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INTEGRATION OF DSTATCOM AND HIGH GAIN TWO STAGE BOOST CONVERTER WITH ENERGY MANAGEMENT FOR PQ IMPROVEMENT

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ABSTRACT

Ensuring power quality in modern electrical networks is crucial for maintaining stability and efficiency, especially when dealing with voltage fluctuations, harmonics, and reactive power imbalances. Traditional methods often fall short under dynamic and non-linear load conditions, prompting the need for an advanced solution. This research presents an integrated Distribution Static Compensator (DSTATCOM) based system for Power Quality (PQ) enhancement, supported by a Photovoltaic (PV) system connected through High Gain Two Stage Boost (HGTSB) Converter to increase DC-link voltage. The PV system utilizes a Parrot Optimization Algorithm (POA) based Artificial Neural Network (ANN) MPPT for optimal energy harvesting. A hysteresis current-controlled PWM generator manages DSTATCOM switching, while dq0-abc transformation with PI controllers ensures accurate reactive power compensation and load balancing. A supercapacitor further enhances reliability by storing excess PV energy and maintaining voltage during low generation periods. The proposed system is developed and evaluated with MATLAB/Simulink, achieving 97% efficiency, unity power factor, and reduced harmonics in grid connected environments.

Keywords: DSTATCOM, power quality, POA, ANN, supercapacitor, hysteresis PWM control.

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1. INTRODUCTION

In, Modern power consumers are placing greater emphasis on power quality due to the growing use of sensitive electronic equipment and the accelerated integration of renewable energy sources. While these developments support environmental sustainability, they also introduce complex PQ challenges, including current distortions, voltage sags, swells, and system imbalances. These issues largely stem from the use of power electronic converters and unbalanced, reactive loads, which adversely affect the performance of electrical systems. DSTATCOM emerged as effective solutions to these problems, particularly when operated in Current Control Mode (CCM), offering mitigation for issues such as harmonics, poor power factor, and current unbalance. However, CCM has limited capability in addressing voltage-related disturbances [1-2]. To overcome this, operating DSTATCOMs in Voltage Control Mode (VCM) enables both voltage and current compensation, leading to enhanced power system stability and improved overall PQ.

Hydrate is especially promising for off-grid and rural electrification. Nevertheless, their intermittent and variable nature introduces further PQ issues when integrated with the utility grid. These challenges necessitate advanced energy management and compensation strategies to maintain reliable and efficient operation. The proposed work, Integration of DSTATCOM and DCBC with energy management for PQ Improvement, presents a unified solution that enhances power quality and grid stability. By integrating the voltage and current compensation capabilities of a VCM operated DSTATCOM with the efficient voltage regulation of HGTSBC and smart energy management, the system ensures reliable operation and smooth integration of renewable energy into modern power networks [3-4].

Various power electronic converters, such as Cuk, Luo, and Zeta converters, are commonly used in PV systems to increase voltage levels. While the Cuk converter offers continuous input/output currents, low ripple, and bidirectional voltage conversion, its complex control, higher component stress, and inverted output voltage limit its effectiveness for power quality improvement. The Luo converter, known for high voltage gain and low input current ripple, enhances power quality but faces issues with complex control and stability under varying loads. Similarly, the Zeta converter improves power quality with continuous current and bidirectional voltage conversion, but its complexity and higher component stress make it less ideal [5-7]. In contrast, the HGTSBC provides superior voltage regulation, better

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dynamic response, and higher efficiency, making it a more suitable solution for enhancing power quality in PV systems. The control performance is essential for achieving stable output without oscillations ANN MPPT controller is used to maintain a constant voltage and ensure POA operates efficiently. Several existing algorithms and their limitations are shown in Figure-1 [8-10].

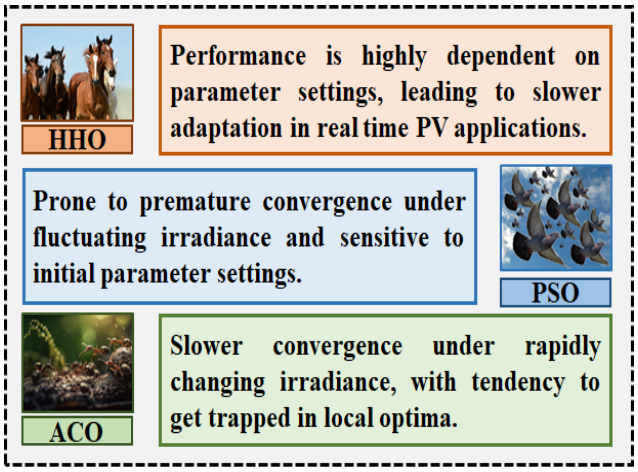


Figure-1. Existing algorithms and their limitations.

The proposed system combines an HGTSBC for high voltage gain and steady DC output with a DSTATCOM to efficiently address power quality concerns such as harmonics, voltage sags, and unbalanced loads. An intelligent energy management strategy that employs parrot optimized ANN based MPPT enables maximum power extraction from the PV system under different conditions. This integrated strategy improves system efficiency, dynamic response, and grid stability.

2. PROPOSED SYSTEM DESCRIPTION

The block diagram shows DSTATCOM and HGTSBC combined with a PV-based energy management strategy to improve power quality on a three-phase grid, as shown in Figure-2. The system requires power from the grid and transfers it through source inductance to the Point of Common Coupling (PCC), which connects linear and nonlinear loads. A PV system combined with a Parrot Optimized ANN-MPPT controller achieves maximum power extraction. The collected energy is processed through a PWM-controlled HGTSBC to maintain a stable DC link voltage (V_DC) and charge a supercapacitor for energy storage and recovery.

The DC output powers the DSTATCOM, which is connected to the PCC through an LC filter to eliminate harmonics and voltage fluctuations. DSTATCOM switching is controlled by a hysteresis current controller that employs PWM signals. The control system transforms currents to the dq0 frame and uses PI controllers to regulate active and reactive power (P, Q) using reference values. This integrated system ensures improved power quality, grid stability, and the most effective use of renewable energy resources.

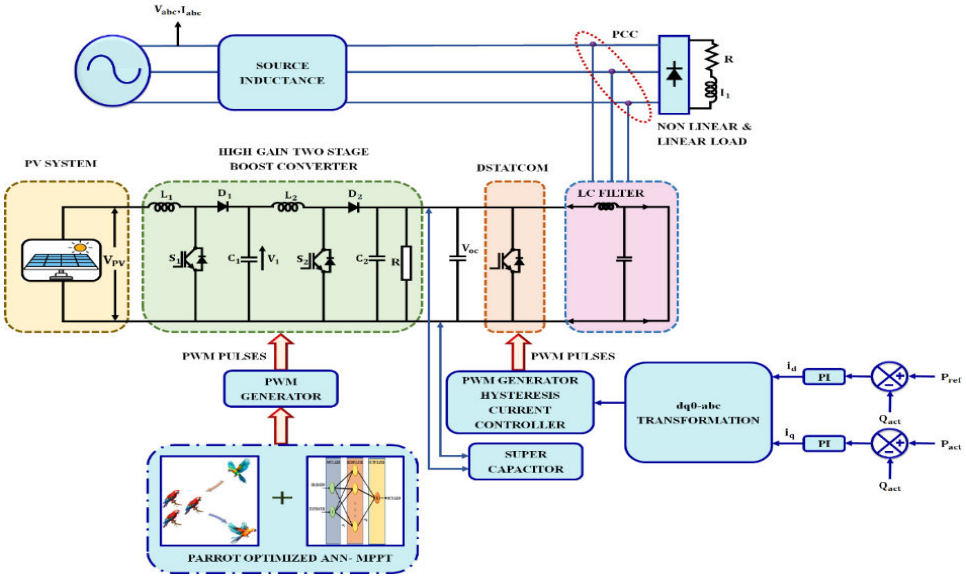


Figure-2. Block diagram of the proposed work.

3. PROPOSED SYSTEM MODELLING

3.1 DSTATCOM

DSTATCOM is used to increase power quality and stability in the system. It compensates for reactive power and reduces voltage fluctuations in the distribution network, keeping the voltage within the acceptable range? It provides reactive power support to keep the voltage in proper range, which improves overall system performance using DSTATCOM delivering consistent and clean electricity and proceed to the energy generation phase using the PV System.

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Deadbeat Voltage Control Law

The control law is determined by the circuit's state space representation, which comprises the filter capacitor voltage and injected current as state variables and the control signal and injected terminal current as control vectors. The continuous-time state-space equation is given by

$$\dot{x} = Ax(t) + Bz(t) \quad (1)$$

The system parameters are simplified, and the future reference voltage is estimated using a second-order Lagrange extrapolation based on the current state.

$$v_t^*(k+1) = 3v_t^*(k) - 3v_t^*(k-1) + v_t^*(k-2) \quad (2)$$

Generation of Reference Terminal Voltage

The reference voltage allows the DSTATCOM to operate in VCM while using CCM benefits, aligning source current with the fundamental positive sequence to maintain power factor using symmetrical component theory. The generated reference terminal voltage acts as:

$$V_{ta}^*(t) = \sqrt{2}V_t^*\sin(\omega t - \delta) \quad (3)$$

$$V_{tb}^*(t) = \sqrt{2}V_t^*\sin\left(\omega t - \frac{2\pi}{3}\delta\right) \quad (4)$$

$$V_{tc}^*(t) = \sqrt{2}V_t^*\sin\left(\omega t + \frac{2\pi}{3} - \delta\right) \quad (5)$$

The DSTATCOM ensures steady power generation by utilizing the PV system as a supply source for its DC link. Since the output from the PV system is at a low voltage, HGTSBC is employed to step up the voltage to the required level for further processing.

3.2 High Gain Two Stage Boost Converter (HGTSBC)

HGTSBC is a DC-DC converter that improves voltage gain by connecting two identical boost stages in series. The circuit in Figure-3 includes an input voltage source (V_{in}), two inductors (L_a) and (L_b), capacitors (C_a) and (C_b), diodes (D_a) and (D_b), and two switches (S_a) and (S_b) that operate independently. This configuration efficiently boosts the input voltage in two stages, making it more efficient for high gain applications than a single-stage boost converter.

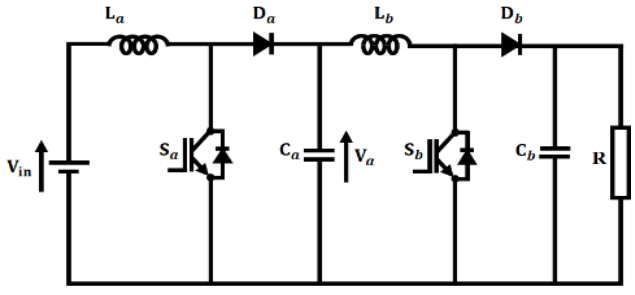


Figure-3. High Gain Two Stage Boost Converter.

Mode 1:

When switch (S_a) is turned on and (S_b) is turned off, the input supply voltage (V_in) charges the inductor (L_a), allowing it to store energy in its magnetic field. This state extends until (S_a) is turned off, which terminates (L_a) energy storage phase.

Mode 2

When switch (S_a) is turned off and (S_b) is turned on. The output of the first boost stage now provides the input for the second. The intermediate voltage boosts the inductor (L_b), which stores energy in its magnetic field. This state continues until (S_b) is turned off, which concludes the (L_b) energy storage phase. Figure-4 illustrates various double cascade boost converter designs in continuous conduction mode and the waveform as shown in Figure-5.

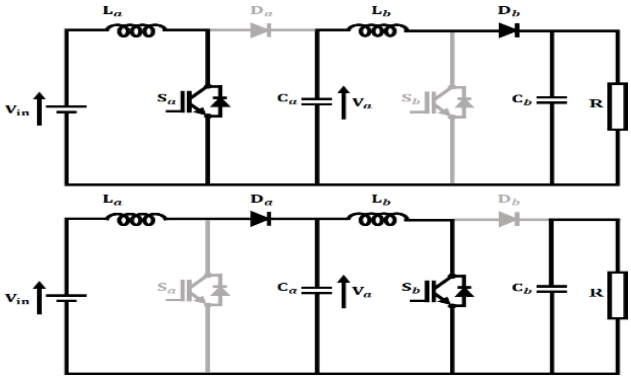


Figure-4. Modes of operation.

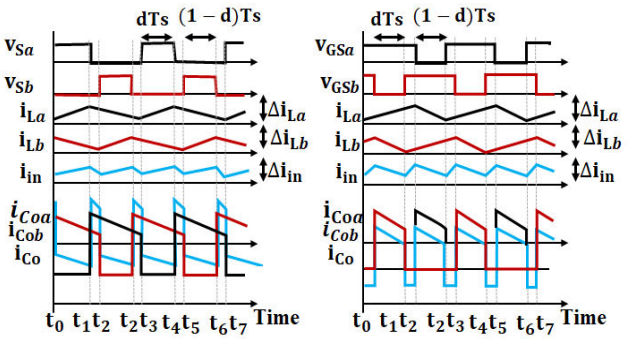


Figure-5. Converter waveform.

The voltage ratio is determined as follows:

$$\frac{V_{out}}{V_{in}} = \frac{1}{(1-D_1)}\frac{1}{(1-D_2)} \quad (7)$$

Let (D_a) and (D_b) be the duty cycles for the first and second boost stages, respectively. The output voltage and inductor currents are determined using the duty cycles as shown below.

$$I_{out} = \frac{V_{out}}{R} \quad (8)$$

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$$I_{Lb}=\frac{I_{out}}{(1-D_2)} \quad (9)$$

$$I_{La}=\frac{I_{Lb}}{(1-D_a)} \quad (10)$$

(I_{Lb}) represents the output current of the first boost stage. The inductor values for both stages are as follows:

$$L_a = \frac{D_a V_{in}}{f\Delta i_{La}} \quad (11)$$

$$L_b = \frac{D_b V_{in}}{f\Delta i_{Lb}} \quad (12)$$

The values of capacitors are designed as follows:

$$C_a = \frac{D_a V_a}{\Delta v_{ca} f R} \quad (13)$$

$$C_b = \frac{D_b V_{out}}{\Delta v_{cb} f R} \quad (14)$$

Where (V_a) is the output voltage for the first boost. Once the voltage is effectively increased, tracking the maximum power point (MPP) becomes critical for optimizing the energy harvested from the PV system. This method is carried out with the Parrot Optimized ANN based MPPT Controller.

3.3 Parrot Optimized (PO) ANN based MPPT Controller

ANN based MPPT system accepts solar temperature and irradiance as inputs and provides the optimal duty ratio to the DC-DC converter, enabling accurate and dynamic MPP tracking under changing conditions, as shown in Figure-6.

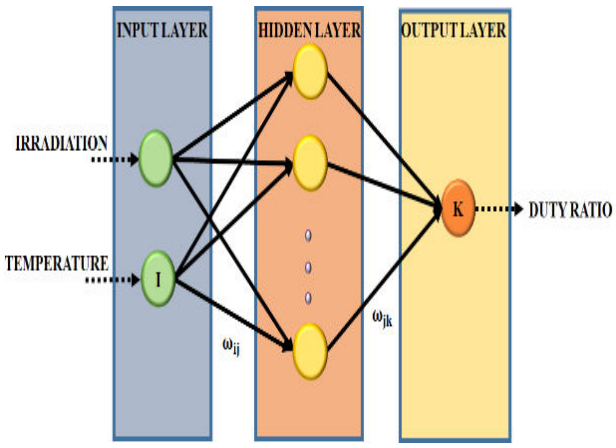


Figure-6. ANN-MPPT controller.

ANN is trained using a Parrot optimized control algorithm. Duty ratios corresponding to various combinations of solar irradiance and temperature are used to train the network, with weights of each layer adjusted to minimize error and properly achieve the target values for efficient system operation. The Mean Squared Error (MSE) is used to evaluate ANN performance. It is calculated as the average squared difference between the output (a) and the target (t).

$$F = \frac{1}{N}\sum_{i=1}^{N}(t_i - a_i)^2 \quad (15)$$

The ANN MPPT controller constantly modifies the control function to reduce errors. This paper proposes using the POA approach to optimize parameters for better performance, as shown in Figure-7. The ANN-MPPT controller constantly modifies the control function to reduce errors. The POA is a novel and strong optimization technique based on specific characteristics of trained Pyrrhura Molinae parrots, including foraging, staying, communication, and fear of strangers, as seen in fig 7.

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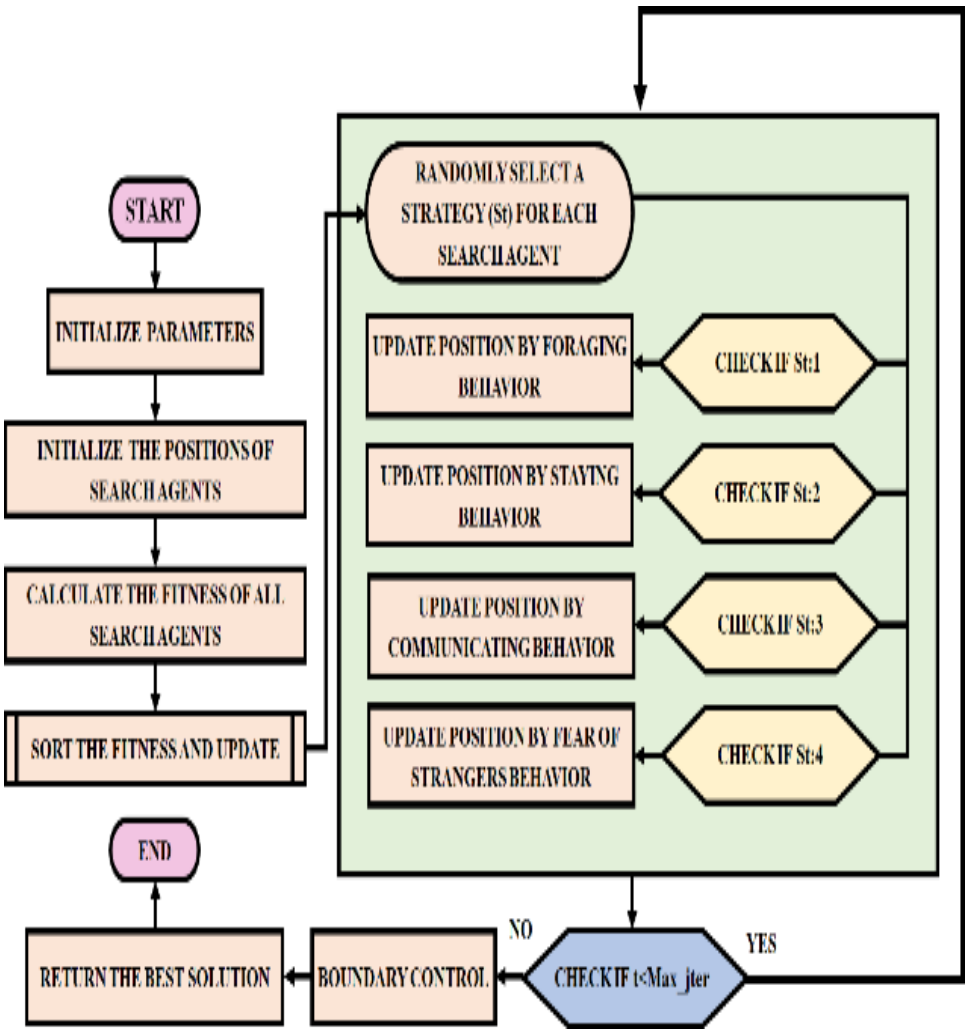


Figure-7. Flowchart POA.

POA appears by establishing a population of size N within the search domain defined by the lower (lb) and upper (ub) bounds, with a maximum of T iterations.

$$X_i^0 = lb + rand(0,1) \times (ub - lb) \quad (16)$$

The POA algorithm randomly assigns each parrot's initial position inside the search constraints, and foraging behavior is emulated by updating positions towards food or the owner's location.

$$X_i^{t+1} = (X_i^t - X_{best}).\,Levy(dim) + rand(0,1).\left(1 - \frac{t}{T}\right)^{\frac{2t}{T}}.X_{mean}^t \quad (17)$$

A parrot's future position is determined by its current position, the population average, and the most known solution, with Lévy flights adding unpredictability and a time-based term refining the search, resulting in balanced and effective convergence. The Lévy distribution used in Equation (1) assumes γ = 1.5.

$$\begin{cases} Levy(dim) = \frac{\mu.\sigma}{|v|^{\frac{1}{\gamma}}} \\ \mu \sim N(0, dim) \\ v \sim N(0, dim) \\ \sigma = \left(\frac{\Gamma(1+\gamma).sin\left(\frac{\pi\gamma}{2}\right)}{\Gamma\left(\frac{1+\gamma}{2}\right).\gamma.2^{\frac{1+\gamma}{2}}}\right)^{\gamma+1} \end{cases} \quad (18)$$

Pyrrhura Molinae's social behavior, which includes unexpectedly flying to and perching on its owner, is statistically modelled to reflect this tendency.

$$X_i^{t+1} = X_i^t + X_{best}.\,Levy(dim) + rand(0,1).\,ones(1, dim) \quad (19)$$

This cautious behavior, in which parrots ignore strangers and flock near their owners for safety, is mathematically depicted below:

$$X_i^{t+1} = X_i^t + rand(0,1).\cos\left(0.5\pi.\frac{t}{T}\right).(X_{best} - X_i^t) - cos(rand(0,1).\pi).\left(\frac{t}{T}\right)^{\frac{2}{T}}.(X_i^t - X_{best}) \quad (20)$$

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This model depicts the parrot's natural desire to seek safety by moving closer to its owner and away from strangers. The first phrase implies realignment with the owner, while the second represents avoidance of new things, which mirrors the Pyrrhura Molinae's typical flight behavior. With MPP tracking in place, the system provides maximum power extraction under variable environmental circumstances, while supercapacitors are used concurrently to allow for effective energy storage.

3.4 Supercapacitor-Based Power Management

Supercapacitors are coupled in both series and parallel to accomplish storage requirements in applications such as transmission capacity relief, peak power adjustments, and renewable energy storage. The supercapacitor pack is designed to provide the energy required in dynamic conditions, with capacitance determining the maximum energy (E_{sc}) it is allowed to deliver, and it is given by,

$$E_{sc} = \frac{C_{sc}(V_{max}^2 - V_{min}^2)}{2} \quad (21)$$

To simplify equation (4), the supercapacitor pack's capacitance (C_{sc}) is expressed as follows:

$$C_{sc} = \frac{2E_{sc}}{\eta V_{max}^2\left[1-\left(\frac{\vartheta}{100}\right)^2\right]} \quad (22)$$

(V_{max}) and (V_{min}) are the maximum and minimum supercapacitor pack voltages, ϑ is the discharge voltage ratio, and η is the supercapacitor pack efficiency. By integrating supercapacitors, the system deals with intermittent nature of solar electricity, ensuring a steady and reliable energy source [11] - [15].

4. SIMULATION RESULTS DISCUSSIONS

A DSTATCOM integrated with HGTSBC and coordinated through an energy management system is developed in this study to improve power quality in distribution networks. MATLAB based simulations are conducted to evaluate the system performance under various grid disturbances.

Figure-8 shows the grid conditions, which include waveforms for grid voltage and current. The grid voltage remains stable at 450V, ensuring a consistent voltage level, while the grid current remains constant at 12A, indicating continuous current flow. Together, these elements provide a balanced and stable power supply from the grid, ensuring stability throughout the test period. Figure-9 displays the waveforms of reactive and real power in alternating current systems, which show fluctuations despite maintaining a steady power flow. This ensures stable and efficient energy transfer. Figure-10 represents the temperature and intensity waveforms of the PV panel under constant conditions. The temperature remains consistently maintained at 30^0C throughout the duration, ensuring a stable operating condition. Similarly, the intensity waveform shows a steady irradiance level of $1000\ W/\ sq.$m, indicating uniform solar exposure on the PV panel. Figure-11 shows the Solar Panel Voltage Waveform over 0.4 seconds, where the voltage remains stable at around 160 V, and the current is steady at 65 A, indicating consistent and disturbance-free power generation.

Table-1. Parameter specification.

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

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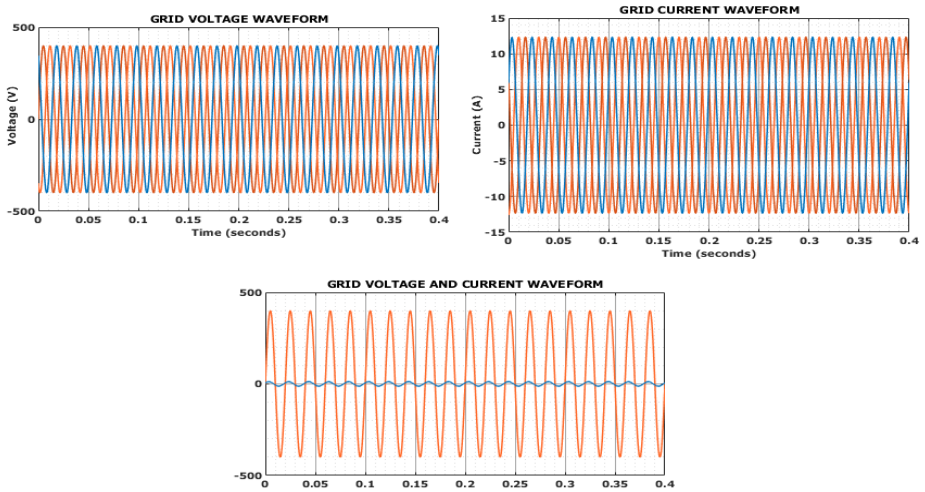


Figure-8. Grid waveform.

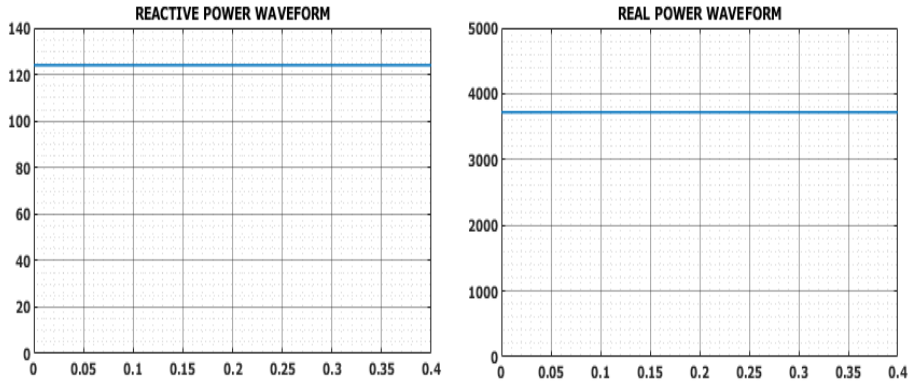


Figure-9. Real and reactive power waveform.

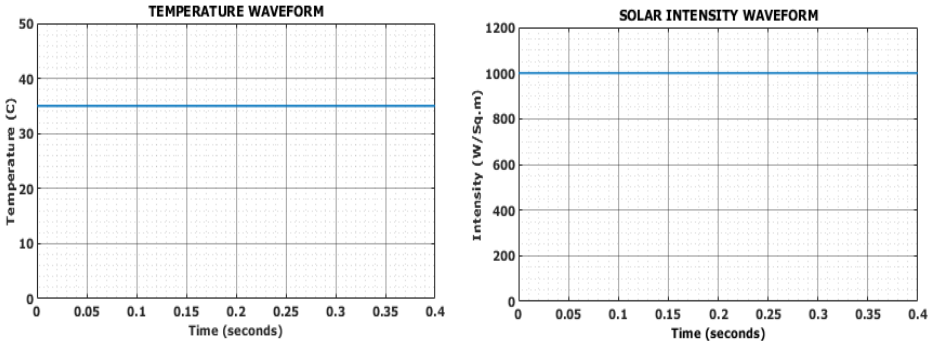


Figure-10. PV panel waveform.

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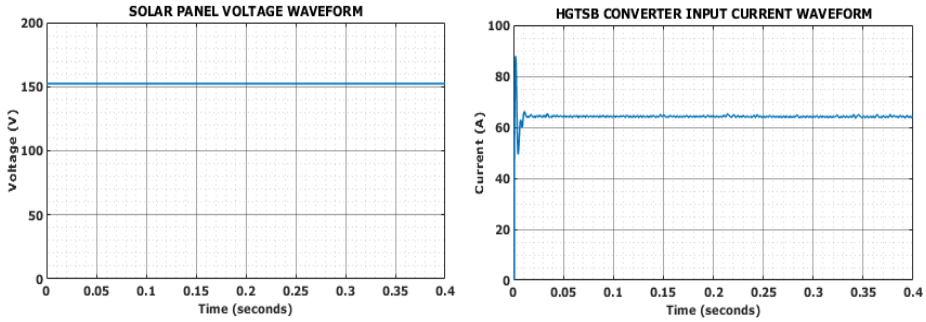


Figure-11. PV current and voltage waveform.

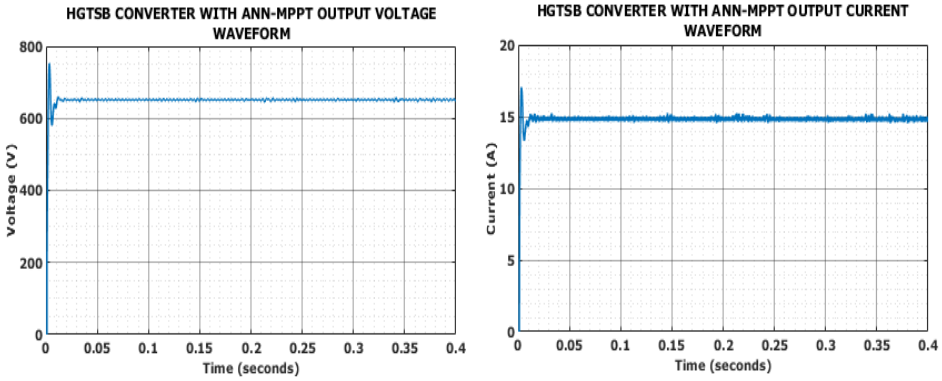


Figure-12. Converter waveform.

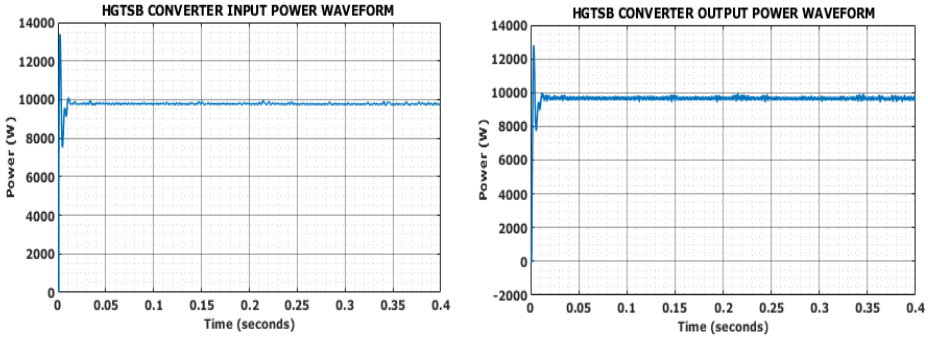


Figure-13. Input and output power waveform.

Figure-12 shows the HGTSB converter with ANN-MPPT output voltage and current Waveforms. The voltage quickly rises and stabilizes at around 620 V, while the current settles at 14.5A, indicating effective voltage boosting and stable power delivery. Figure-13 shows HGTSB converter power waveforms, with input power at 9600 W and output power at 9000 W, indicating efficient energy conversion witAn overall efficiency of about 93.75% using ANN-MPPT.

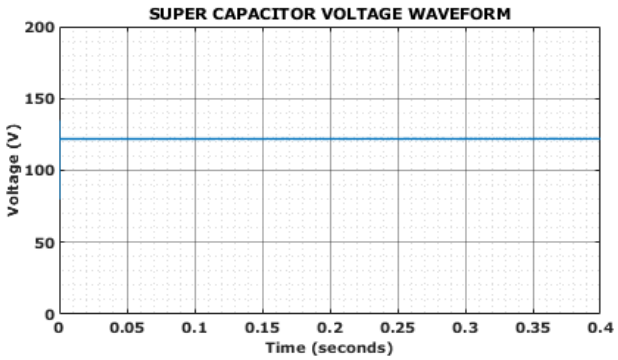


Figure-14. Waveform of the supercapacitor.

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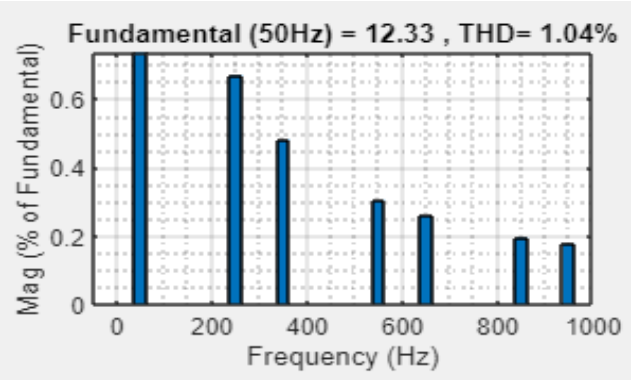


Figure-15. THD waveform.

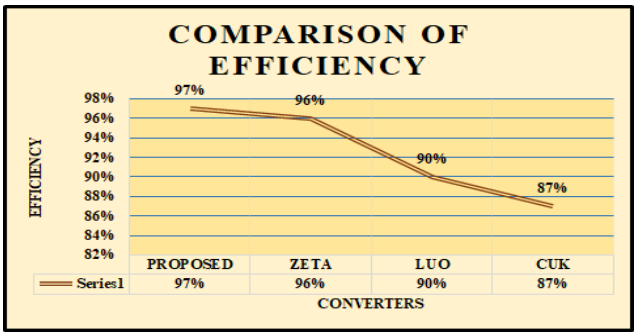


Figure-16. Comparison of efficiency.

Table-2. Comparison of tracking efficiency.

Controller	Tracking Efficiency
Proposed	98%
PSO[14]	96.5%
CSO[15]	95%

Figure-14 shows the supercapacitor voltage waveform over 0.4 seconds, with a steady voltage of about 130 V, indicating reliable energy storage and effective voltage regulation. The THD values for the grid system are presented in Figure-15, highlighting variations in harmonic distortion; the THD value is 2.98%. Figure-16 compares the efficiency of various converters, highlighting that the proposed converter achieves the highest efficiency at 97%, outperforming the ZETA (96%) [11], LUO (90%) [12], and CUK (87%) [13]. Table-2 presents a comparison of tracking efficiency, showing that the proposed system achieves the highest efficiency at 98%.

5. CONCLUSIONS

In this paper, a DSTATCOM based system integrated with a PV source is proposed to enhance power quality in grid connected networks. The HGTSBC efficiently boosts PV output, while a POA-ANN-MPPT ensures optimal energy extraction. Hysteresis current control and dq0-abc transformation with PI controllers enable precise reactive power compensation and load balancing. A supercapacitor further stabilizes voltage during low PV generation. Simulation results (provide numerical values) validate the system's ability to improve voltage stability, reduce harmonics, and enhance power factor, confirming its effectiveness in dynamic grid conditions.

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