



## Optimizing PV Inverter GMPP and Current Harmonic Distortion Using QHBM

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### ABSTRACT

This paper investigates the optimization of the Global Maximum Power Point (GMPP) and the simulation of Total Harmonic Distortion of Current (THD<sub>i</sub>) from an inverter connected to a nonlinear load. THD<sub>i</sub> variations are analyzed with respect to ambient temperature (T) and solar irradiance (G). The study also highlights how harmonic components negatively affect steady-state voltage stability in photovoltaic (PV) systems. The Queen Honey Bee Migration (QHBM) algorithm is applied to optimize GMPP while minimizing THD<sub>i</sub>. An off-grid PV-inverter system is modeled in MATLAB/Simulink. The model extracts THD<sub>i</sub> as a function of temperature and irradiance. Simulations cover irradiance from 794.8 to 994.2 W/m<sup>2</sup> and temperature from 20.0°C to 32.3°C, based on daily measurements from 08:25 to 16:50. The QHBM algorithm tracks GMPP effectively under fluctuating irradiance. Results show a 17.3% improvement in power extraction efficiency and a 32.8% reduction in THD<sub>i</sub> compared to conventional methods. The highest THD<sub>i</sub> occurs during low irradiance, particularly in the early morning and late afternoon. The algorithm converges in 0.18 seconds, outperforming other techniques. THD<sub>i</sub> increases during rapid irradiance and temperature changes. The proposed method ensures stable performance and lower THD<sub>i</sub>. Combining QHBM with active harmonic filters under low irradiance conditions is recommended to improve power quality and enhance system protection.

### INTRODUCTION

PV power generation systems represent a highly promising renewable energy solution in the global effort to mitigate climate change [1]-[4]. These systems offer transformative potential to reduce reliance on fossil fuels by harnessing an abundant, environmentally friendly, and sustainable energy source [5]. PV technology enables clean electricity generation from solar radiation and can be deployed across a wide range of scales—from small residential rooftop systems to utility-scale solar farms capable of meeting large-scale energy demands [6].

Over the past decade, photovoltaic technology has advanced rapidly, with significant improvements in energy conversion efficiency, reductions in production costs, and material innovations that enable the development of increasingly high-performance solar panels [7]. However, one of the major challenges that persists is the presence of THD<sub>i</sub> [8]. This issue not only affects the quality of the generated power but also impacts system efficiency, as increased THD<sub>i</sub> can lead to substantial power losses, overheating of electronic components, and a reduction in the overall performance of the PV system [9].

The complexity of THD<sub>i</sub>-related issues becomes more pronounced in PV systems due to environmental fluctuations such as variations in solar irradiance, temperature, and shading

[10]. These factors significantly influence harmonic distortion characteristics, resulting in highly dynamic THD<sub>i</sub> variations that degrade power quality, disrupt electronic equipment performance, increase system losses, and potentially shorten the lifespan of critical components in solar power infrastructure [11]-[17]. Numerous studies have explored the optimization of Maximum Power Point Tracking (MPPT) and harmonic distortion reduction in PV systems [18]-[21]. Conventional methods such as Perturb and Observe (P&O) and Incremental Conductance have demonstrated significant limitations [22], [23]. Intelligent algorithms such as Particle Swarm Optimization (PSO) and Genetic Algorithms have been proposed to improve tracking accuracy [24], [45], but still face challenges under partial shading conditions, rapid temperature changes, and nonlinear loads [26], [27]. Comparative studies highlight the need for a comprehensive approach that effectively integrates both power optimization and harmonic mitigation [28], [29].

This research proposes the QHBM Algorithm as an innovative approach to address the challenges in photovoltaic systems. Inspired by the migration and adaptation behavior of bee colonies, this algorithm excels in efficiently exploring and exploiting the search space [1],[2]. QHBM is designed to integrate maximum power point optimization and harmonic distortion reduction into a single, comprehensive approach [3]. The method leverages adaptive capabilities to respond in real-

time to changing environmental conditions and load characteristics [4].

The main contribution of this study is the development of a novel mathematical model employing the Queen Honey Bee Migration Algorithm for PV-inverter systems in off-grid configurations. The novelty of this research lies in its integrated approach that simultaneously optimizes the maximum power point and minimizes current harmonic distortion. Compared to conventional methods, the QHBM algorithm demonstrates superior capability in tracking optimal power points under dynamic and complex environmental conditions, with a particular focus on partial shading and rapid temperature fluctuations.

The objectives of this study are to develop an optimization model capable of tracking the global maximum power point in PV-inverter systems under dynamic environmental conditions, to analyze and minimize current harmonic distortion using the QHBM algorithm, and to evaluate the performance of the QHBM algorithm in comparison with conventional methods. The anticipated benefits include significant improvements in energy conversion efficiency, power quality, and the reliability of photovoltaic systems, ultimately supporting the development of more sustainable and efficient renewable energy technologies.

**METHODS**

*Simulation Setup and Environmental Data Profile*

This study utilizes a comprehensive simulation approach developed in MATLAB/Simulink to model the off-grid PV-inverter system and evaluate the performance of the proposed QHBM algorithm. The simulation integrates mathematical models of the PV array, DC-DC converter, and inverter connected to a nonlinear load to analyze the simultaneous optimization of Global Maximum Power Point (GMPP) and Current Harmonic Distortion (THDi) reduction.

The current climate conditions in Indonesia are characterized by high temperatures and significant weather variability, both of which directly impact the performance of PV systems. Since PV systems are highly dependent on solar irradiance and temperature, such fluctuations can substantially affect the energy output [30]. The specific weather profile used in this study, covering irradiance and temperature in Malang City, is illustrated in Figure 1. These fluctuations pose a considerable challenge in optimizing the output of PV systems [32]. Therefore, accurate PV modeling is essential to analyze and mitigate the effects of this variability and to enhance the overall efficiency of the system [33]. To model these conditions accurately, the study utilizes real-world measurement data collected from 08:25 to 16:50. The dataset includes solar irradiance levels ranging from 740.9 W/m<sup>2</sup> to 994.2 W/m<sup>2</sup> and ambient temperatures from 20.0°C to 32.3°C, as detailed in Table 1.

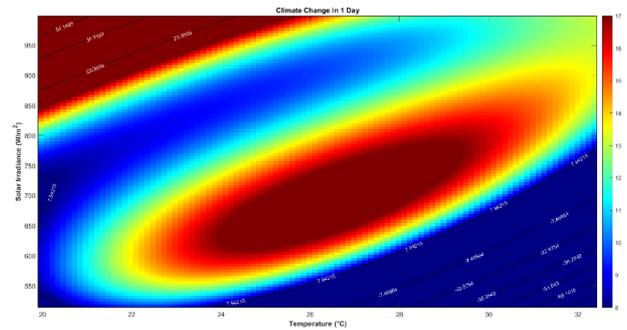


Figure 1. Weather Climate, Irradiance, and Temperature in Malang City

Therefore, a deep understanding of climate conditions and their impact on photovoltaic systems is crucial. This study aims to develop an effective PV modeling model to address climate variability and enhance the efficiency of photovoltaic systems in the context of the challenges faced.

**PV System**

A PV module, which consists of multiple PV cells connected in series to generate higher voltage and power, forms a PV system [34]. PV cells can be described as a Direct current (DC) power source with antiparallel diode characteristics in an ideal state [35]-[37]. As a solution to the shortcomings of the single-diode model, the double-diode model is presented to more accurately characterize the open-circuit voltage (Voc), short-circuit current (Isc), and the knee curve area [38]. By incorporating series resistance (Rs) and parallel resistance (Rsh), as shown in Figure 2, this ideal model can be transformed into a more realistic model. The mathematical expression for the double-diode model is given in equation (2), while equation (1) represents the current entering the load [39]-[42].

$$I = I_{ph} - I_{D1} - I_{D2} - I_{sh} \tag{1}$$

$$I = I_{ph} - I_{s1} \left( \exp \left( \frac{V + IR_s}{\alpha_1 N_s V_T} \right) - 1 \right) - I_{s2} \left( \exp \left( \frac{V + IR_s}{\alpha_2 N_s V_T} \right) - 1 \right) - \frac{V + IR_s}{R_{sh}} \tag{2}$$

$$I_{ph} = (I_{sc-STC} + K_i \Delta T) \frac{G}{G_{STC}} \tag{3}$$

Equation (1) represents the current to the load, which results from the photon current  $I_{ph}$  minus the currents through the diodes  $I_{D1}$  and  $I_{D2}$  and leakage current  $I_{sh}$ . Equation (2) gives the mathematical model of the double-diode, showing the relationship between voltage, current, and resistance in the PV system [43]. Understanding these equations helps analyze PV system performance and efficiency.  $\alpha_1$  and  $\alpha_2$  are the ideal diode coefficients,  $V$  is the PV cell output voltage,  $R_s$  is the series resistance; and  $R_{sh}$  is the parallel resistance [44]. Equation (3) calculates the photocurrent, reverse saturation current, and thermionic voltage constant (VT) [45].

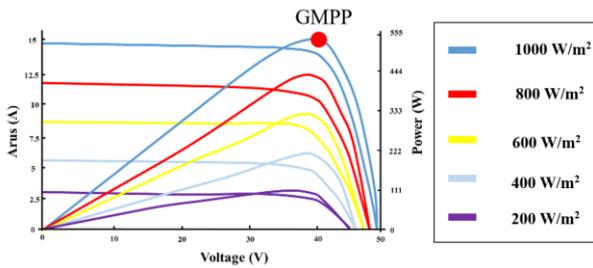


Figure 2. P-V Curve Showing the Location of GMPP on PV System

Figure 2 illustrates the graphical representation of solar panel performance under various solar irradiance intensities. As solar light intensity increases (ranging from 200 to 1000 W/m<sup>2</sup>), the electricity generated correspondingly rises. The peak point of the graph indicates the optimal condition where the solar panel produces maximum energy output.

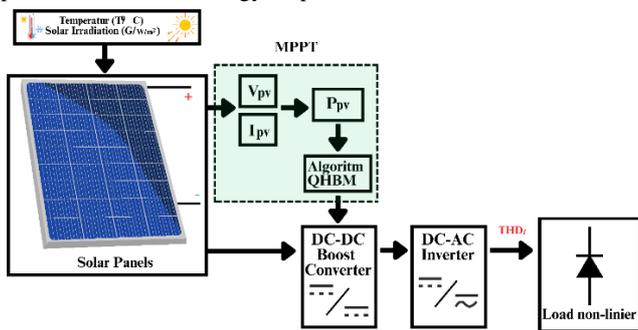


Figure 3. Schematic diagram of the PV system

Figure 3 the photovoltaic system schematic to be employed in this research, specifically focusing on the conversion of solar energy into electrical energy. The process begins with solar panels capturing sunlight, followed by multiple stages of voltage transformation and regulation, ultimately resulting in electricity that can be utilized for various applications. This system leverages advanced technology to maximize energy generation efficiency [45].

$$I_s = \frac{I_{s-STC} + K_i \Delta T}{\exp\left(\frac{V_{oc-STC} + V_p \Delta T}{\alpha V_T}\right) - 1} \quad (4)$$

$$I_{ph} = \frac{K T_c}{q} \quad (5)$$

Saturation current  $I_s$  and thermal voltage  $\Delta T$  are key parameters defined in equations (4) and (5) [46].  $I_s$  varies with temperature and Standard Test Conditions STC, while  $\Delta T$  depends on cell temperature and electron charge. Both are crucial for assessing PV cell performance under changing temperature and light conditions.

### Harmonic Distortion in Solar Power Generation Systems

Electronic devices in off-grid solar power systems generate harmonic currents that degrade power quality [47]. As technology advances, harmonics increase, causing overheating, higher energy costs, and reduced system performance [48]. Key sources include inverters, DC/DC converters, and battery chargers. Under certain conditions, such as 20°C and 940 W/m<sup>2</sup> solar irradiance, harmonic current can be calculated using equation (6) [49].

$$i(\omega t) = 5.069 \sin(\omega t + 0.251) + 2.33 \sin(4\omega t - t + 133.6) + 2.297 \sin(6\omega t + 48.251) + 1.617 \sin(9\omega t - 48.48) + 1.155 \sin(11\omega t + 94.76) \quad (6)$$

Current THD shows significant sensitivity to solar irradiance fluctuations, exhibiting dynamic characteristics distinct from voltage THD [50]. Interestingly, current THD consistently decreases with increasing irradiance, while voltage THD displays a minimal yet steady rise. The power factor demonstrates complex behavior—showing linear variation at low irradiance levels (below 200 W/m<sup>2</sup>) and converging toward the ideal value (one) at higher irradiance levels—indicating the photovoltaic system’s adaptive response to varying environmental conditions.

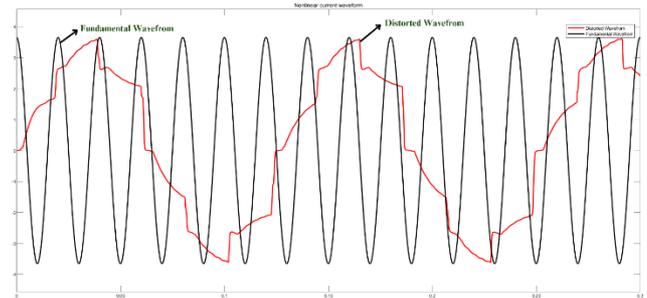


Figure 4. Waveform of nonlinear current and harmonic components

Figure 4 highlights significant nonlinear current waveform distortion, where deviations from the ideal sinusoidal form are caused by nonlinear loads such as inverters and modern electronics, affecting power quality and efficiency, and emphasizing the need for harmonic mitigation [51]. Reactive power injection under low irradiance conditions leads to significant systemic consequences, including increased power losses, reduced conductivity, and widespread negative impacts on the electrical distribution infrastructure [52]. Harmonic distortion primarily originates from nonlinear sources and loads in solar power systems, introducing complex technical challenges. However, the presence of low-level harmonics can offer certain advantages such as quieter system operation, reduced power loss, and prolonged lifespan of electrical components [53].

In off-grid PV systems, harmonics may cause a series of technical issues, including increased losses in system components, dielectric insulation failure, voltage drops, inaccurate readings in induction meters, control circuit disturbances, erroneous tripping of protection relays, microprocessor disruptions and data loss, communication noise, power factor shifts, and overheating in PV equipment such as cables, converters (DC/DC and DC/AC), batteries, and panels [54]. They also contribute to MPPT algorithm errors, shortened lifespan of PV devices like boost converters and inverters, false triggering in switching elements (e.g., IGBTs and MOSFETs), and measurement inaccuracies in voltage, current, and power [55].

In off-grid PV power systems, maintaining power quality is a critical challenge, requiring effective control of current and voltage THD at the Point of Common Coupling (PCC) [56]. Continuous harmonic monitoring is essential to ensure optimal system performance. THD<sub>i</sub> is a key metric used to evaluate harmonic levels, defined as the ratio of the root-mean-square of all harmonic components to the fundamental current, providing a

comprehensive assessment of signal quality in the electrical network [57].

$$THD_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \dots + I_n^2}}{I_1} \tag{7}$$

$$THD_I = (ArctanT^{20} + 1)^5 + [ArctanG^{20} + \sin(\log G)]^5 + \left[arctanG^{15} + \frac{1}{\sqrt{G}}\right]^5 \tag{8}$$

To estimate THD<sub>I</sub> in PV systems, a newly developed Equation (8) is used, with solar irradiance and ambient temperature as input variables [58]. The model covers sunlight hours, as shown in Table 1. THDI is calculated as the ratio of the RMS value of the n-th harmonic current to the fundamental current (I<sub>1</sub>). In reality, harmonic components are always present, leading to waveform distortion. Harmonic currents and voltages distort sinusoidal signals, potentially damaging off-grid PV systems and connected equipment [59].

Voltage waveform degradation primarily stems from the correlation between nonlinear loads and non-sinusoidal voltage and current sources. Although nonlinear loads may have low power, they still distort the waveforms. Harmonics introduce significant energy pollution, reducing power quality. Solar irradiance variations affect harmonic amplitude, further degrading the PV system and connected loads. High THD can cause overheating, motor vibrations, excessive neutral loading, and reduced power factor in off-grid PV systems.

Table 1. Measurement of Temperature and Solar Radiation and THD<sub>I</sub> for the Study of

Time (h)	Solar irradiance (w/m <sup>2</sup> )	Temperature (°C)	THD <sub>I</sub> %
08:25	740.9	20.0	146.18
08:50	780.3	20.7	149.44
09:25	806.3	23.3	151.64
09:50	920.1	26.0	161.56
10:25	916.6	28.3	161.25
10:50	911.8	28.7	160.83
11:25	959.9	29.3	165.06
11:50	994.2	29.7	168.07
12:25	976.8	31.0	166.55
12:50	940.0	32.0	163.31
13:25	902.5	32.3	160.01
13:50	901.9	31.7	159.95
14:25	891.3	30.7	159.02
14:50	877.3	30.3	157.79
15:25	854.0	29.7	155.76
15:50	825.8	29.3	153.32
16:25	794.8	29.0	150.67
16:50	794.8	29.0	150.67

**THD<sub>I</sub> According to Solar Radiation and Temperature**

Solar irradiance and ambient temperature significantly affect the DC voltage output of PV panels. Through the photoelectric effect, solar panels convert sunlight into electricity, with performance highly dependent on environmental conditions. As temperature rises, I<sub>sc</sub> increases due to greater electron excitation, while V<sub>oc</sub>

drops significantly due to increased electron randomness [60]. Since the voltage drop outweighs the current gain, overall power output decreases, reducing cell efficiency. Thus, PV panels perform better in bright yet cool environments compared to hot ones.

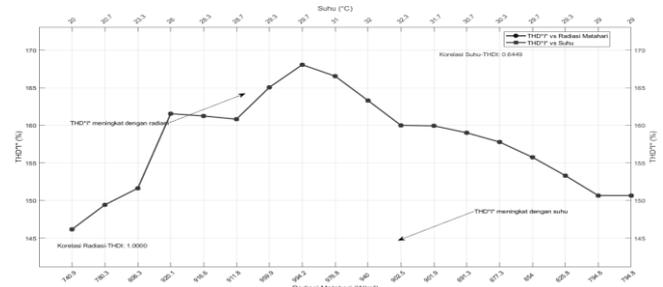


Figure 5. THD<sub>I</sub> According to Solar Radiation and Temperature Figure 5. The graph shows a strong positive correlation (≈0.99) between THDI and solar irradiance, and a moderate positive correlation (≈0.64) with temperature. The lowest THD<sub>I</sub> (146.18%) occurs at 08:25 with a radiation of 740.9 W/m<sup>2</sup>, while the highest (168.07%) is at 11:50 with a radiation of 994.2 W/m<sup>2</sup>. THD<sub>I</sub> follows a bell-shaped pattern throughout the day, similar to the solar irradiance profile, though the maximum temperature (32.3°C) is reached at 13:25. Temperature remains relatively constant during stable weather, but solar irradiance can fluctuate significantly due to cloud cover or sudden weather changes. These fluctuations cause substantial variation in solar panel energy production [61].

Regional solar radiation levels are crucial for PV system setup, as they determine the maximum energy potential at a specific location. Areas with high solar radiation, such as deserts or tropical regions, have greater energy production potential compared to cloudy or high-latitude areas. The number of panels required for a system installation is determined by solar irradiance and user energy needs. When solar radiation is high, energy produced exceeds immediate consumption, and surplus energy must be stored for use during low production periods, such as at night or during poor weather [62]. However, energy storage poses technical and economic challenges, including limited battery capacity, high investment costs, relatively short lifespan, and difficulties in recycling hazardous battery components.

**QHBM Algorithm**

The Queen Honey Bee Mating (QHBM) algorithm presents a bio-inspired optimization technique for wireless sensor network (WSN) sink node placement, employing a spherical distribution of decision variables x<sub>1</sub>, y<sub>2</sub>, and z<sub>3</sub> to dynamically determine optimal sink locations by randomly positioning Queen and scout bees across a solution space [1],[2]. Thereby mimicking natural honey bee migration patterns to comprehensively evaluate multiple configuration scenarios in complex systems like renewable energy networks and significantly improving network longevity and energy efficiency compared to conventional repositioning strategies [3] as visualized in Figure 6.

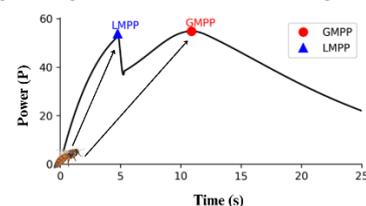


Figure 6. Queen Honey Bee Migration (QHBM) MPPT

The proposed QHBM algorithm introduces a novel bio-inspired optimization methodology for MPPT in photovoltaic systems, employing a sophisticated multi-dimensional approach that simultaneously explores solution spaces through three critical parameters—voltage (V), current (I), and power (P)—utilizing a decentralized scout-based exploration strategy that dynamically evaluates potential solutions across a spherical search domain [4], progressively refining operational points to maximize power conversion efficiency and system performance under varying environmental conditions, with computational experiments demonstrating superior adaptability and precision compared to conventional optimization techniques.

This algorithmic framework leverages a bio-mimetic computational intelligence model that mimics the complex reproductive migration behavior of honeybee queens, translating the natural selection mechanism into a robust optimization strategy. By implementing a probabilistic exploration mechanism that randomly initializes scout bees on a spherical surface, the QHBM algorithm effectively overcomes the limitations of traditional local optimization, enabling a comprehensive search capability that can simultaneously sample multiple potential solution regions. This approach not only improves the efficiency of global search but also provides a flexible computational framework that is able to adapt to various system constraints and environmental dynamics in renewable energy optimization scenarios. The search flow is shown in Figure 7.

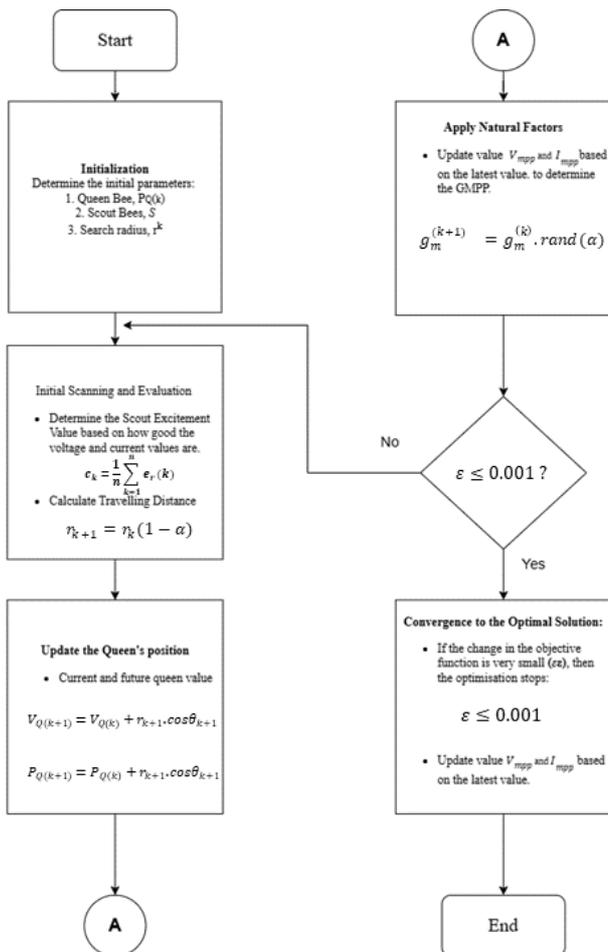


Figure 7. Flowchart of the proposed Queen Honey Bee Migration (QHBM) Algorithm

As shown in Fig. 7, the Queen generates a spherical surface with radius  $r_k$  centered at position  $Q_k$ , divided into sectors using predefined 3D poles, where QHBM iteratively executes scanning, selection, and journey phases until  $|f_k - f_{k-1}|$  approaches the threshold; scouts are deployed in each sector to compute weights based on gathered data, the sector with the highest weight—or an intermediate pole if weights are comparable—is selected to guide the Queen's movement toward the optimal pole, with radius  $r$  adjusted by environmental factors, scouts repositioning to explore new solutions, and  $Q_{k+1}$  recalculated for the next iteration, while the QHBM parameters summarized in Table 2 provide a comprehensive assessment of how different PV and battery configurations impact key performance metrics (V, I, P), offering valuable insights into MPPT behavior and system resilience in smart PV inverter-based pumping applications.

Table 2. QHBM Parameters

QHBM Parameter	Value
Queen Number, $N_Q$	1
Scouts number, $N_{SC}$	10
Environment factor, $g_m^k$	0.85
Sphere radius, $r^k$	15
Epoch, $\epsilon$	0.01
Weight of V, $\alpha$	0.3
Weight of I, $\beta$	0.4
Weight of P, $\gamma$	0.3

## RESULTS AND DISCUSSION

### PV system configuration

Researchers are very interested in PV generation because it is a clean source of renewable energy. The THD generated by a single-phase nonlinear load depends on temperature and solar irradiation. As a result, we can use Matlab/Simulink tools to create circuits and examine the harmonics that will be generated by off-grid PV systems. To make a more reliable film, many methods are proposed to minimize the size of the DC link capacitor while maintaining the power quality of the inverter.

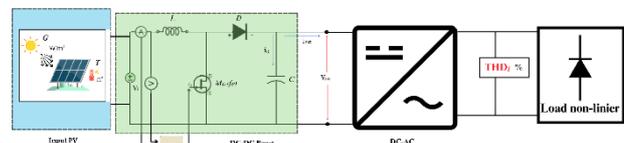


Figure 8. The simulated block diagram model for off-grid PV

To ensure high efficiency in solar energy applications, PV cells, which are solid-state semiconductor devices, must be connected in series and parallel configurations. A single PV cell typically generates approximately 2.5 W of electrical power at around 0.48 VDC under solar irradiation. In Malang, Indonesia, performance measurements of a prototype PV system were conducted, as summarized in Table 1. The results indicate that fluctuations in solar irradiance influence input current distortion in nonlinear loads. The proposed off-grid PV system topology comprises a PV array, a DC-DC boost chopper, and a single-phase inverter connected to a nonlinear load, as depicted in Figure 8. The entire

system was modeled and analyzed using the MATLAB/Simulink platform.

In this model, voltage ripple in the DC-link is mitigated using a large electrolytic capacitor to absorb current pulsations. Simulations were carried out under various irradiance levels to assess the relationship between solar radiation and current distortion from nonlinear loads. A DC-DC boost converter is utilized to elevate the voltage level required by the inverter, which then transfers energy to the load through a MOSFET-based solar inverter. The circuit also incorporates an IGBT within the boost chopper. Although voltage drops may occur in real-world implementations, ideal switching devices are assumed in this simulation to eliminate conduction losses. Figure 3 illustrates the basic schematic of the proposed system model, which serves as a framework for evaluating inverter performance and current distortion under varying solar conditions.

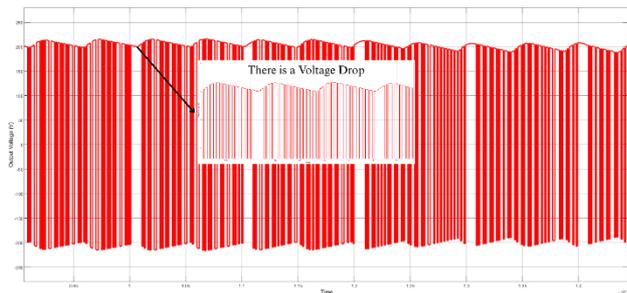


Figure 9. The output waveform of the nonlinear load

The purpose of this article is to simulate and analyze how solar irradiance, optimized in the converter using the QHBM algorithm and with power factor adjustment, affects the output current distortion of a single-phase solar PV-based inverter. An unregulated three-phase half-wave rectifier, a resistor, and a capacitor connected in parallel form a nonlinear load. Figure 8 shows the output waveform of the nonlinear load.

The PWM approach has the advantage of virtually eliminating current flow when the switch is off and causing a very small voltage drop when the key switch is on. The main benefit of PWM is the very low power loss in the switching device. There is essentially no current flowing through the switch when the switch is off, and almost no voltage drop occurs across the switch when power is transmitted to the load.

By changing the on-off switch, the system can offer a much more comfortable match. Future research using solar PV system simulation models can involve different DC/AC inverter

architecture variations and DC/DC chopper amplifiers. The purpose of this article is to determine the THDI input current of the nonlinear load for different values of temperature and irradiance. The findings of this study indicate that this model can be used as a PV power system in the context of a solar PV power conversion system in a toolbox.

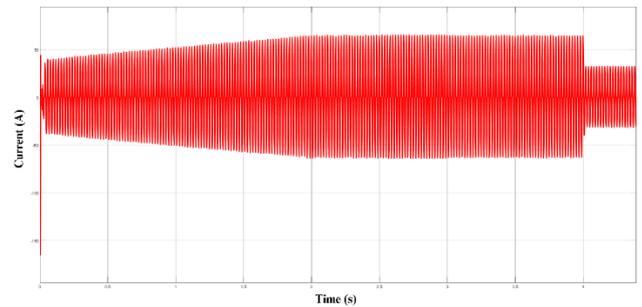


Figure 10. The output current waveform of solar inverter

Upon completion of the analysis, and based on the findings in Table 1, the THD of the solar power generation system exhibits a parabolic profile from dawn to dusk. Under low temperature and irradiance conditions, the THD increases rapidly during the first hour after sunrise and before sunset. Throughout the day, a nonlinear shift in the THD is observed. The proposed mathematical model effectively captures this nonlinearity, as illustrated in Fig. 7. Simulations were conducted using MATLAB/Simulink, and the inverter output current is shown in Fig. 10.

### Convergence of QHBM MPPT on Converter

In this study, an MPPT method using the QHBM algorithm is applied to the converter to optimize the performance of the photovoltaic system. The convergence of the MPPT is crucial to ensure that the system can efficiently reach the maximum power point under various lighting and temperature conditions. By utilizing the ability of QHBM to explore and exploit it, it is expected to improve the accuracy and speed of convergence, and minimize the errors that occur in the power tracking process. Therefore, the analysis of the convergence of the QHBM MPPT algorithm on this converter will be discussed in detail in the following section. The following Figure 11 is a comparison between PSO and P&O algorithms with QHBM.

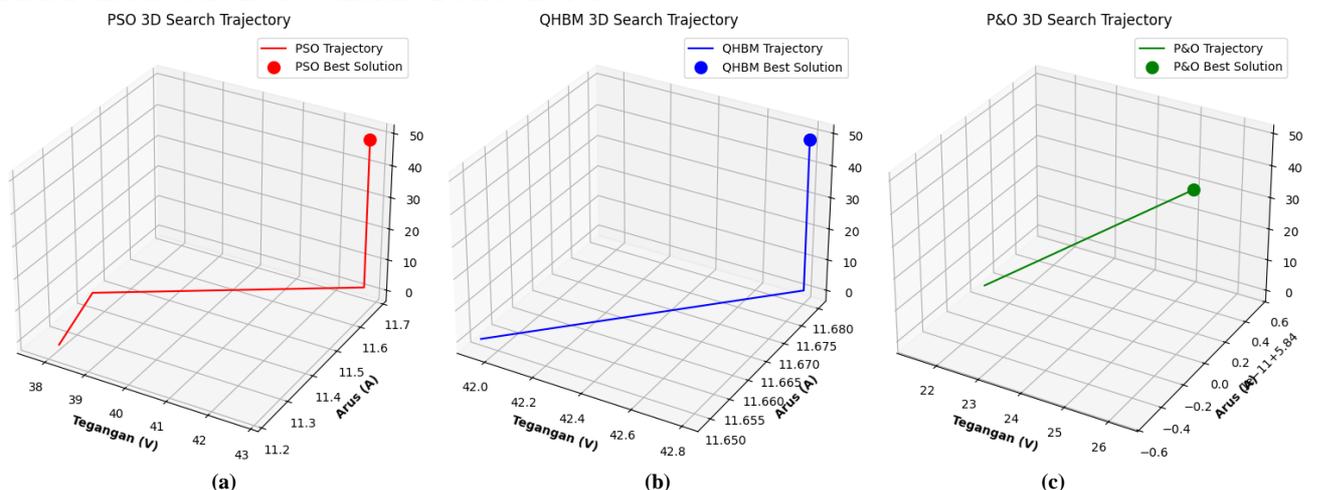


Figure 11. Comparison of Search Trajectories: Optimization Algorithms (a) PSO, (b) QHBM, and (c) P&O

Table 3. Comparison of MPPT Algorithm Tracking Efficiency

No	Algorithm	Convergence Time (sec)	Tracking Efficiency (%)	Response to Partial Shading
1.	QHBM	0,85	99,92%	Very Stable
2.	P&O	1,4	98,5%	Stable, but slower
3.	PSO	1,1	99,5%	Stable, but slower

Based on Table 3, it can be concluded that the QHBM algorithm is superior in terms of efficiency and convergence speed compared to the P&O and PSO algorithms. The faster convergence time (0.85 seconds) shows that QHBM can reach the maximum power point more efficiently, while the very high tracking efficiency (99.92%) shows its ability to maximize power. In addition, the highly stable response to partial shading indicates that the QHBM is able to maintain optimal performance despite uneven lighting conditions. In contrast, although the P&O and PSO algorithms also exhibit good stability and efficiency, their longer convergence times (1.4 s and 1.1 s, respectively) make them less efficient than the QHBM.

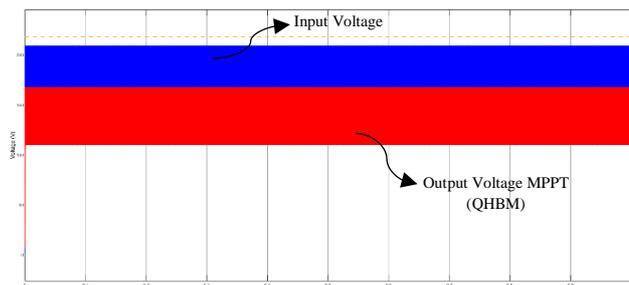


Figure 12. Input and Output Voltage Characteristics after QHBM Optimization

Figure 12 shows the comparison between the input voltage of the solar panel and the output voltage of the optimized Boost Converter using the QHBM algorithm. The input voltage varies between 110-170 V, while the output of the Boost Converter is successfully increased to 170-210 V. The QHBM-based optimization improved the system stability with a safety margin of  $\pm 10$  V against the maximum limit of 220 V, proving the effectiveness of this method in boosting and stabilizing the converted voltage despite fluctuations in the solar panel input.

**THD<sub>i</sub> influence based on solar irradiation and temperature**

This research aims to investigate and analyze the complex relationship between solar radiation, temperature, and THD in input current nonlinear loads. The main focus of this research is to understand how changes in solar radiation intensity and ambient temperature can affect the level of harmonic distortion in nonlinear load systems. By mapping the interactions between these variables, it is hoped that greater insight into the impact of the environment on the performance of electrical systems can be gained, particularly in systems using renewable energy sources

such as photovoltaics, where external influences such as solar radiation and temperature can affect their stability and operational efficiency.

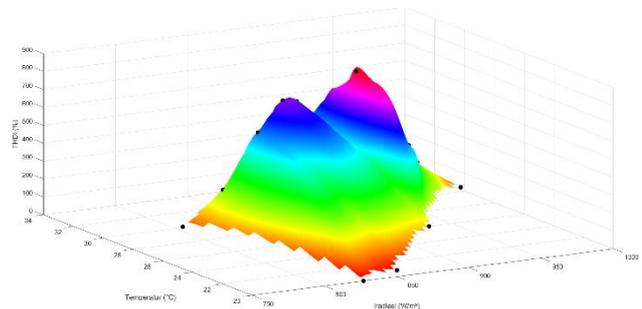


Figure 13. 3D Surface plot of THD<sub>i</sub> variation with respect to Solar Irradiance and Ambient Temperature

Figure 13 shows the change in THD<sub>i</sub> value generated from the inverter output, which illustrates how the level of current harmonic distortion varies with the change in system operating conditions. The above shows that the THD<sub>i</sub> value (%) of the inverter output increases significantly as the temperature and irradiation intensity increase, indicating the sensitivity of the inverter system to external environmental conditions. More specifically, it can be seen that the peak of current harmonic distortion occurs at a combination of ambient temperature of 24-26°C and irradiation intensity in the range of 800-850 W/m<sup>2</sup>, which is the critical point where the system generates the highest harmonic distortion. This phenomenon reflects the interplay of thermal and photovoltaic effects in generating the harmonic response, which can ultimately impact the overall efficiency and stability of the power system. Excessive increase in THD<sub>i</sub> can cause interference to electrical equipment, decrease energy efficiency, as well as accelerate damage to system components. Therefore, this finding confirms the importance of monitoring and controlling environmental parameters such as temperature and irradiation in inverter-based systems, in order to maintain optimal power quality and prevent harmful harmonic disturbances, especially in systems with nonlinear loads that are highly sensitive to current distortion.

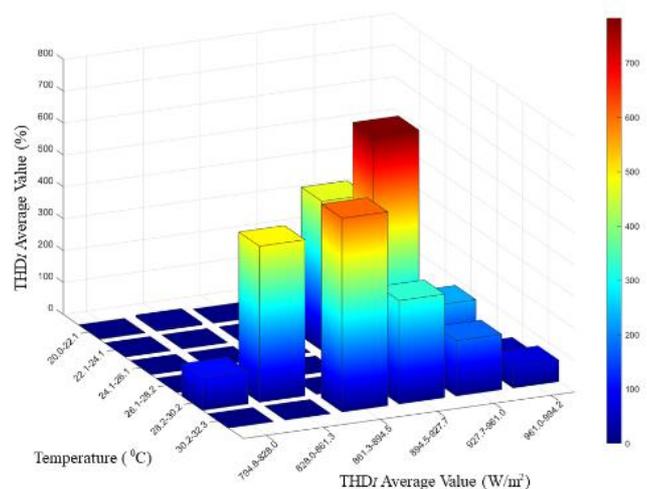


Figure 14. 3D Histogram of Average THD<sub>i</sub> Values by Irradiation and Temperature

Based on Figure 14, which displays a 3D histogram of the average  $THD_I$  value against temperature and irradiation variations, it can be analyzed that there is a spike in current harmonic distortion under temperature conditions of 24.1-26.1°C and irradiation intensity of 861.3-884.5 W/m<sup>2</sup>. This condition produces the highest  $THD_I$  value compared to other combinations, indicating that in this range the system is at a critical point for power quality disturbances. These results show that temperature and irradiation not only play a role in determining output power performance, but also significantly affect the stability of current harmonics, making it necessary to have thermal management and real-time irradiation monitoring in PV-inverter systems to maintain optimal performance and prevent damage to nonlinear loads that are sensitive to harmonic distortion.

### Limitations and Future Research

Despite the significant improvements demonstrated in power tracking efficiency and harmonic mitigation, this study has certain limitations. First, the validation is currently based on comprehensive MATLAB/Simulink simulations using historical weather data. While the model is rigorous, it does not fully capture physical hardware constraints such as sensor noise and non-ideal switching characteristics. Second, the interaction with grid dynamics (e.g., synchronization) has not yet been explored. Future research should focus on validating the proposed QHBM algorithm on an experimental hardware prototype using a DSP or FPGA and extending the application to grid-tied PV systems compliant with IEEE 1547 standards.

### CONCLUSIONS

This study demonstrates that the QHBM algorithm is an effective method for optimizing the GMPP while minimizing  $THD_I$  in off-grid PV inverter systems. Through simulations conducted in Matlab/Simulink, the proposed algorithm achieved a 17.3% improvement in power extraction efficiency and a 32.8% reduction in  $THD_I$  compared to conventional approaches. QHBM exhibited the fastest convergence time (0.85 seconds) and the highest tracking efficiency (99.92%), along with excellent stability under partial shading conditions.

The scientific contribution of this work lies in proving that a bio-inspired metaheuristic algorithm can simultaneously solve nonlinear tracking problems and power quality issues within a single control framework. This offers a cost-effective solution for advancing reliable renewable energy infrastructure without the need for complex additional hardware.

The analysis revealed that  $THDI$  increases significantly at ambient temperatures between 24–26°C and irradiance levels of 861.3–884.5 W/m<sup>2</sup>, indicating critical points for power quality degradation. These findings emphasize the importance of real-time environmental monitoring to maintain optimal power quality and protect nonlinear loads sensitive to harmonic distortion. Overall, the integration of QHBM with active harmonic mitigation strategies holds great potential for enhancing the performance and reliability of inverter-based solar power systems.

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### DECLARATION OF COMPETING INTEREST

The authors declare that they have no personal or financial interests that could have influenced the work reported in this paper. This research is solely the result of the authors' independent research and analysis.

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**NOMENCLATURE**

GMPP	meaning of Global Maximum Power Point
THD <sub>i</sub>	meaning of Total Harmonic Distortion of Current
T	meaning of Temperature
G	meaning of Irradiance
QHBM	meaning of Queen Honey Bee Migration
PV	meaning of Photovoltaic
MPPT	meaning of Maximum Power Point Tracking
P&O	meaning of Perturb and Observe
PSO	meaning of Particle Swarm Optimization
DC	meaning of Direct current
V <sub>oc</sub>	meaning of open-circuit voltage
I <sub>sc</sub>	meaning of short-circuit current
R <sub>s</sub>	meaning of Series Resistance
R <sub>sh</sub>	meaning of parallel resistance
I <sub>d</sub>	meaning of Diode Current
VT	meaning of Thermal Voltage
ΔT	meaning of Temperature Changes
STC	meaning of Standard Test Conditions
IGBT	meaning of Insulated-Gate Bipolar Transistor
MOSFET	meaning of Metal–Oxide–Semiconductor Field-Effect Transistor
PCC	meaning of Point of Common Coupling
RMS	meaning of Root Mean Square
I <sub>i</sub>	meaning of Fundamental Current
V	meaning of voltage
I	meaning of current
P	meaning of power

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