International Journal of Basic and Applied Sciences, 14 (3) (2025) 431-438

International Journal of Basic and Applied Sciences

Website: www.sciencepubco.com/index.php/IJBAS
https://doi.org/10.14419/keaawr97
Research paper

Effective MPPT Technique Featuring Class Topper Optimization for Modified Quadratic Boost Converter-Driven Renewable System

Dr. R. Anuja [1]*, Dr. Mary A. G. Ezhil [1], Dr. S. Anish [2], Mrs. M. Dhiviya Nycil [1], Dr. M. Suthanthira [1], Dr. P. V. Deepa [3]

[1] *Department of Electrical and Electronics Engineering, Arunachala College of Engineering for Women, Tamilnadu, India*
[2] *Department of Electrical and Electronics Engineering, Mar Ephraem College of Engineering and Technology, Tamilnadu, India*
[3] *Department of Electronics and Communication Engineering, Arunachala College of Engineering for Women Tamilnadu, India*

**Corresponding author E-mail: anujakrish84@gmail.com*

Received: June 11, 2025, Accepted: July 16, 2025, Published: July 30, 2025

Abstract

The sustainable growth of energy solutions depends significantly on the integration of renewable sources into grid-connected systems. This paper presents a grid-tied Photovoltaic (PV) system that incorporates a Modified Quadratic Boost Converter (MQBC) and a Class Topper Optimized (CTO) Maximum Power Point Tracking (MPPT) algorithm to enhance energy harvesting and ensure efficient power delivery. The converter is used to increase the voltage under varying environmental conditions, such as sunlight and temperature changes. The CTO-based MPPT algorithm generates precise control signals based on real-time PV voltage and current, optimizing power extraction. These signals are processed by a dsPIC30F4011 microcontroller. Additionally, the system uses Direct Quadrature-Zero(dq0)-Three phase(abc) transformation theory to convert grid currents into d-q components, enabling accurate active and reactive power control through PI controllers. Real-time power calculations ensure dynamic regulation of power flow, aiding grid synchronization and optimizing energy efficiency. The proposed system is implemented using MATLAB, achieving 95% efficiency and minimizing power losses, ensuring reliable power delivery. This advanced control strategy offers a comprehensive and intelligent approach to improving the performance and stability of grid-connected PV systems.

Keywords: *Grid-Tied Photovoltaic System; MQBC; CTO-MPPT Algorithm; DC-DC Conversion; VSI; PI Controller.*

1. Introduction

Rising worldwide energy demand contributed to the transition from fossil fuels to sustainable alternatives, with solar energy emerging as a key choice due to its availability, ease of deployment, and declining costs [1-2]. PV systems, which use semiconductor diodes to convert sunlight directly into DC electricity, gained widespread adoption in both grid-connected and off-grid applications, particularly at utility scale [3-5]. These systems, composed of PV cell arrays connected in series and parallel, require precise design and modeling to account for factors like solar insolation and temperature [6]. However, their relatively high installation costs and moderate energy conversion efficiency make it essential to maximize power output. This is achieved through MPPT techniques integrated with DC-DC converters, which enable real-time adjustment of operating parameters to ensure the system consistently operates at its optimal power point. Reliable and accurate MPPT performance under both steady-state and dynamic conditions significantly enhances the overall efficiency and effectiveness of PV systems [7-9].

Traditional DC-DC converters used to increase the voltage from PV, such as the CUK and Flyback, are widely used for power conditioning in PV systems. The CUK converter is suitable for medium to low power applications due to its variable voltage conversion and low ripple, making it ideal for battery charging and sensitive loads. However, its complexity, size, cost, and increased switching losses limit its use in high-power applications. Furthermore, the Flyback converter is smaller and provides galvanic isolation, making it ideal for off-grid PV installations. However, its low efficiency and restricted scalability make it unsuitable for use in large-scale systems. The control performance is essential for achieving stable output without oscillations. MPPT is used to maintain a constant voltage and ensure CTO operates efficiently. Similarly, MPPT-based algorithms such as the Perturb and Observe (P&O) approach are simple and cost-effective, making them appropriate for steady situations. However, it suffers from oscillations, poor reaction to quick changes, and noise sensitivity, making it less effective in the presence of variable irradiance. In contrast, the Incremental Conductance (INC) method provides precise and quick MPP tracking while minimizing oscillations and controlling noise effectively, especially in dynamic circumstances. Furthermore, its complexity, higher computing burden, and requirement for extra sensors increase power consumption, making it unsuitable for resource-constrained systems [10-12]. Kumar et al proposed new methods based on MPPT and IDNN (improved deep neural network) for producing electricity from solar and wind energy. The simulation results confirmed that the proposed IDNN system works better than the current method in a variety of operational circumstances [17]. Kakularapu et al explained ANN-based MPPT algorithms and fuzzy logic in solar PV systems. Both approaches attempt to track the maximum power point (MPP) of the PV array by varying the operating voltage and current [18].

This study describes an effective MPPT method for grid-connected PV systems that uses CTO Optimization in conjunction with a MQBC DC-DC converter. The proposed MPPT technique allows for fast and exact tracking of the maximum power point in dynamic situations, while the MQBC ensures high voltage gain and consistent DC power delivery. Together, this improves energy conversion efficiency, reduces power losses, and allows for consistent grid involvement.

2. Proposed system description

The proposed solar-powered system efficiently converts solar energy into grid-compatible power, as illustrated in Figure 1. The PV panel captures solar irradiance and generates DC electricity, which is processed by a CTO Optimized MPPT Algorithm to ensure maximum power extraction under varying environmental conditions. The MPPT output controls a PWM generator, which regulates MQBC and a 3-phase inverter that converts this boosted DC into AC power.

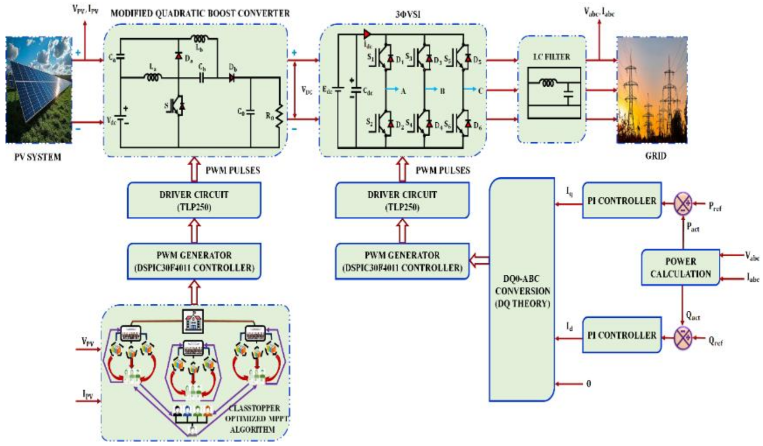

Fig. 1: Block Diagram of the Proposed Work.

The inverter's AC output is filtered through an LC filter to eliminate high-frequency harmonics, producing a clean sinusoidal waveform suitable for grid integration. A power calculation block monitors active and reactive power, comparing them with reference values. Any deviation is corrected by PI controllers, which generate signals to adjust the dq0-abc conversion block, ensuring optimal current control and stable energy transfer to the 3-phase grid. This setup ensures efficient energy conversion and consistent power quality.

2.1. PV system

The simplified equivalent circuit of a PV cell includes a diode that simulates cell polarization and a current source that represents the image generated current. A shunt resistor (R_{sh}) and a series resistor (R_s) are added, which represent ohm losses at the contacts and metal-semiconductor interface, while (R_{sh}) accounts for leakage losses at the cell edges and contacts, as shown in Fig. 2.

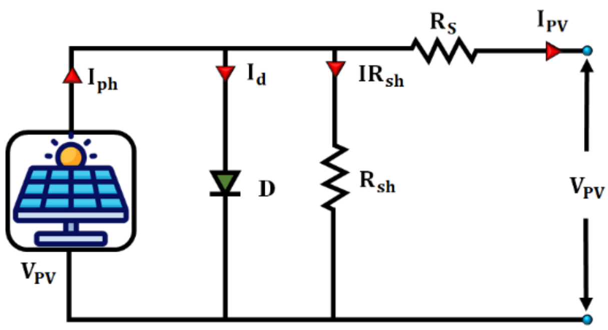

Fig. 2: Equivalent Model of Solar Cell.

The output current of the PV cell is represented as,

$$I_{pv} = I_{ph} - I_d - I_{Rsh} \quad (1)$$

The photocurrent (I_{ph}), which depends on incident irradiance (G) and operating temperature (T), is calculated using equation (2).

$$I_{ph} = I_0 \left(\exp\left(\frac{q(V + I_{Rs})}{K.n.T} \right) - 1 \right) \quad (2)$$

A final equation for the PV cell model is provided in equation (3)

$$I_{ph} = I_0\left(\exp\left(\frac{q(V+)I_{Rs}}{K.n.T}\right) - 1\right) - \frac{V+I_{Rs}}{R_{sh}} \quad (3)$$

Where (I_{Ph}) is the maximum short-circuit current, (q) is the electron charge, (I_0) is the p-n junction's reverse saturation current, (T) is the temperature in Kelvin, and (k_B) is the Boltzmann constant. The energy output of a solar cell fluctuates with atmospheric conditions, requiring the use of a MQBC converter to boost PV power.

2.2. Modified quadratic boost converter (MQBC)

The MQBC is a non-isolated step-up converter that outputs a greater voltage. The design is simplistic, requiring a smaller controller to maintain a constant output voltage with minimal ripple. Figure 3 depicts a circuit diagram for the proposed MQBC.

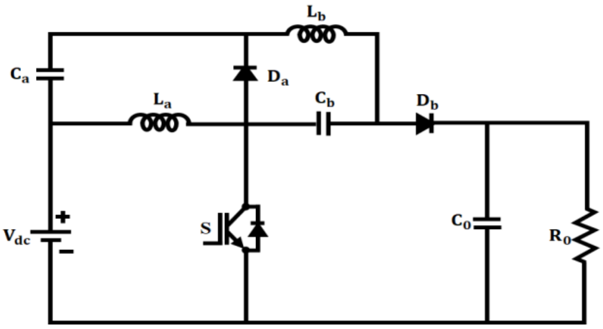

Fig. 3: Circuit Diagram of MQBC.

Under ideal conditions, MQBC reduces switching losses and voltage stress on active switches, making it suitable for applications that require a high output voltage. A large capacitor provides a constant output voltage (V_0), and all semiconductors are deemed ideal. The MQBC circuit operates in two modes and a switching waveform as shown in Figures 4 and 5.

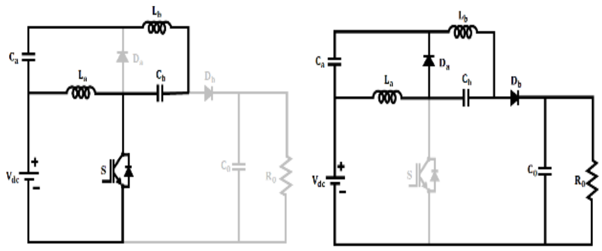

Fig. 4: Modes of Operation.

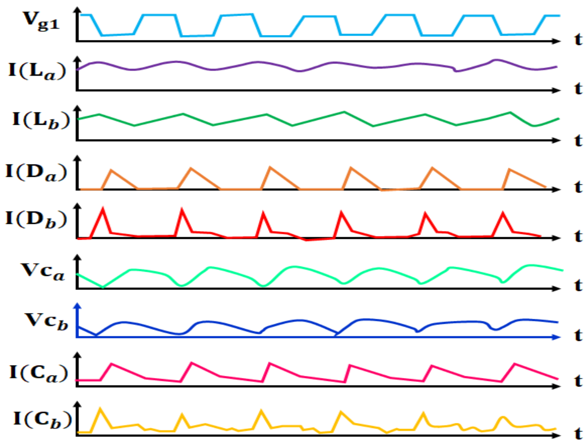

Fig. 5: Operating Waveform.

Mode 1:
In mode 1, switch S is closed, charging the capacitors and inductors. Diode (D_a) is reverse biased, which means the anode is more negative than the cathode. The current flowing through inductors (L_a) and (l_B) increases linearly, and the voltage across the inductor (L_a) equals the gate voltage. The inductor and capacitor voltages are expressed as,

$$V_{La} = V_g \quad (4)$$

$$V_{ca} = V_{cb} = \frac{D*V_g}{(1-D)} \quad (5)$$

$$V_{Lb} = V_g + V_{ca} - V_{cb} \tag{6}$$

Mode 2:

In Mode 2, the switch is turned off, and the diode (D_a) is forward biased. The inductor current discharges, and the capacitors and inductor are connected in parallel, resulting in voltages across the capacitors and the DC source at the output. The current with inductors (L_a) and (l_B) decreases linearly, and the voltage across (L_a) equals the gate voltage. The inductor and output voltages are computed using equations as follows,

$$V_{La} = V_{ca} \tag{7}$$

$$V_{Lb} = V_{cb} \tag{8}$$

$$V_0 = V_G + V_{ca} - V_{cb} \tag{9}$$

Voltage gain

$$\frac{V_0}{V_g} = \frac{1}{(1-D)^2} \tag{10}$$

This quadratic voltage gain shows the MQBC achieves significantly higher step-up than a traditional boost converter, which gain ($\frac{1}{(1-D)^2}$). For ensuring the modified QBC converter operates effectively, the MPPT controller is integrated for maintaining stable voltage as described in the following section.

2.3. Class topper (CTO) optimized MPPT algorithm

CTO is a novel approach based on academic learning dynamics that aims to improve the performance of MPPT in solar systems. CTO algorithm introducing direct instruction from the class topper and a self-evaluation stage, allowing students to analyze past and present performance. Students learn from their section toppers, while section toppers gather information from class topper, maintaining dual dual-phase learning process. Optimal controller gains are determined by minimizing the objective function, with course weightages represented by randomly initialized student sets, where each gain reflects a student's success in a section, as shown in Fig. 6.

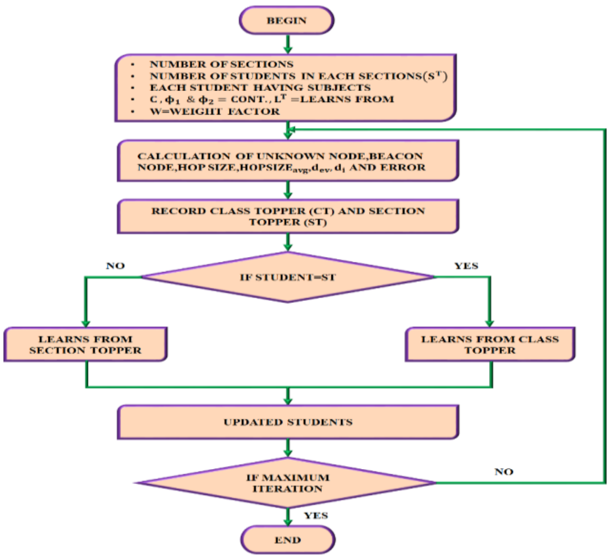

Fig. 6: CTO Flowchart.

The class structure is made up of these sets combined. The following is a definition of the (m) number of sections with n students in each section,

$$SE_{1,2,..m} = \begin{bmatrix} S_1 = [K_p\ T_1\ T_D\ T_f] \\ \cdots \\ \cdots \\ S_n = [K_p\ T_1\ T_D\ T_f] \end{bmatrix}_{(n\times1)} \tag{11}$$

The overall performance of students tests the objective function for the LFC issue. The objective function 4 is used to assess each student's performance in the case of a two-area power system.

$$ITAE_{m,n}^{E_{max}} = \int_0^{t_{max}} (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie1-2}| t dt) \tag{12}$$

Student-level instruction for the LFC problem:

$$S_{gains^{(S,E+1)}} = S_{gains^{(S,E)}} + I^{(S,E+1)} \tag{13}$$

Where stands for student gains, ST_{gains} for ST gains, and gains for the controller parameter.
Section-level instruction for the LFC problem:

$$ST_{gains^{(SE,E+1)}} = ST_{gains^{(SE,E)}} + I_1^{(S,E+1)} \quad (14)$$

This methodology provides a structured approach to optimizing MPPT control parameters, enhancing tracking accuracy and system robustness, even under fluctuating environmental conditions. The system uses MQBC and CTO-based MPPT for efficient power generation, with dq0-abc transformation and PI controllers ensuring grid stability. DQ theory optimizes power control and tracking performance.

3. Results and Discussion

A CTO-based MPPT method is implemented using MQBC integrated PV system to improve energy extraction. The system is simulated in MATLAB/Simulink, with results and parameters outlined in Table 1.

Table 1: Parameter Specification

Parameter	Specification
PV System	
Rated Power	10kW
No. of panels in Parallel	5
Open Circuit Voltage	37.25V
Cell linked in Series	36
No. of Panels in series	8
Short Circuit Current	8.95 A
MQBC Converter	
L_a, L_b	4.7 mH
Switching frequency	10KHz
C_0	4.7 µF
C_a, C_b	22µF

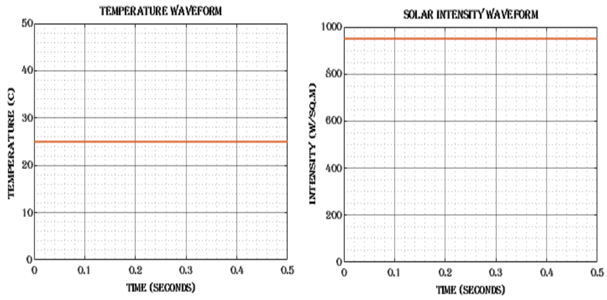

Fig. 7: Solar Panel Waveform.

Fig. 7 shows steady environmental conditions with constant temperature of 25°C and solar irradiance of 1000 W/m² over 0.5 seconds, ensuring a stable setup for evaluating the PV system's performance.

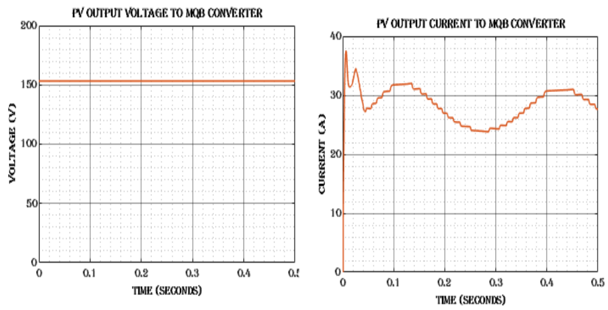

Fig. 8: Converter Output Waveform.

Figure 8 shows the PV output MPPT converter. The voltage stays constant at 320V, while the current peaks at 38A and settles around 28A, indicating dynamic MPPT operation over 0.5 seconds.

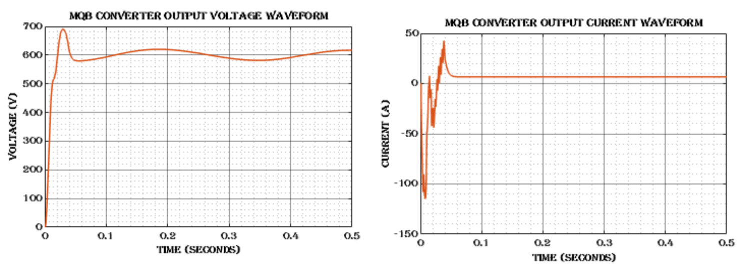

Fig. 9: Converter Output Waveform.

Fig. 9 shows the MPPT converter output voltage rising to 680 V before stabilizing at 640 V within 0.5 seconds, demonstrating efficient voltage regulation.

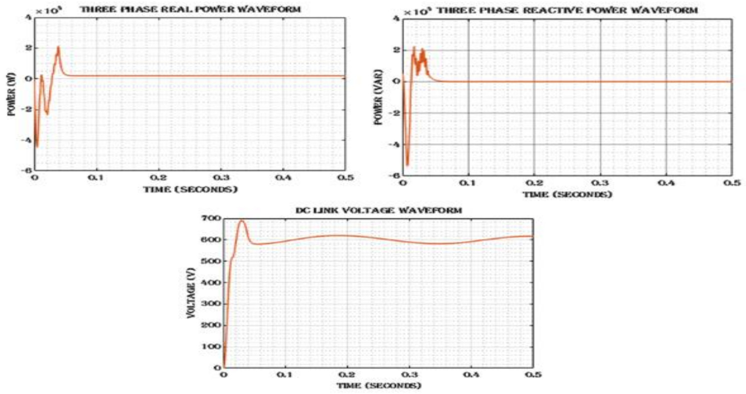

Fig. 10: Power and Voltage Waveform.

Fig. 10 shows the proposed system's fast dynamic response, with real power stabilizing near 3000W, reactive power near 0, and DC link voltage settling around 800V when subjected to a change in input, before settling into a steady state. The ability of an electrical grid to maintain a consistent frequency and voltage, ensuring a reliable power supply even when there are disturbances or changes in demand and generation.

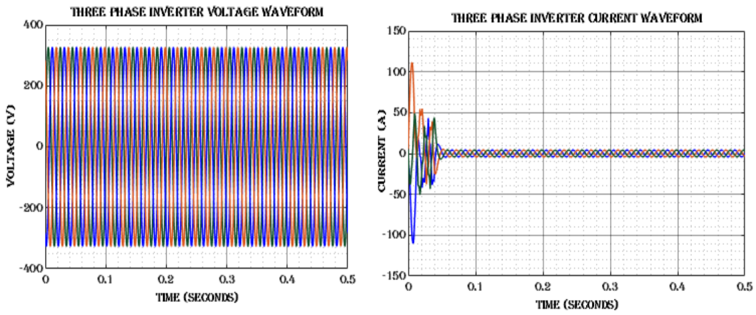

Fig. 11: Inverter Waveform.

Fig. 11 shows the three-phase inverter voltage and current waveforms, with constant sinusoidal voltages around (±400V) and currents stabilizing near (±100A) after brief transients, confirming effective and stable inverter operation.

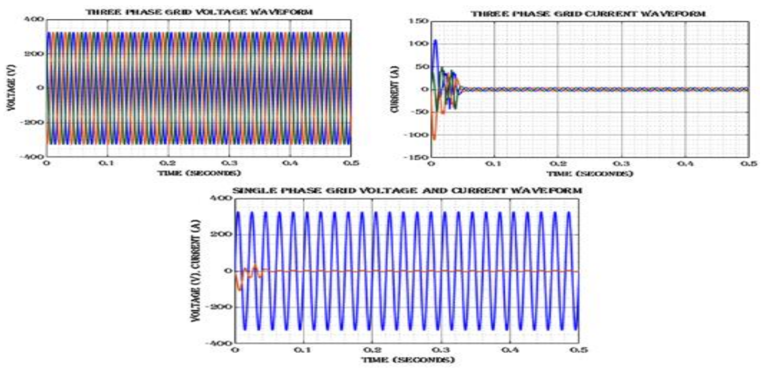

Fig. 12: Grid Voltage Waveform.

Fig. 12 illustrates the grid performance with balanced three-phase voltages (±400 V) and currents (±100 A) stabilizing quickly, while the single-phase voltage and current remain constant and sinusoidal, confirming efficient grid integration.

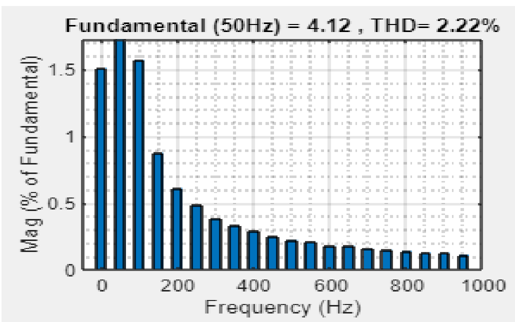

Fig. 13: THD Waveform.

The THD values for the grid system presented in fig 13, highlighting the variations in harmonic distortion, and the THD value is 2.98%.

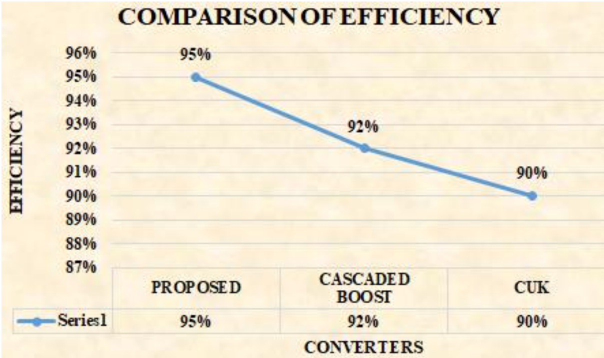

Fig. 14: Comparison of Efficiency.

Fig. 14 compares the efficiency of various converters, highlighting that the proposed converter achieves the highest efficiency at 95%, outperforming the Cascaded Boost converter (92%) [13] and the Cuk converter (90%) [14].

Table 2: Comparison of Tracking Efficiency

Controllers	Tracking Efficiency
Proposed	98%
PSO [15]	96.52%
CSO [16]	95%

Table 2 presents a comparison of tracking efficiency, showing that the proposed system achieves the highest efficiency at 98%.

4. Conclusion

The proposed grid-tied PV system, integrating MQBC and CTO-MPPT algorithm, significantly improves energy harvesting and power delivery efficiency. The MQBC adapts to varying environmental conditions, while CTO-MPPT ensures optimal power extraction. Using a dsPIC30F4011 microcontroller and advanced control strategies, including PWM-based converter control and 3-phase VSI management, the system achieves efficient grid synchronization. The dq0-abc transformation enables precise power control, ensuring stability and improved energy efficiency at 95%. The system demonstrates reliability and contributes to the sustainable growth of renewable energy solutions. In the future, Machine learning or deep learning models with recent optimization will be used for the effective design of PV systems.

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