from 150 Hz to 450 Hz show a consistent decline, indicating effective suppression of higher-order distortions.

Further observed improvement in performance, with THD reduced to 0.43% at a fundamental frequency of 60 Hz and a starting time of 0.03 s for a 0.1 s waveform, can be attributed to the optimal alignment of the switching instant with the waveform’s zero-crossing points. This timing minimizes harmonic generation during the switching process, ensuring smoother voltage transitions. Additionally, the converter and associated filtering elements effectively suppress higher-order harmonics, leading to a cleaner output waveform and enhanced overall system efficiency, as reflected in the low THD value shown in Figure 12(c) This reduction in THD indicates improved waveform quality, reflecting effective harmonic suppression within the system. The low THD at this specific starting instant suggests that the converter and switching strategy are operating optimally, thereby enhancing overall efficiency and reducing potential distortions in the output voltage

The table 4 has patented the comparative performance evaluation for the various case of timings for % THD at 60 Hz the significant THD level is observed by the prosper tuning of FFT analysis tool.

Table 4 Comparative THD Performance for various tested sampling and starting times

Case	Fundamental Frequency	Sampling Time	Total Time Span	THD
Initial system	60 Hz	0 s	1 s	44.83%
Modified BC Shunt filter	60 Hz	0 s	0.5 s	~20%
Modified BC Shunt filter	60 Hz	0.03 s	0.5 s	3.08%
Reduced sampling size	60 Hz	0 s	0.1 s	19.48%
Reduced sampling size	60 Hz	0.03 s	0.1 s	0.43%

Table 5 State of art THD performance for various Solar PV system at Grid

Reference Method	THD
M. P. Thakre [24]	6.0%
Lakhan Singh et al [25]	0.230%
Proposed Modified BC Shunt filter	3.08%
Proposed Reduced sampling size	0.43%

A state of performance comparative analysis of THD across contemporary methodologies highlights significant differences in performance as given in Table 5. The reference method by M. P. Thakre exhibits the highest THD of 6.0%, indicating considerable harmonic content and potential waveform distortion. In contrast, the technique proposed by Lakhan Singh et al. [25] achieves superior harmonic suppression, with a remarkably low THD of 0.230%, demonstrating the effectiveness of advanced filtering and control strategies. The performance is further clearly represented in error bar chart in Figure 13. it is clear form the Table 5 and Figure 13 that proposed modified Boost converter integrated with a shunt filter attains a moderate THD of 3.08%, reflecting improved performance over conventional designs, though it remains behind the most optimized approaches. Notably, the reduced sampling size technique further minimizes THD to 0.43%, highlighting its potential as a promising solution that balances computational efficiency with effective harmonic mitigation. These findings underscore

the critical role of sampling strategies and filter integration in enhancing power quality and advancing converter design

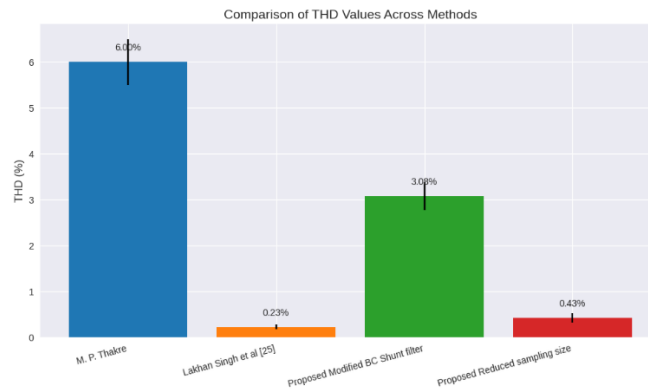


Figure 13 State of art performance with error bar chart

6. Conclusion and Future Work

This research has provided a thorough analysis of MPPT algorithms for solar PV systems under a range of irradiance conditions. By comparing traditional methods such as P&O and Incremental Conductance (Inc_{Cond}) with advanced techniques including PSO and GA based Optimizations, and their hybrid combinations. The research has demonstrated the significant benefits of integrating hybrid evolutionary algorithms with traditional approaches. The hybrid methods, particularly P&O-PSO, showed superior performance in terms of faster convergence, greater stability, higher power output, and reduced oscillations around the maximum power point. These hybrid models proved adaptable to different irradiance profiles, making them suitable for practical solar energy applications.

- The paper performed simulations in three phases in the first phase the sinusoidal, square and trapezoidal irradiance profiles are used for comparing performance of different basic MPPT methods. It is concluded that PSO optimization based MPPT method achieves the higher MPP in all cases.
- In second phase initial validation Case 1 with $I_{sc} = 8A$ the Incremental Conductance (Inc_{Cond}) achieves a MPP of 29.4 W while PSO outperforms other methods with an MPP of 29.6 W for minimum irradiance of 400 W/m².
- Finally for the case 2 in the hybrid model, P&O with increased $I_{sc} = 80A$ starts at around 294 W and achieves an MPP of about 296 W. And the hybrid P&O+PSO hybrid reaches and stabilizes quickly at a peak power of 296 W for minimum irradiance of 400 W/m²,

At all tested irradiance levels (400, 600, 800, and 1000 W/m²), the PSO and P&O methods consistently achieved higher MPPs compared to Inc_{Cond} method. Hybrid models, such as P&O with PSO or GA, also demonstrated competitive MPP performance, with the P&O+PSO hybrid noted for its rapid stabilization. IQR analysis revealed that the P&O method generally exhibited wider performance variations (larger IQRs) across different irradiances, whereas the hybrid methods consistently displayed narrower IQRs, indicating greater stability. These numerical results consistently demonstrate that the hybrid MPPT methods, particularly P&O+PSO, outperform traditional methods in terms of power output, convergence speed, and stability across various irradiance levels.

6.1 Future Work

In future it is expected to test the systems under various real-world scenarios, including rapidly changing irradiance and partial shading conditions. Partial shading scenarios and how the hybrid algorithms respond to non-uniform irradiance across panels. Another scope for future is implementing and comparing other nature-inspired optimization algorithms

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