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Design and Validation of BAT Algorithm-Based Photovoltaic System Using Simplified High Gain Quasi Boost Inverter

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Abstract: Owing to the intermittent nature of renewable energy systems, an improved power extraction technique and modernized power modulators are to be designed to overcome power quality challenges. Attesting to this fact, this work aims to enhance the efficiency of the photovoltaic (PV) system using the BAT algorithm (BA) and enhances the overall performance of the system using modified inverter topology. Specifically, a new power electronic modulator, i.e., a simplified high gain quasi-boost inverter (SHGqBI), is implemented to eliminate the downsides of the conventional system. The proposed inverter reduces the additional components that can condense the volume of the design with reduced conduction and switching losses. The combination of BA-based PV rated 250 W and novel inverter configuration pick the global peak power with enhanced power quality. Notably, BA extracts the maximum power from the panel meritoriously with about 98.8% efficiency. This is because BA uses the global input parameters to track the maximum power of the PV panel, whereas other conventional maximum power point tracking (MPPT) techniques used limited parameters. Further, the current and voltage total harmonic distortion (THD) of the proposed inverter are recorded, which show a commendable range of 2.7% and 10.2%, respectively. In addition, the efficiency of the inverter is found to be 97%. Consequently, the overall system efficiency is calculated and found to be 97.9%, providing greater advantages over a conventional system. The system is mathematically modelled using MATLAB/Simulink and validated through an experimental setup with the laboratory prototype model.

Keywords: BAT algorithm; SHGqBI; photovoltaic; boost inverter; total harmonic distortions

1. Introduction

Global modernization is one of the key driving forces for a continual increase in energy demand. Because of population and technological growth, energy consumption increases significantly, which influences environmental pollution [1,2]. The energy efficiency initiatives are consistently identified as the lowest impact and cost-effective means of meeting energy needs. The increase in environmental pollution and the cost of fossil fuels have become a challenging factor without compromising the ecology. Among the environmentally friendly renewable energy systems (RESs), solar photovoltaic (SPV) has attracted attention over the decades. To attain the maximum power point tracking (MPPT), modernized techniques are being adopted in the solar energy system using various methods and algorithms. Moreover, the converting system takes another important role in solar

applications for stand-alone and grid applications. Further, the renewable energy source integrated with the electric grid system is referred to as renewable energy distributed generation (REDG). It is more sensitive to harmonics generation in both domestic and industrial applications.

1.1. Literature Survey on MPPT Algorithms

There are several MPPT algorithms available for the SPV system, but it must have fast tracking responses, robust control, simple coding, and high power output. Because SPV is a non-linear dynamic system, challenges like steady-state oscillation diverge tracking direction and the inability to detect the global peak during partial shading are the common limitations. Therefore, researchers are aiming to provide robust control by replacing the conventional MPPT techniques with advanced techniques like perturb and observe (P&O), particle swarm optimization (PSO), and grey wolf optimizer (GWO). Jubaer Ahmed et al. [3] suggested an enhanced adaptive P&O (EA-P&O) to mitigate the limitations of conventional techniques. Considering the environmental impact, the EA-P&O used an intelligent prediction method to track the global peaks. The authors also compared the effectiveness of the algorithm with other techniques like modified incremental conductance (MIC), artificial bee colony (ABC), cuckoo search (CS) and hybrid ant colony optimization, and P&O (ACO-P&O). The EA-P&O was found to be a simple structure and does not require any additional sensor like temperature and irradiance. However, the efficiency of the proposed technique was not validated with the experimental study. Further, a blend of PSO and DE (differential evolution) was implemented for hybrid optimization [4]. Notably, PSO and DE were adopted for unique tasks, i.e., odd and even iterations, respectively. However, it exhibited the requirement of large iterations for convergence that could produce a large fluctuation of power during GMPP (global maximum power point) before attaining the steady-state. A modified hill-climbing (HC) algorithm [5] recently demonstrated by researchers overcame challenges like the dynamic speed of response and steady-state tracking efficiency when compared with the conventional HC technique. It attained a dynamic speed of response of about 75% and a steady-state accuracy of 99.8%. However, the experimental validations of the results were not demonstrated. Further, PSO was one of the techniques used for fast-tracking of global maximum points with higher efficiency. Specifically, the improved PSO (IPSO) [6] achieved better performance against PSCs (partial shading conditions). The GWO algorithm was a better option for convergence to the optimal region through iterations, but exhibited lesser performance against fast-tracking applications [7]. In accordance with the solar irradiation conditions [8–10], the MPPT techniques are related to the uniform and non-uniformity of the solar irradiances. It is an essential need to improve the performance of conventional MPPT techniques during uniform and uncertain situations [11,12]. In a nutshell, advanced MPPT techniques are required to achieve global maximum power point tracking (GMPPT). Based on the survey report, it is concluded that the selection of MPPT techniques may have both benefits and limitations.

The principal shortcoming of the above-mentioned MPPT technique is low trade-off exploration-exploitation. During the optimization process, it may exhibit large operating power fluctuations, specifically against PSCs. The BAT algorithm (BA) adopts a frequency-tuning procedure to raise the diversity of the solutions in the population [13]. Moreover, it offers an automatic switching operation between explorative moves and exploitation during the MPPT process. It has a fast convergence rate to attain GMPP without premature convergence. Moreover, the combination of global and local search supports the tracking system to maintain less oscillation with better dynamic characteristics before the global peak.

1.2. Literature Survey on Converters and Inverters

DC–DC converters play an important role in PV systems [7]. The high gain DC/DC converters—both isolated and non-isolated types—have more advantages in solar applications, but the major limitation is the usage of a high number of components [14]. Therefore,

converters with high voltage gain and fewer components are preferred. For high voltage gain, various DC–DC converters are available, particularly the cascaded topologies that produce high voltage gain outputs. The quasi-Z source DC/DC converters provide high voltage gain output, but have the limitation of a cascaded type with more components. Farhad Abbasi et al. [14] implemented a modified switched capacitance q-Z Source DC–DC converter for the low voltage stress application. Moreover, a qZS DC–DC converter adapted a VL cell [15] that had the boosting capacity up to five times for low duty cycles. However, high voltage stresses and more components in the converter part lead to an increased volume. Similarly, a high voltage-gain converter was used that employed a qZS (Quasi Z source) network and a voltage multiplier cell [16]. Nonetheless, it exhibited similar drawbacks; a higher number of components were adapted. The qZS DC–DC converters-based SL (switched inductance) and SC (switched capacitance) configurations [17,18] were used to enhance the voltage gain, but the voltage gain enhancement was not significant. In the family of switched ZSC (impedance source converter)/switched q-Z source converter [19], the boost factor was increased by avoiding the instability caused by inductors. Further, multiport DC–DC converters [20] were widely used in hybrid applications. The authors validated the results through the experimental study of the converter for renewable energy systems. The DC link voltage, battery voltage, and currents are regulated. A quasi-resonant series DC–DC converter [21] was designed for wide input application and load regulation. The ripple-free voltage output with continuous input current over the entire voltage and load variation without additional components were achieved, but the efficiency of the system needs to be improved. Consolidating all these inferences, there is a need to demonstrate a lower volume (reduced components) and highly efficient converter for PV applications.

In domestic and industrial applications, the dc output from the SPV must be converted to AC using inverters. The selection of inverters is purely based on sinusoidal output waveforms. The output voltage and currents with ripple-free, zero harmonic distortions (HDs), and unity power factor are always preferred to obtain the maximum system efficiency. Owing to power conversion stages using energy storage components and variable loads, zero HD is not possible. These functional requirements can achieve the maximum value by selecting a proper power modulator and control techniques. The inverters for solar energy conversion applications require maintaining various parameters including bus voltage control [22], peak current control [4], common-mode current/voltage elimination [23,24], and reduced harmonic distortions [25]. Notably, by reducing the size of the capacitor, second-order harmonics increase, and this can be mitigating by controlling the bus voltage [22]. This was achieved by employing a digital finite impulse response (FIR) filter without additional components. The digital FIR filter requires approximations in design and the power stages are assumed to be ideal. Practically, these ideal factors might affect the transient conditions of the system. Yoash Levron et al. [24] introduced a novel control method that increased the efficiency of the system by generating a low peak current. At both high power and low power, the switching frequencies modulated to minimize the RMS (root mean square) current and switching losses. However, this variable switching frequency required a control design, i.e., digital FIR, which again increases the complexity. Further, a novel transformerless inverter [23] was used to produce no varying common mode current with high efficiency. To produce no varying common mode current, the new topology was employed, consisting of six switches and two diodes for the 1Ø system. However, it increased the size of the power modulator and design complexity. Moreover, the increased number of switches lowered the practical efficiency of the system. Meraj et al. [24] suggested a quasi Z-source inverter with a novel pulse width modulation (PWM). It reduced the common mode current by adding additional semiconductor switches. Consequently, the total harmonic distortion (THD) was better, but the efficiency of the inverter decreased owing to additional switches. Considering the THD for a grid side inverter, a multi-harmonic decoupling cell phase-locked loop (MHDC PLL) was designed [25]. This frequency adaptive design reduced the harmonics even during

the disturbances, but is considered to be a complex integral design with inner closed-loop control. Therefore, a simplified inverting strategy with improved efficiency and a reduced THD rate needs to be designed for SPV applications.

1.3. Contributions

From the above literature studies, the control selection of various power conversion topologies like PV system, DC–DC converter, and the inverter is very important for a solar PV interfaced with a grid system or standalone applications. Consolidating all the inferences from literature surveys, this work proposes an SPV system that is controlled using the BAT algorithm for generating the global maximum power. Further, a novel SHGqBI is developed to reduce both the voltage stress and current stress without the implementation of additional components requiring ZVS (zero voltage switching) or ZCS (zero current switching) techniques. Moreover, the proposed converter uses a lower number of active and passive components that reduce the switching losses. Based on the proposed design, this work aims to attain the following objectives:

- To obtain efficient SPV conversion by implementing the mathematical model of BA for a 250 W solar panel;
- To improve the efficiency of the inverter using a novel SHGqBI for an SPV system, thereby reducing the voltage and current stress without additional components;
- To reduce the total harmonic distortion at the load side and provide high efficiency;
- To validate the proposed system using the experimental setup.

The remainder of the work is organized as follows. Section 2 describes the modelling of the proposed system such as PV, inverter, and BA algorithm. Section 3 demonstrates the performance of the proposed system using experimental and simulation set up. Further, a comparative analysis is carried out in Section 4 to validate the simulated results with the experimental outcome and existing works. Finally, Section 5 concludes the work with key outcomes.

2. Modelling of the Proposed System

Figure 1 demonstrates the overall configuration of the proposed system consisting of PV arrays, DC–DC converter, and inverter. For better utilization of power from the PV array, the BAT algorithm is adopted and the harvested power is converted into AC using a novel inverter configuration SHGqBI that injects power into the grid-connected applications.

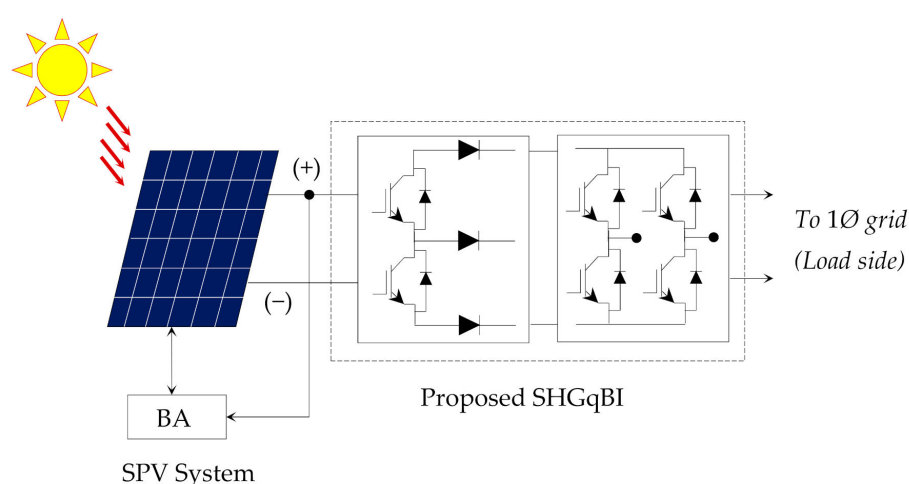


Figure 1. Block diagram of the proposed topology: BA, BAT algorithm; SPV, solar photovoltaic; SHGqBI, simplified high gain quasi-boost inverter.

2.1. SPV System

There are numerous PV models described in the literature, specifically the single diode model and two-diode model [26]. The main purpose of the model is to investigate the characteristics of PV modules that can be integrated into the virtual platform. The characteristic of SPV is simulated using a general equivalent circuit of a single diode configuration, as described in Figure 2. The term I_{ph} denotes a photocurrent (source); G represents the irradiation; R_L denotes the load resistance; and R_p and R_s are parallel and series resistances, respectively. Typically, the value of R_p is larger than R_s , hence these parameters are ignored to simplify the study. Essentially, a group of PV cells and modules are arranged in series and parallel to form PV arrays that are adapted to produce electricity in SPV generation systems.

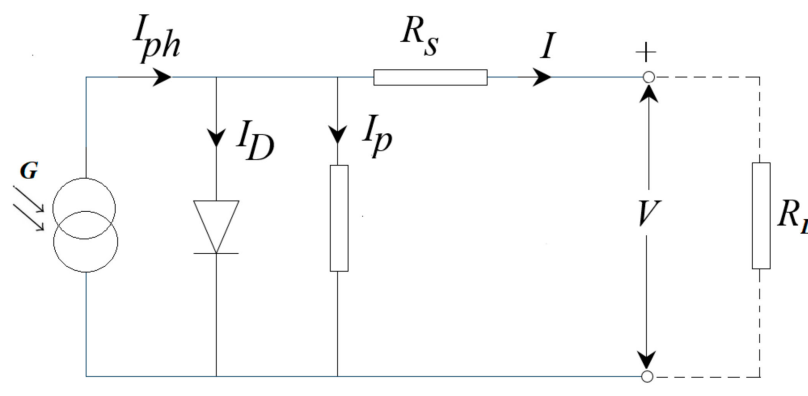


Figure 2. Equivalent circuit of the PV cell.

The V–I characteristic equation of a PV cell is considered as a module and the generated photocurrent (I_{ph}) can be derived as follows:

$$I_{ph} = [I_{sc} + K_i(T - 298)] \times I_r / 1000 \quad (1)$$

where the term I_{sc} represents the short circuit current in Ampere; K_i denotes the short-circuit current of a PV cell at 25 °C with the power density of 1000 W/m²; T states the working temperature in Kelvin; and I_r represents the solar radiation on the panel in W/m². The reverse saturation current of the module can be computed using Equation (2).

$$I_{rs} = I_{sc} / [\exp(qV_{oc}/N_s k n T) - 1] \quad (2)$$

where q defines the electron charge, i.e., 1.6×10^{-19} C; V_{oc} states the open-circuit voltage in Volts; N_s symbolizes the series-connected cells; n represents the diode ideality factor; and k states the Boltzmann's constant, i.e., 1.3805×10^{-23} J/K. The complete design parameters of the SPV configuration are shown in Table 1.

Table 1. Design parameters of the solar photovoltaic (SPV) module.

Parameters	Value	Units
Isolation	1000	W/m ²
Temperature	32	°C
No. of parallel cells	2	Nos
No. of series cells	216	Nos
Output power	250	Watts
Open circuit voltage	43.0	Volts
Short circuit current	6.70	Ampere

The analytical modelling of the SPV system is verified using I–V and P–V characteristics, displayed in Figure 3.

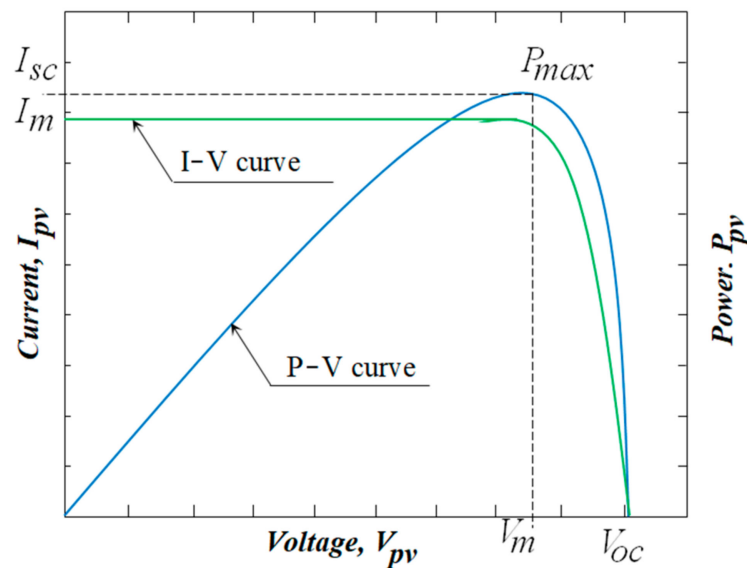


Figure 3. Characteristics plot of solar PV.

2.2. Proposed SHGqBI

The modified qSBI is adopted with a reduced number of passive elements as compared with the Z-source inverter. It is an essential attempt to reduce the size of the inverter, because semiconductor devices occupy a lesser volume than the passive elements. In this work, the proposed topology is simplified by replacing the DC-link components with an embedded DC–DC converter and single-phase inverter. Because of this modification, the design of the conversion topology becomes easy. Figure 4 represents the proposed SHGqBI, and its modes of operation are classified as follows:

- Mode 1: Inverter stage 01.
 - (A) Non-shoot through mode.
 - (B) Shoot through mode.
- Mode 2: Inverter stage 02.
 - (A) Non-shoot through mode.
 - (B) Shoot through mode.

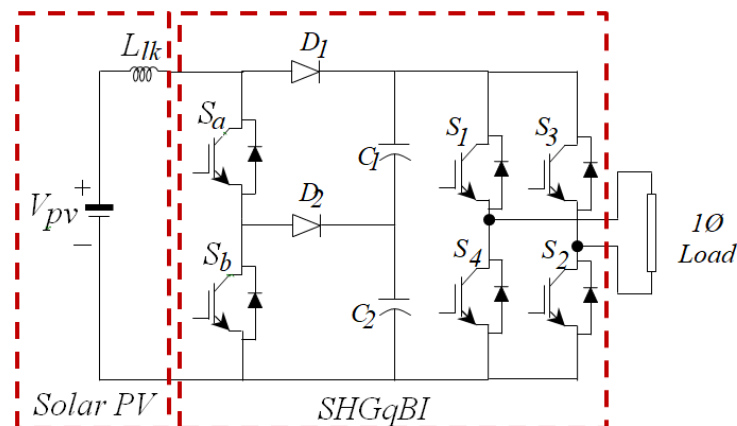


Figure 4. Circuit diagram of the proposed SHGqBI.

The inverter is operated to generate a sinusoidal output waveform at a fundamental frequency of 50 Hz and a switching frequency of 20 kHz to power the domestic appliances. The proposed inverter is embedded with a DC–DC converter, which is operated at a frequency of 500 Hz to provide a continuous dc-link voltage without the link components. The non-shoot through and shoot through modes of the DC–DC converter are the same at both stages of the inverter operation. The embedded DC–DC converter during each inversion cycles keeps the voltage constant across the capacitors C_1 and C_2 . Thus, the capacitors supply energy to the inverter simultaneously. The design parameters of the proposed SHGqBI are shown in Table 2.

Table 2. Proposed simplified high gain quasi-boost inverter (SHGqBI) parameters.

Parameters	Symbols	Values
Leakage inductance	L_{lk}	570 mH
Capacitance	C_1 & C_2	10 μ F
Converter switching frequency	f_s	500 Hz
Duty cycle	δ	0.65
Inverter fundamental frequency	f_{inv-0}	50 Hz
Inverter switching frequency	f_{inv-s}	20 kHz

2.2.1. Mode 1 [$0 \leq t \leq t_1$]: Inverter Non-Shoot through Mode

In this mode (Figure 5a), the inverter is operated at a frequency of 20 kHz with a fundamental frequency of 50 Hz. The positive half cycle of the sinusoidal PWM inverter comprises the embedded dc–dc converter, operated at both non-shoot through and shoot through modes at a frequency of 500 Hz.

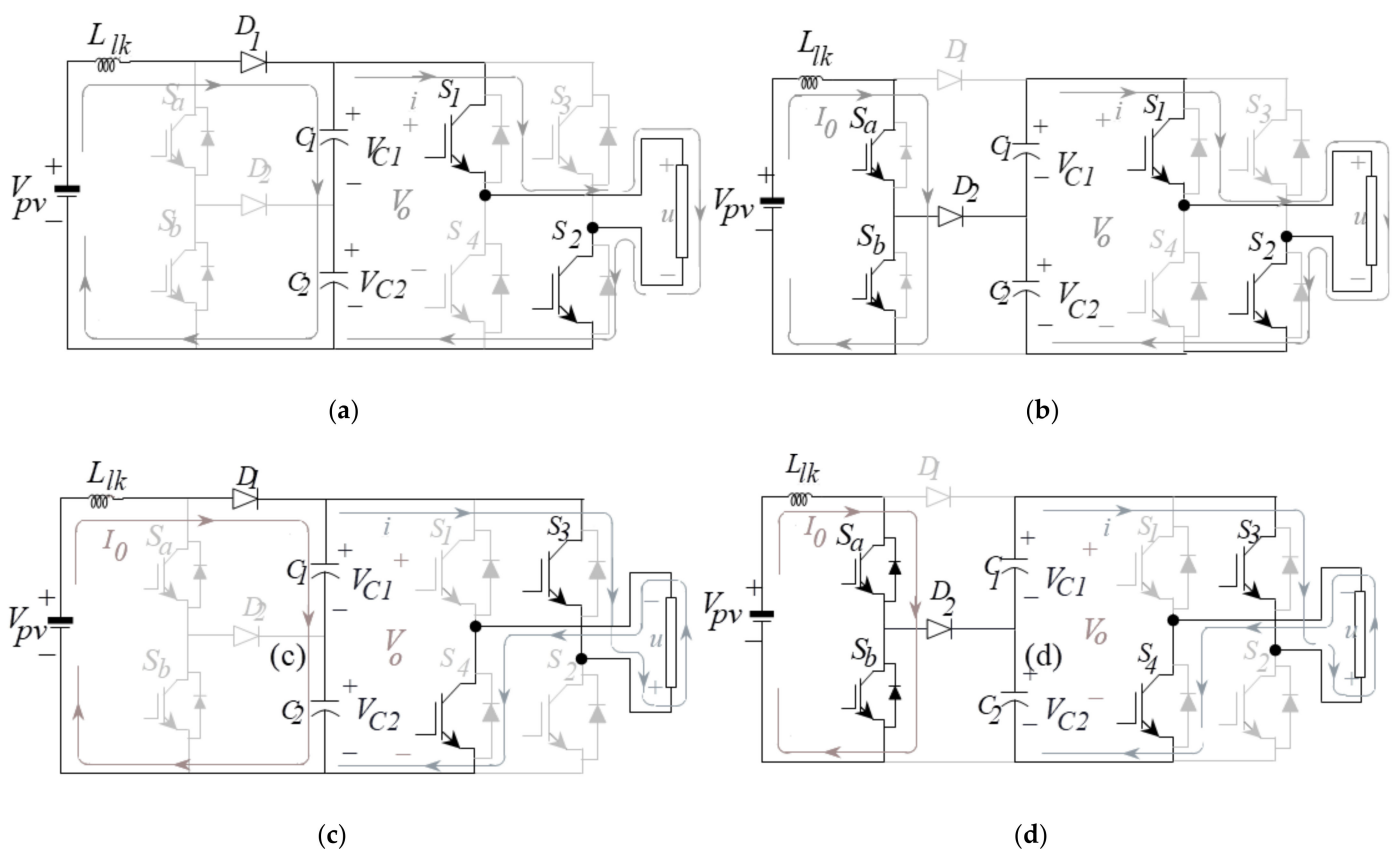


Figure 5. Modes of operation of SHGqBI: (a) inverter non-shoot through mode $0 \leq t \leq t_1$; (b) inverter shoot through mode $t_1 \leq t \leq t_2$; (c) inverter non-shoot through mode $t_2 \leq t \leq t_3$; and (d) inverter shoot through mode $t_3 \leq t \leq t_4$.

The switches S_a and S_b of the embedded dc–dc converter remain in OFF position. The input current (I_{in}) obtained from the solar panel flows through the leakage inductance (L_{lk}) and charges the capacitor C_1 and C_2 to a voltage of V_{c1} and V_{c2} , respectively. The capacitance voltages are equal and can be derived using Equation (7).

$$V_{c1} = V_{c2} = V_{in} \quad (3)$$

The voltages across the capacitors are derived as follows:

$$V_{c1} + \frac{1}{L} \int_{t_0}^{t_1} V_{lk} \cdot dt = V_{in} \quad (4)$$

$$-V_{c2} + \frac{1}{L} \int_{t_0}^{t_1} V_{lk} \cdot dt = -V_{in} \quad (5)$$

$$V_{c1} + \frac{1}{L} \int_{t_0}^{t_1} V_{lk} \cdot dt + V_{c2} - \frac{1}{L} \int_{t_0}^{t_1} V_{lk} \cdot dt = V_0 \quad (6)$$

$$V_{c1} + V_{c2} = V_0 \quad (7)$$

Using Equation (1), the output voltage can be formulated as follows:

$$\begin{aligned} V_{in} + V_{in} &= V_0 \\ 2V_{in} &= V_0 \end{aligned} \quad (8)$$

From Equation (8), it is obtained that the output voltage during non-shoot through mode is double the input voltage. The gate current i_{gs} (i_{gsa} and i_{gsb}) is not applied during this mode. The leakage current i_{lk} charges the inductor L_{lk} during the previous mode of operation. Consequently, the inductor L_{lk} discharges the current through the diode D_1 , and can be formulated as below:

$$i_{D1} = \frac{I_{in}}{n+1} \quad (9)$$

The diode D_2 is reverse biased and the diode current i_{D1} falls to zero at $t = t_c$, such that the converter operates in continuous conduction mode (CCM).

The current charges the capacitors C_1 and C_2 to a voltage V_c equal to $V_0/2$, as represented in Equation (8). Then, the average voltage is expressed as follows:

$$V_c = \frac{V_0 + nV_{in}}{n} \quad (10)$$

where n states the number of steps and the current i_{sa} and i_{sb} through the switches is equal to zero.

2.2.2. Mode 1 [$t_1 \leq t \leq t_2$]: Inverter Shoot through Mode

In this mode (Figure 5b), the switches S_a and S_b are switched in the ON position. During this mode, the input is short-circuited and the current I_{lk} is allowed to circulate. The voltages across the switches are balanced and, therefore, the switching losses are reduced. Subsequently, the capacitors C_1 and C_2 discharge through the load. Therefore, the load voltage is maintained as defined in Equation (12). Consequently, the diode D_2 is forward biased to bypass the excess leakage current. During shoot through mode, switching frequencies and duty cycle are defined, i.e., $f_{s1} = f_{s2} = 500\text{Hz}$ and $\delta = 0.35$, respectively, to operate the switches. Then, the output voltage is expressed as follows:

$$V_0 = V_{c1} + V_{c2} \quad (11)$$

$$V_{c1} = V_{c2} = V_{in}$$

From the above equations, the output voltage can be computed using Equation (16).

$$V_0 = 2V_{in} \quad (12)$$

The current starts to flow through the inductor L_{lk} and charges the inductor. During this stage, the capacitor discharges through the load and maintains the peak voltage at the output. Then, the current through the switches S_a and S_b is derived as follows:

$$i_{sa} = I_{in} + \frac{V_{cr}(t_b)}{Z_2} \quad (13)$$

The leakage current is bypassed and discharged through the diode D_2 between $t_b \leq t \leq t_c$. It can be derived as follows:

$$i_{D2} = -\frac{V_{cr}(t_d)}{Z_2} \quad (14)$$

where Z_2 symbolizes the equivalent impedance of the converter at mode 2.

Mode 2 [$t_2 \leq t \leq t_4$]: This mode is very similar to mode 1, except for the inverter operation. The embedded dc-dc converter repeats the operation and the dc voltage across the capacitors is maintained. The non-shoot through mode (Figure 5c) occurs between $t_2 \leq t \leq t_3$ and the shoot through mode (Figure 5d) occurs between $t_3 \leq t \leq t_4$ during the negative half cycle of the single-phase inverter. The performance study of this model can be derived using the same equations as derived in mode 1. The performance characteristics of the proposed SHGqBI during two modes of operations in terms of waveforms are illustrated in Figure 6.

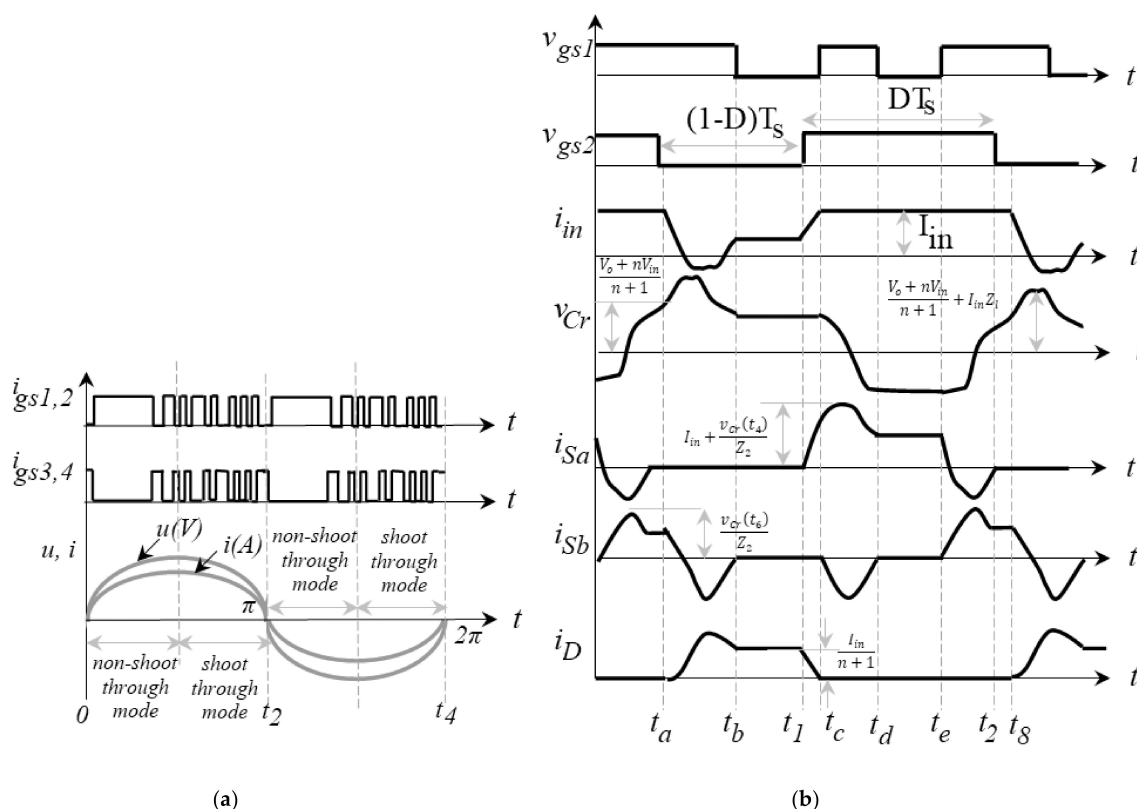


Figure 6. Waveforms: (a) inverter and (b) DC-DC converter.

2.3. BAT Algorithm for SPV

BA is a population-based optimization technique inspired by the echolocation characteristics of microbats in locating their foods. Among swarm intelligent optimizations, the fastest convergence can be obtained using BA. Similar to a bat's behavior, which echoes to prey using pulses and loudness, the BA follows the pattern.

The bats release impulsive sounds about 10 to 100 times per second. The released pulses are transmitted and reverted as an echo; bats decode the reverted data and translate it into beneficial info to scale the track of the prey. Moreover, this information provides the distance of the prey from the bat's position. This behavior can be decoded for low-dimensional engineering optimization problems, but is restricted for high-dimensional optimization owing to its tendency to converge very fast at initialization. In this work, a concept of MPPT on PV systems is adapted because it comprises a very low-dimensional engineering optimization problem.

The execution of the BA signifies the performance of bats as derivations and logic. It is implemented in a virtual platform using computer code to track the global peak for the optimization problem. The rate of pulses is considered between 0 (no pulse) and 1 (maximum pulses per second). The comprehensive steps of the proposed BA for maximum power point tracking are described as below:

Step 1: Using echolocation, bats distinguish their foods, obstacles, and distances.

Step 2: Initially, bats record their present position (d_i) and start flying randomly with velocity (v_i).

Step 3: They emit the pulses during searching of food with varying wavelength (λ) and loudness (A_0) at a fixed frequency ($f_{\min}$).

Step 4: Bats adjust their transmitting sound pulse parameters such as λ , f , and rate (r) based on the proximity of food between 0 and 1.

Step 5: The range of loudness is anticipated to vary from A_0 (largely positive) to $A_{\min}$ (minimum constant value).

Step 6: The product of transmitted sound pulses (f and λ) should be maintained at constant (i.e. range of $f_{\min}; f_{\max}$ corresponds directly to a range of $\lambda_{\min}; \lambda_{\max}$).

Step 7: For an effective searching scheme of BA during initiation, a larger value of wavelength is adapted and this can be lowered progressively for each successive step.

Initialization:

The BAT algorithm is mathematically modelled with the initial set values as below:

Speed of each bat $v_0^{1:n} = 0$;

Pulse frequency $f_0^{1:n} = 0$;

Pulse rate $r_0^{1:n} = 0$;

Loudness $A_0^{1:n} = 1$;

With this initialization, the bat population ratio $k = 1 : N_{BA}$

Where, N_{BA} = Bat population

The optimal duty ratio can be derived as follows:

$$d^{(k)} = 1 - \frac{(n - k + 1) * k_v}{n} * \frac{V_{OC}}{V_{DC}} \quad (15)$$

where

V_{DC} = DC link voltage,

V_{OC} = open circuit voltage,

n = total number of peaks,

k = order of duty ratio.

The output power (P_{out}) of the proposed system is determined from all the evaluated bats. If all bats are not evaluated, the order of the duty cycle is incremented by 1. The bat ratio is then updated and Equation (10) is repeated. With the bat evaluation, the best power is calculated from the initial bat population, given as below:

$$P_{best,0} = d_0^{1:N_{BA}} \quad (16)$$

The iterations are carried out with an increment of $i = 1 : Iterations$ and the value of k is again updated. The new bat positions are generated using the below equations:

$$A_i^{1:n} = \alpha A_{i-1}^{1:n} \quad (17)$$

$$r_i^{1:n} = r_0^{1:n} [1 - \exp(-\gamma i)] \quad (18)$$

These expressions are used to generate the new positions with the logic, for $k = 1:n$, if $P_i^{1:n} > P_{best}$, then $P_{best} = P_i^k$ and $d_{best} = d_i^k$. This iterative process is repeated to obtain the best power of the global tracking points. The complete description of the proposed algorithm is demonstrated in Figure 7.

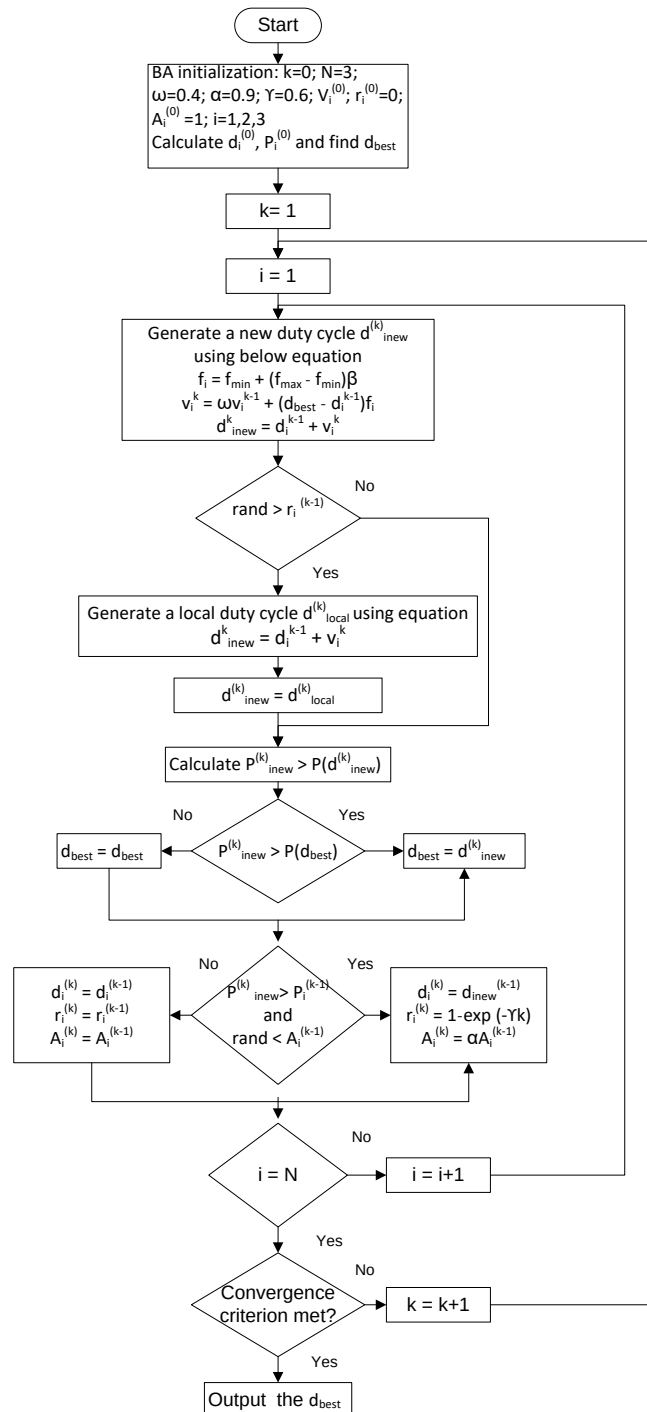


Figure 7. Flowchart of the proposed algorithm.

3. Results and Discussions

This section discusses the results of the proposed system in terms of two sides: (i) simulation and (ii) experimental results. In addition, the comparison and validation of the results are provided.

3.1. Simulation Results

The proposed system is mathematically modelled using the MATLAB Simulink. The system parameters are used as per the design values as mentioned in Section 2. The modelling tools are considered to be ideal at steady-state conditions. The input parameters for the SPV are designed to match the real-time values. The results obtained from the simulation modelling are explained below.

3.1.1. Solar PV

The mathematical modelling of SPV for 250 W is considered using the above design parameters. Further, the output characteristics of the SPV are illustrated in Figure 8. From Figure 8a, I–V characteristics show the values of short circuit current (i_{sc}) of 7.50 A, maximum current (i_m) of 6.70 A, maximum voltage (V_m) of 37.31 V, and open-circuit voltage (V_{oc}) of 43.0 V. Moreover, the maximum output power of the array is observed from P–V characteristics (Figure 8b), i.e., 250 W.

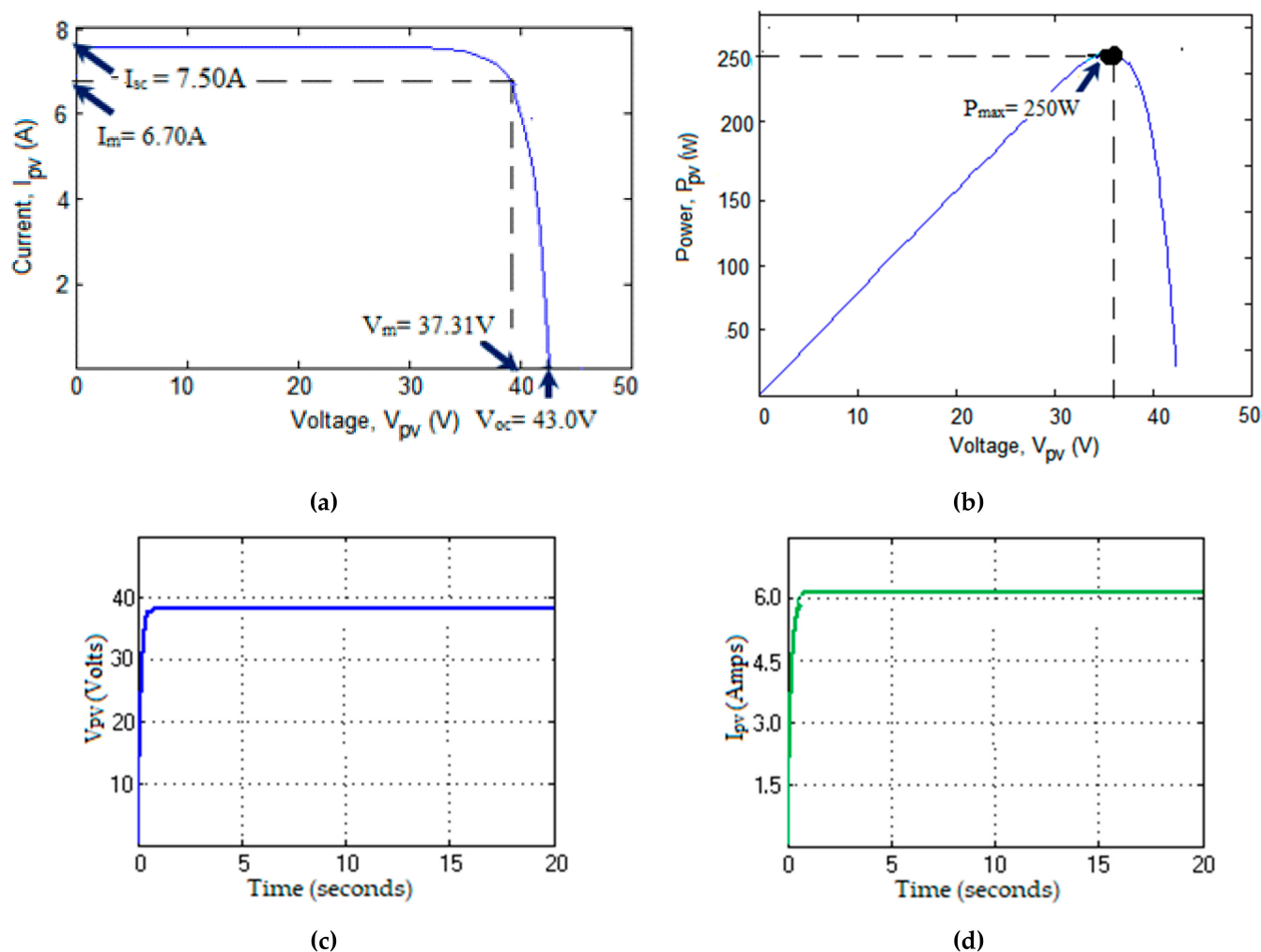


Figure 8. Solar PV: (a) I–V characteristics, (b) P–V characteristics, (c) PV output voltage, and (d) PV output current.

The output voltage (V_{pv}) and current (I_{pv}) of the PV during the attainment of maximum power are observed to be 37.31 V and 6.70 A, respectively (Figure 8c,d). This constant output is fed into the proposed SHGqBI.

3.1.2. SHGqBI

The proposed DC–DC converter is connected to a single-phase inverter operated by four IGBT switches using simple sinusoidal pulse width modulation (PWM). The converter operated with a duty cycle (δ) of 0.65 at a switching frequency (f_s) of 500 Hz that produces the output. The voltages across the capacitances are found to be 49.60 V ($V_{c1} = V_{c2}$), as illustrated in Figure 9a. After considering the voltage drops, the output voltage (V_o) and average current (i_o) are observed to be 80.80 V and 2.97 A, respectively, as illustrated in Figure 9b.

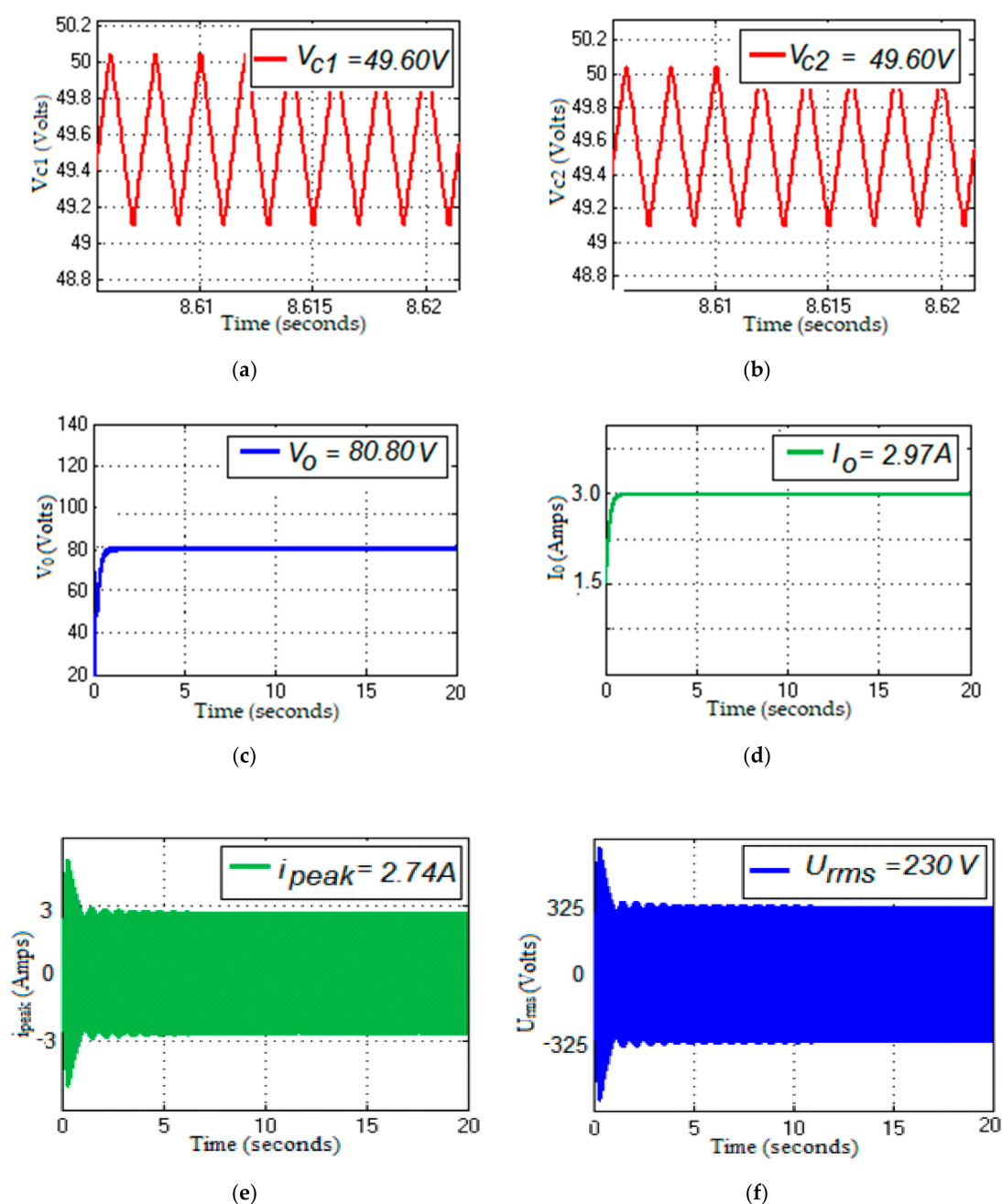


Figure 9. Proposed SHGqBI: (a) voltage across the capacitor C1, (b) voltage across the capacitor C2, (c) output voltage of the DC–DC converter, (d) output current of the DC–DC converter, (e) output voltage of inverter, and (f) output current of the inverter.

The output of the converter is fed to the single-phase inverter circuit and the output current and voltage are observed at the inverter load terminals and displayed in Figure 9c. From the figure, root mean square (RMS) voltage (U_{rms}), peak current (i_{peak}), and RMS current (i_{rms}) of the inverter are found to be 230 V, 2.74 A, and 1.10 A, respectively. Further, the THD is obtained from the fast Fourier transform (FFT) analysis, and the voltage and the current THDs are found to be 7.25% and 2.30%, respectively (Figure 10).

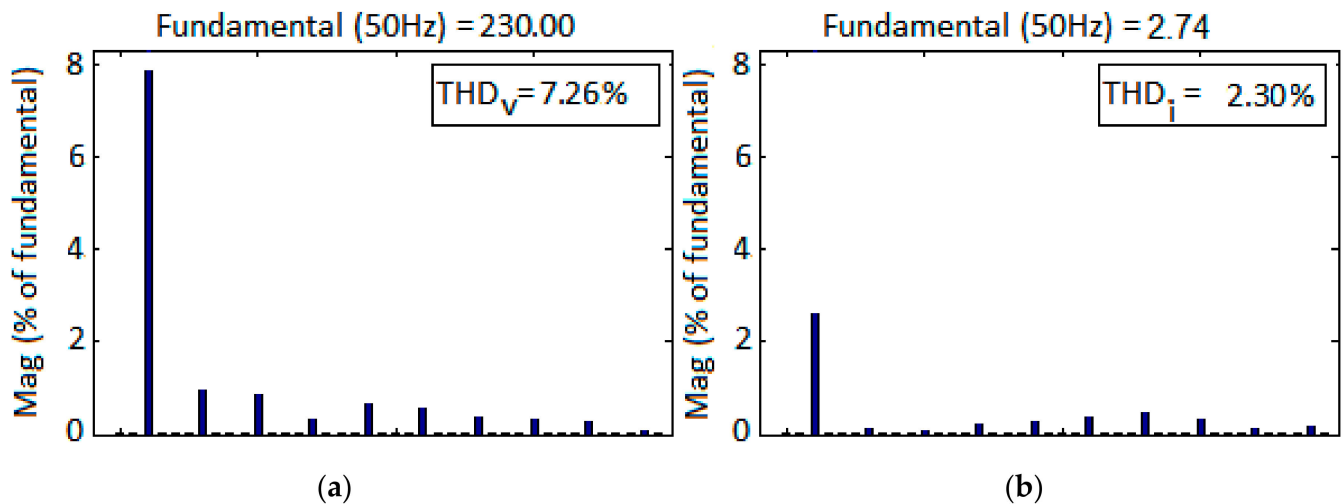


Figure 10. Total harmonic distortions (THDs): (a) voltage THD and (b) current THD.

3.2. Experimental Results

The experimental validation of the proposed system is carried out using a 250 W PV panel along with a switchless quasi switched boost inverter (qSBI). It is built with TLP-350 optocoupler driver circuit rated 15 Vdc that drives the pulses to the switches through a microcontroller. The complete setup of the system is illustrated in Figure 11 and the parameters of the system are the same as a simulation study for effective validation.

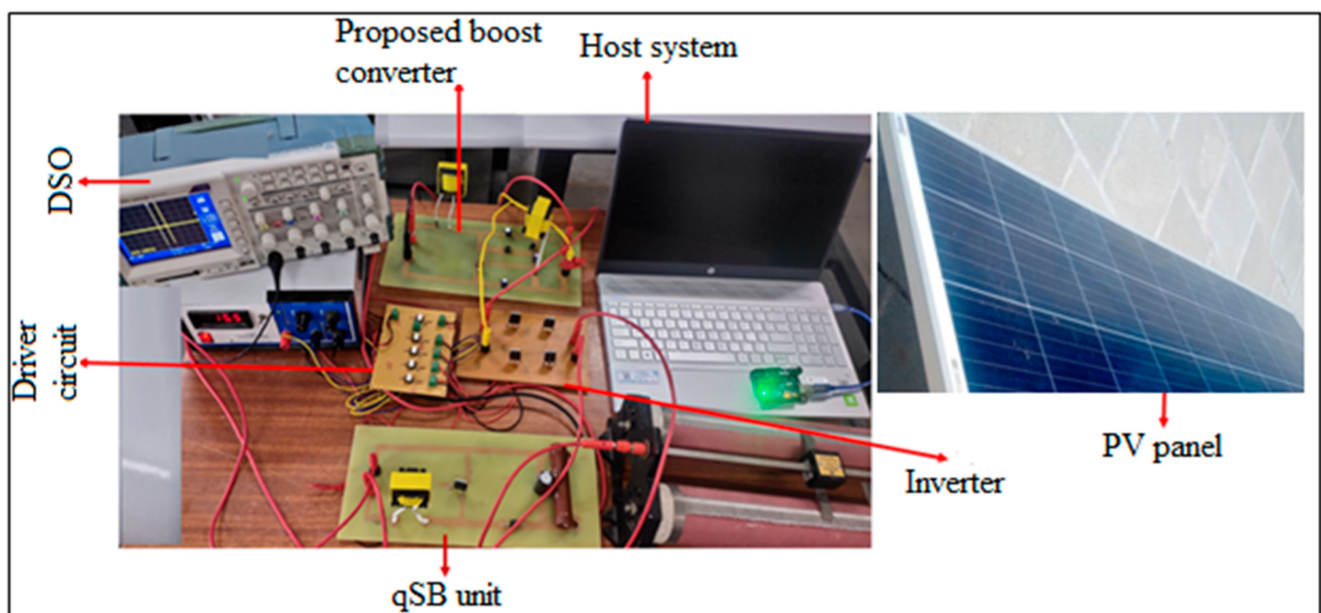


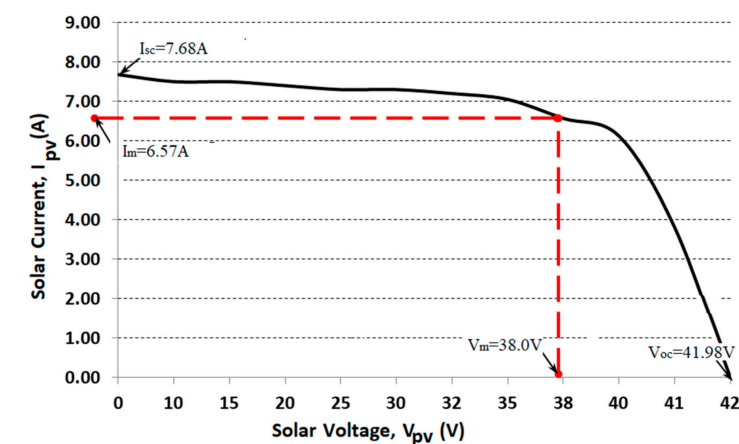
Figure 11. Experimental setup of the proposed SHGqBI.

3.2.1. SPV

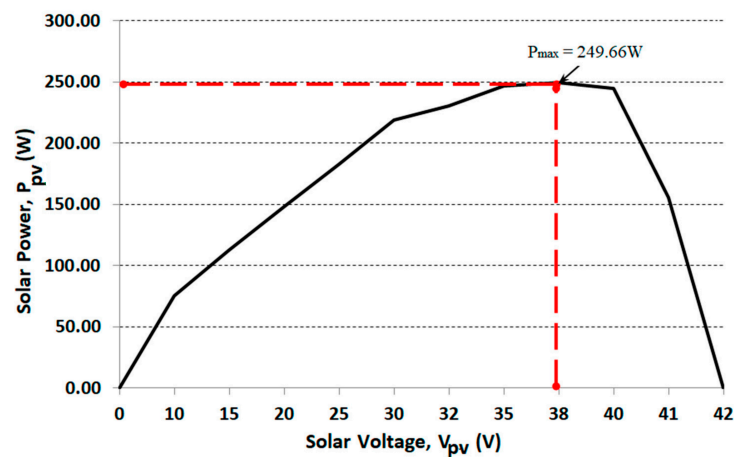
The SPV panel is initially connected to a variable resistive load of 200 W/1.5 A. Subsequently, the voltage and the current of the panel are measured under different values of the load to obtain the I–V characteristics (Table 3). From the I–V characteristics, the short circuit current (I_{sc}) and open-circuit voltage (V_{oc}) are traced and found to be 7.68 A and 41.98 V, respectively (Figure 12a). Moreover, the maximum power extraction from the PV is found to be 249.66 W, which is very close to the simulation results (Figure 12b).

Table 3. I–V characteristics of the photovoltaic (PV) panel.

Voltage (V_{pv}) in Volts	Current (I_{pv}) in Ampere	Power (P_{pv}) in Watts
0	7.68	0.00
10	7.50	75.00
15	7.50	112.50
20	7.40	148.00
25	7.30	182.50
30	7.30	219.00
32	7.20	230.40
35	7.05	246.75
38	6.57	249.66
40	6.12	244.80
41	3.80	155.80
42	0	0.00



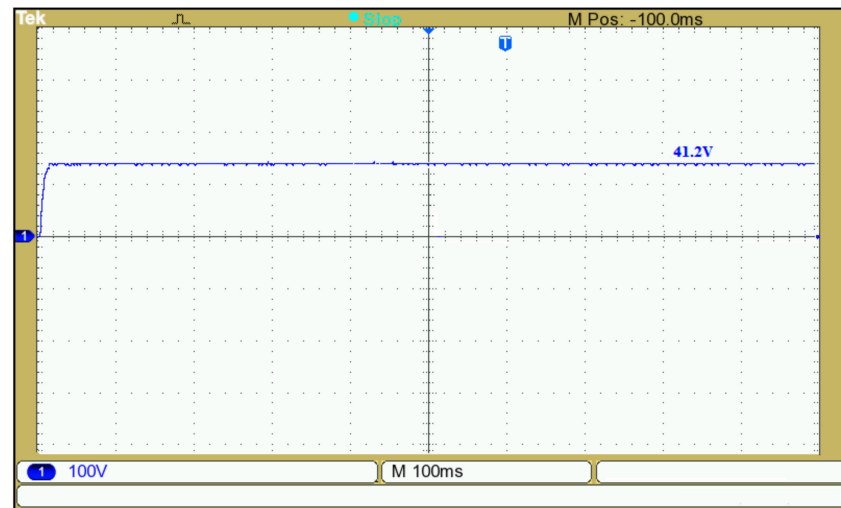
(a)



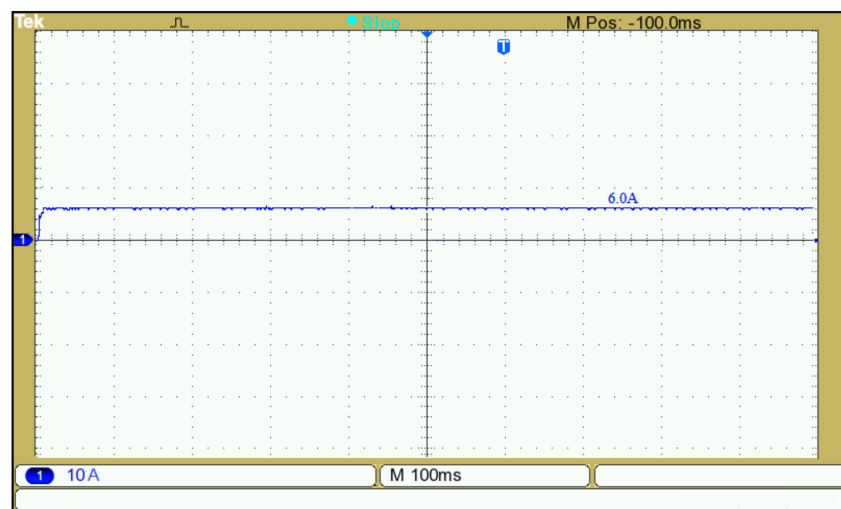
(b)

Figure 12. Experimental characteristics of PV: (a) I–V characteristics and (b) P–V characteristics.

The application of the BAT algorithm is verified and the observed output voltage (V_{pv}) and current (I_{pv}) are illustrated in Figure 13. It is noted that the V_{pv} and I_{pv} maintained constant characteristics over time, i.e., 41.20 V and 6.0 A, respectively. Moreover, the proposed algorithm reduces the deviation in the input voltage and input current that can enhance the performance of the proposed SHGqBI.



(a)



(b)

Figure 13. Experimental results: (a) output voltage (V_{pv}) and (b) output current (I_{pv}).

3.2.2. SHGqBI

The output obtained from the PV system is fed to the proposed SHGqBI. The values of the currents and voltages at different stages are recorded. The voltage across the capacitors is found to be almost equal, i.e., $V_{c1} = V_{c2} = 57.0$ V, as displayed in Figure 14.

The converter boosts the input parameters fed by the PV panel, which maintains a constant power at the terminals. The output voltage and current at the load terminal are measured to be 110.10 V and 2.70 A, respectively (Figure 15).

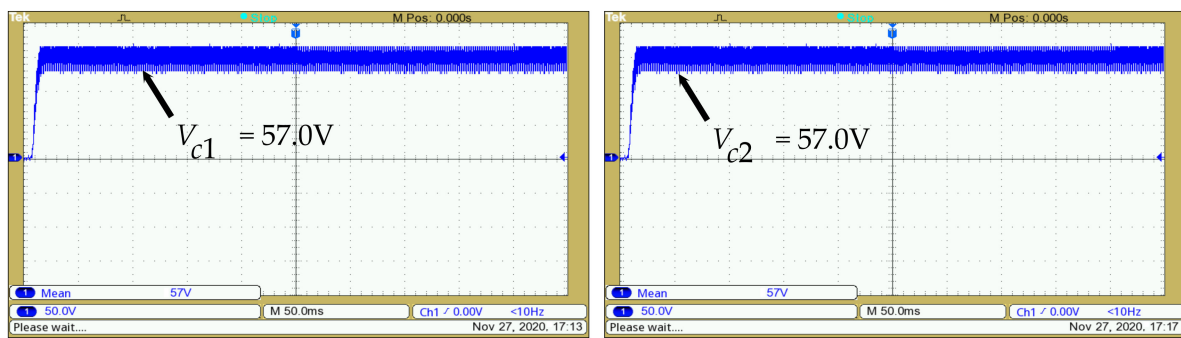
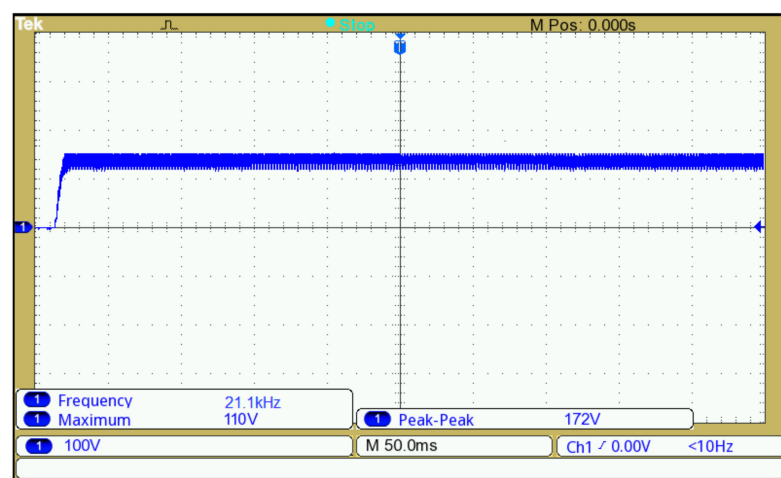
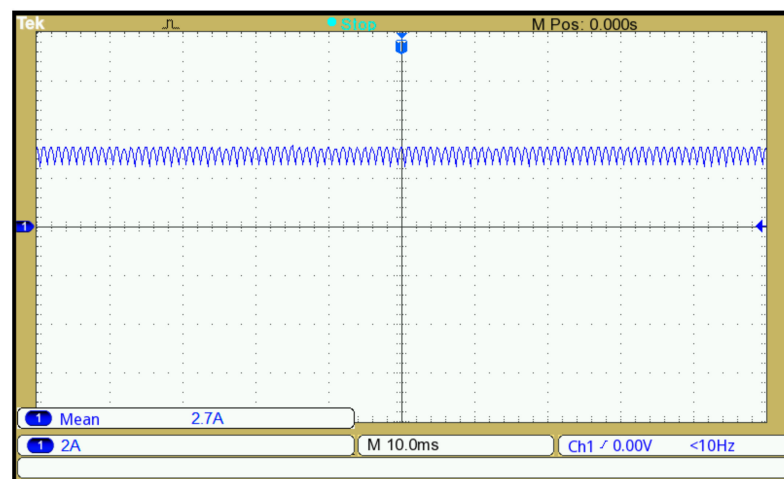


Figure 14. Voltage across the capacitors.



(a)



(b)

Figure 15. Experimental results of the converter: (a) voltage (110 V) and (b) current (2.7 A).

The single-phase inverter connected to the converter boosts the voltage to a pure sinusoidal output as per the proposed topology. The output voltage ($U_{rms} = 224.9$ V) and load current ($i_{rms} = 2.69$ A) are recorded. Moreover, the observed waveforms are pure sinusoidal from the hardware setup illustrated in Figure 16. Moreover, the inverter output voltage and current are found to be in phase with each other.

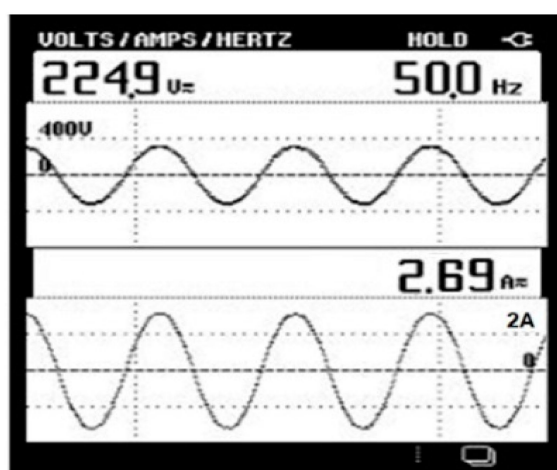


Figure 16. Experimental results of the inverter (voltage and current).

Then, the ranges of THDs are measured and the values are almost closer to the obtained results from the simulation modelling. The voltage and current THDs are recorded to be 10.2% and 2.7%, respectively (Figure 17). The experimental validation confirms the stability of the system to produce a pure sine waveform for utilities and domestic applications.

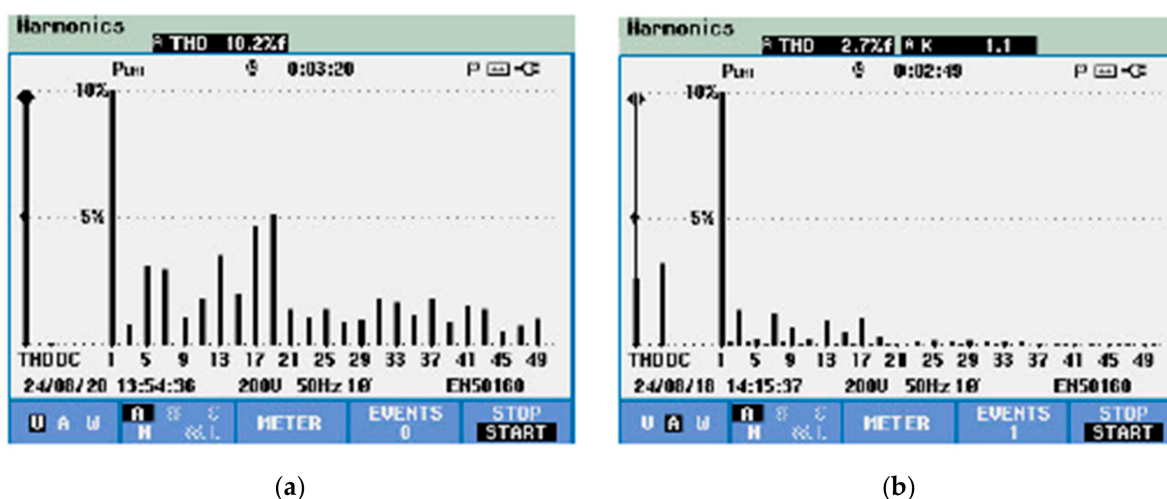


Figure 17. (a) Voltage THD (THD_v) and (b) current THD (THD_i).

4. Comparative Analysis and Validation

4.1. System Validation

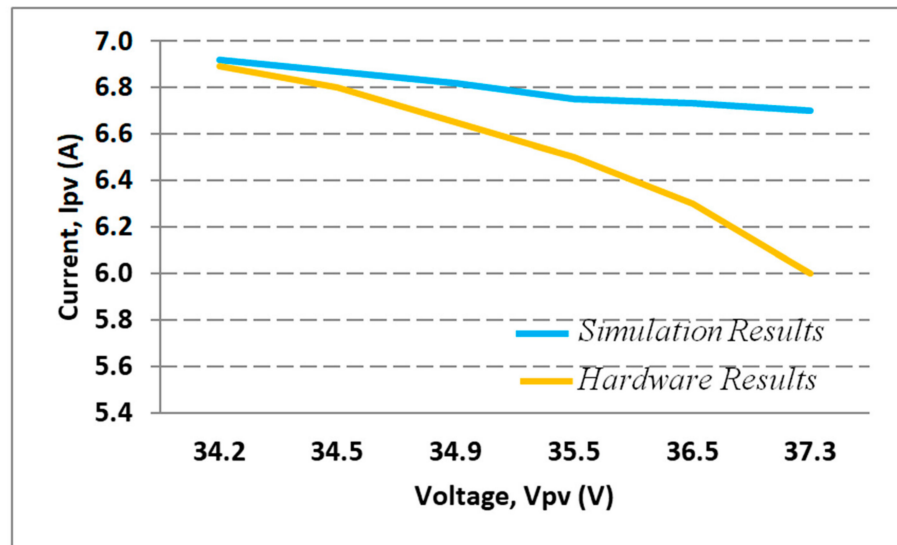
The proposed system is mathematically modelled in MATLAB Simulink and the same set up is demonstrated experimentally as described in Section 3. To validate the simulated results with the experimental outcome, the comparative analysis is performed extensively for an individual component of the system. Specifically, the characteristics of the PV panel (I–V and voltage versus efficiency plot) are derived for both the simulation and hardware setup and compared at different voltage levels. Moreover, the efficiency of the PV system is obtained using Equation (19). The error percentage between the experiment and simulation of I–V characteristics shows minimum level initially, accelerates with voltage, and attains a maximum of 10.44% (Figure 18a). Similarly, the percentage error of efficiency recorded the least scale of about 1.35% (Figure 18b).

$$\text{Efficiency, } \eta (\%) = \frac{P_{pv_out}}{P_{pv_in}} \times 100 \quad (19)$$

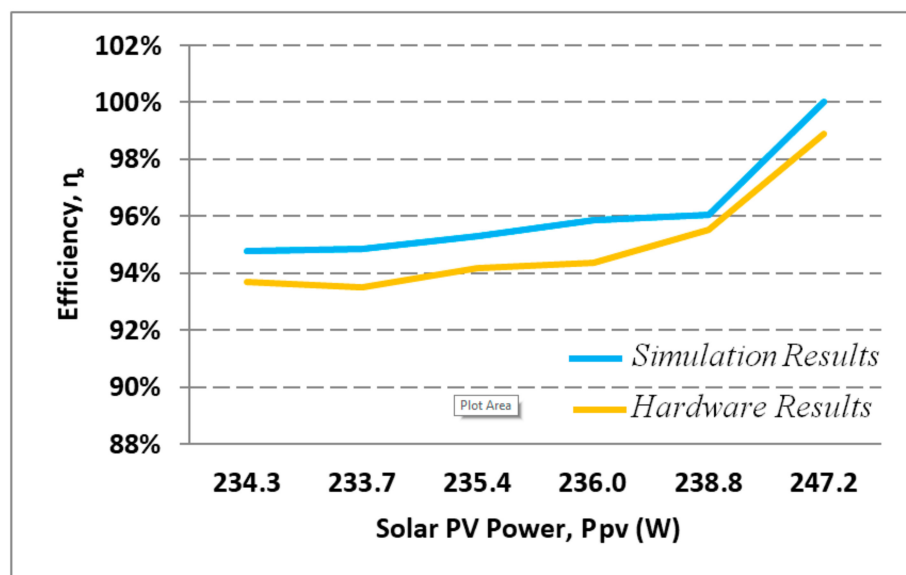
where

P_{pv_in} = input power or designed power in Watts,

P_{pv_out} = output power in Watts.



(a)



(b)

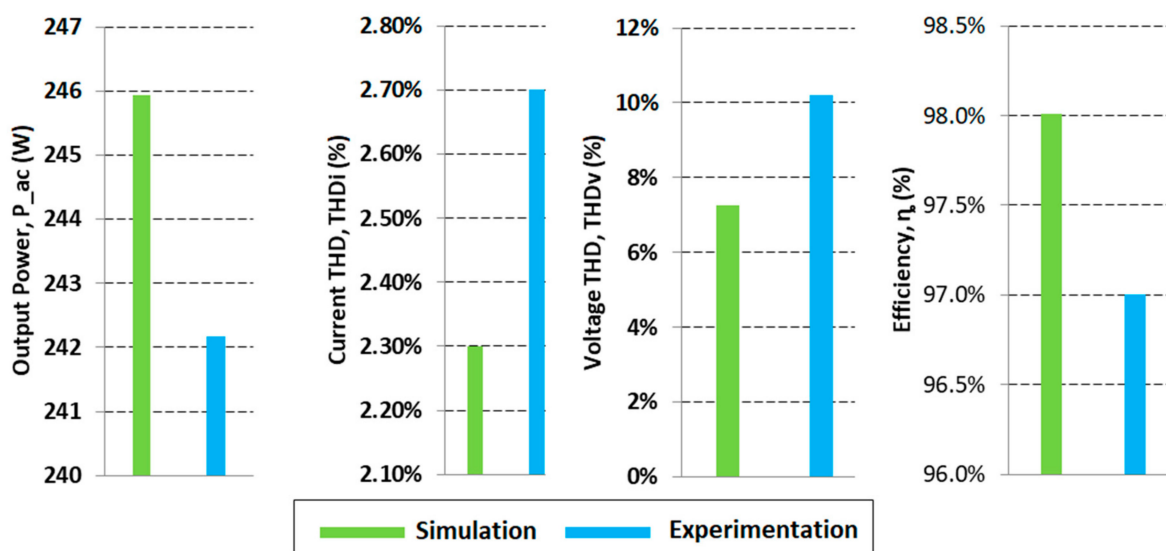
Figure 18. Validation: (a) I–V characteristics and (b) efficiency versus power outputs.

Further, the comparative analysis is carried out for the proposed SHGqBI. The proposed converter boosts the voltage to almost double the value of the input. The voltages across the switching capacitances are close between experimental and simulation results, at 57 V and 49.6 V, respectively. The individual performances of the components are described comprehensively in Table 4, which is self-explanatory.

Table 4. Individual components' performance comparison.

Component	Parameters	Simulation Results	Experimental Results	Relative Differences
PV	V_{oc} (V)	43.00	42.98	0.02
	I_{sc} (A)	7.50	7.68	−0.18
	V_m (V)	37.31	38.00	−0.69
	I_m (A)	6.70	6.57	0.13
	P_{max} (W)	250.00	249.66	0.34
	η_{pv} (%)	100	98.88	1.12
SHGqBI	$V_{c1} = V_{c2}$ (V)	49.60	57.00	−7.4
	V_0 (V)	80.80	110.10	−29.3
	U_{rms} (V)	230	224.90	5.1
	i_{peak} (A)	2.74	2.69	0.05
	i_{rms} (A)	1.93	1.90	0.03
	P_{ac} (W)	245.94	242.17	3.77
	THD_i (%)	2.30	2.70	−0.4
	THD_v (%)	7.26	10.20	−2.94
	η_i (%)	98.30	97.00	1.38

To sum up, the overall system performances such as output power (P_{ac}), current THD, voltage THD, and efficiency are compared between the simulated and experimental results and plotted in Figure 19. It is found to be great owing to their least deviation of output power (1.6%) and efficiency (1.1%). Moreover, the THD of current and voltage was found to be better by about 14.8% and 25%, respectively.

**Figure 19.** Overall system performance comparisons.

4.2. Comparison with the Existing Technique

The maximum power extraction from PV is carried out using BA. It shows remarkable outcomes particularly for obtaining the maximum power. For similar system parameters, existing technologies such as P&O, PSO, HC, and GWO optimization techniques [3,5,6] are used to compare the performance of the proposed optimization algorithm. The proposed method attained maximum power extraction over other existing methods, as illustrated in Figure 20. From the figure, it is observed that the power extraction of BA is superior to

existing techniques by about 1.82%, 3.92%, 6.91%, and 13.18% more than GWO, PSO, HC, and P&O, respectively. Similarly, the current is found to be great, i.e., about 1.38%, 2.3%, 3.84%, and 5.86% more than GWO, PSO, HC, and P&O, respectively.

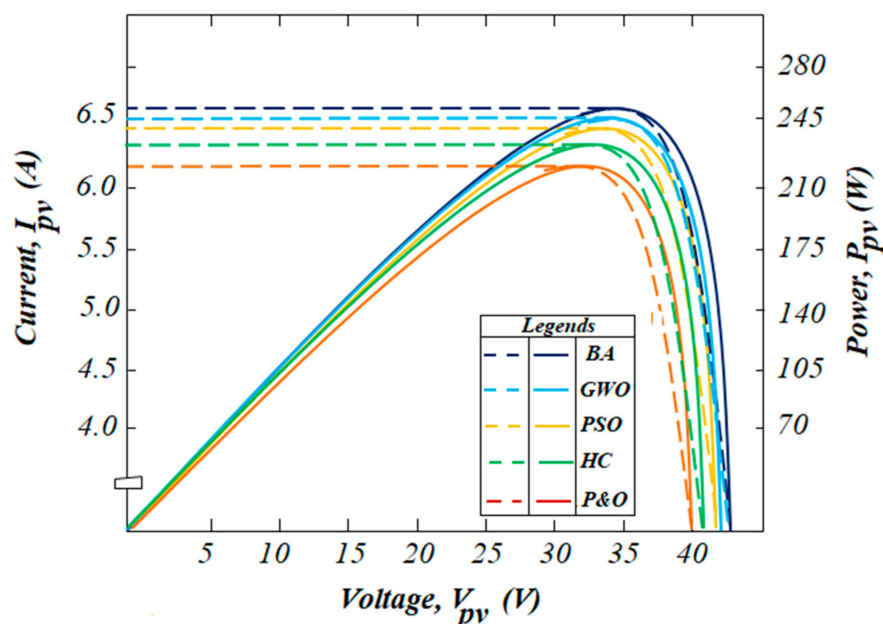


Figure 20. P–V (solid line) and I–V (broken line) characteristics obtained from different maximum power point trackings (MPPTs).

Further, the embedded configuration of the proposed SHGqBI is compared with other conventional inverters such as the buck-boost inverter (BBI) [27], differential boost inverter (DBI) [28], improved differential boost inverter (IDBI) [29], switched-coupled inductor inverter (SCII) [30], quasi Z-source inverter (QZSI) [31,32], split-source inverter (SSI) [33], split-inductor differential boost inverter type-I (SIDBI-T1) [34], and split-inductor differential boost inverter type-II (SIDBI-T2) [34]. The comparative analysis with different existing configuration is illustrated in Table 5. It is observed that the proposed inverter attains a higher efficiency rate of 98.3% and is found to be greater than other conventional inverters.

Table 5. Comparison of different inverter configurations. BBI, buck-boost inverter; DBI, differential boost inverter; IDBI, improved DBI; SCII, switched-coupled inductor inverter; QZSI, quasi Z-source inverter; SSI, split-source inverter; SIDBI-T1, split-inductor differential boost inverter type-I; SIDBI-T2, split-inductor differential boost inverter type-II.

Ref No.	Configuration	Efficiency (%)
[27]	BBI	96.10
[28]	DBI	83.33
[29]	IDBI	92.60
[30]	SCII	90.50
[31,32]	QZSI	90.20
[33]	SSI	95.50
[34]	SIDBI-T1	96.50
[34]	SIDBI-T2	97.00
Proposed method	SHGqBI	98.30

Consolidating all the above discussions, it is observed that the proposed system, i.e., the combination of the BA algorithm and SHGqBI, can be extended to stand-alone drive applications and domestic utilities through the solar photovoltaic system for efficient and sustainable utilization. However, the recent study demonstrated by Immad Shams et al.

adapted the modified butterfly optimization algorithm (MBOA), which attained higher efficiency against partial shading, uniform shading, and fast varying load conditions [35]. Therefore, future work focuses on integration of hybridized BAT-MBOA and SHGqBI, and its effectiveness against different shading patterns and loading conditions will be validated through experimental study.

As global annual SPV additions are predicted to accelerate from 2023 to 2025, commercialization of these outcomes provides great advantages. However, it requires real-time and large-scale demonstrations that require a higher rate of investment. Nonetheless, it forms a strong roadmap to investors and stakeholders in the renewable energy sector to commercialize this product globally.

5. Conclusions

In this work, an MPPT algorithm-based BA is suggested for the PV system along with a novel SHGqBI. The mathematical modelling and experimental set up are demonstrated to validate the effectiveness of the proposed system. The key outcomes of the proposed system are as follows:

- The proposed algorithm extracted the power from the PV panel (250 W) effectively when compared with other existing techniques and attained an efficiency of about 98.8% owing to its extensive local search during the MPPT process.
- The SHGqBI can eliminate the additional dc-link components that enhances the compactness of the design and increases the efficiency by about 97%.
- The proposed inverter attained a reduced current and voltage THD percentile owing to its embedded version of the converter and inverter.
- The simulated results of the proposed scheme were validated with an experimental study that shows a closer mark with the least deviation.
- The overall performance of the system displayed significant outcomes, notably efficiency, and it can be incorporated with a standalone system effectually.

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Abbreviations

ABC	Artificial bee colony
ACO-P&O	Ant colony optimization and P&O
BA	Bat algorithm
BBI	Buck-boost inverter
CS	Cuckoo search
DBI	Differential boost inverter
DE	Differential evolution

DSO	Digital storage oscilloscope
EA-P&O	Enhanced adaptive P&O
FFT	Fast Fourier transform
FIR	Finite impulse response
GMPP	Global maximum power point
GMPTT	Global maximum power point tracking
GWO	Grey wolf optimizer
HC	Hill-climbing
HD	Harmonic distortions
I-V	Current-voltage
IDBI	Improved differential boost inverter
IPSOMBOA	Improved PSOModified butterfly optimization algorithm
MHDC PLL	Multi-harmonic decoupling cell phase-locked loop
MIC	Modified incremental conductance
MPPT	Maximum power point tracking
P&O	Perturb and observe
PSC	Partial shading conditions
PSO	Particle swarm optimization
PV	Photovoltaic
P-V	Power-voltage
PWM	Pulse width modulation
qSBI	Quasi switched boost inverter
qZS	Quasi Z source
QZSI	Quasi Z-source inverter
REDG	Renewable energy distributed generation
RES	Renewable energy systems
RMS	Root mean square
SC	Switched capacitance
SCII	Switched-coupled inductor inverter
SHGqBI	Simplified high gain quasi-boost inverter
SIDBI-T1	Split-inductor differential boost inverters type-I
SIDBI-T2	Split-inductor differential boost inverters type-II
SL	Switched inductance
SPV	Solar photovoltaic
SSI	Split-source inverter
THD	Total harmonic distortion
ZCS	Zero current switching
ZSC	Impedance source converter
ZVS	Zero voltage switching

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