

Design of Three-Phase Grid-Connected PV System with Z-Source Boost Converter and Neural Network Based Harmonic Elimination

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Abstract:

The progress towards Renewable Energy Sources (RESs) has highlighted the crucial role of Photovoltaic (PV) systems in meeting the energy demands of the world. As energy from PV system becomes significant, there is need for efficient and high quality grid systems becomes essential. As a consequence, this research proposes a grid connected PV system to address the challenges by integrating Z-Source Boost Converter (ZSBC) and neural network based controller for eliminating harmonics. The ZSBC is employed to overcome the limitations of conventional DC-DC converters, offering greater flexibility in voltage boosting and improved reliability in power conversion. Additionally, the system utilizes a Cascaded Adaptive Neuro-Fuzzy Inference System (ANFIS) based Maximum Power Point Tracking (MPPT) controller to ensure that the PV array operates at its maximum efficiency under all conditions, thereby maximizing energy harvest. To continue high power quality and ensure grid compliance, the system incorporates a DQ based Artificial Neural Network (ANN) controller. The system validation is carried out using MATLAB, with results demonstrating superior performance in terms of 96.42% converter efficiency and 1.23% Total Harmonic Distortion (THD). This innovative approach not only improves the overall efficiency and reliability but also ensures that it meets the requirements of modern grids.

Keywords:

Photovoltaic, ZSBC, Cascaded ANFIS MPPT, DQ based ANN Controller, Harmonic Elimination.

1. Introduction

The gradual progress of small-scale RESs into power grid has been driven by their economic, technical and environmental advantages, even though larger power plants offers several benefits [1, 2]. Solar PV systems are a particularly attractive option since they convert sunlight directly into electrical energy using power electronics. These systems are either connected to grid tied or stand alone units [3]. Nevertheless, before implementation of solar PV system [4], it is crucial to address constraints imposed by existing power generation infrastructure, for ensuring stable and reliable performance under normal operations and during grid faults.

Enhancing PV voltage for compatible grid operation necessitates the utilization of DC-DC converters. Traditionally used Boost converter [5] steps up the input voltage but is limited by maximum duty cycle and reduced efficiency at higher voltages. The Buck-Boost converter [6] increase or decrease voltage, but inverts the polarity, adding design complexity and resulting in higher switching losses. The Cuk converter [7] both step up/ down the voltage while maintaining polarity, but its complex design with extra inductors and capacitors increases size, leading to higher component stress and lower efficiency at high power levels. The Single Ended Primary Inductor Converter (SEPIC) [8] allows non-inverted voltage stepping up or down but has a complex design with a higher component count and causes EMI issues. To overcome these challenges, modified converters have been introduced. The improved quadratic boost converter combined with switch-capacitor cell structure [9], offers ultra-high voltage gain without additional doubler circuit. This reduces the component count, with lower voltage stress and offers continuous source current. But, still requires careful design and control to manage the high voltage gain and ensure stability. Cascaded modified Cuk converter [10], uses cascade design with three cells for accomplish improved gain in voltage. Nevertheless, increased number of components results with higher losses in voltage and necessitates careful designing for maintaining higher efficiency. Another, often used converter is Z-source inverter [11, 12]

developed for addressing limitations of voltage and current source inverters with its unique impedance network. This allows for both boosting of voltage and single stage inversion. But demands sophisticated control strategies to handle shoot-through states and to accomplish boosting of voltage. In addition, the passive components in the topology introduce issues of Electromagnetic Interference (EMI). In response to these challenges, this work introduces a novel ZSBC as a superior alternative.

Renewable energy systems, specifically PV, utilize MPPT for optimal extraction of power. Among the most frequently used traditional approaches are Perturb and Observe (P&O) [13], which increases the system power continuously in same direction. While P&O technique is simple, leads to suboptimal performance. The Incremental Conductance (InCond) [14, 15], performs by examining the slope of power curve in relation with voltage, but results in slower convergence at the MPP, and also difficult for Partial Shading Condition (PSC). Addressing these limitations, the intelligent MPPT techniques have gained importance, using algorithms including Artificial Neural Network (ANN) [16, 17], Fuzzy Logic [18], ANFIS [19], utilize linguistic variables and rule to track the MPP. The major benefits for these mentioned techniques includes handling system non-linearity, and uncertainty without any precise control. Anyhow, designing an effective logic controller necessitates, expert knowledge and proper tuning to optimal performance. Overwhelming the limitations of these approach this paper utilized Cascaded ANFIS MPPT, owing to their faster convergence and better adaptability to dynamic environmental scenarios.

Efficient generation of compensating current for VSI is crucial to improve the quality of power. This paper designs a DQ theory-based ANN to eliminate the harmonics and control the PCC voltage. The key contributions of the proposed work includes:

- ✓ Implementing a novel ZSBC for handling low voltage outputs from PV system and enhancing system efficiency under variable load conditions.
- ✓ Incorporation of Cascaded ANFIS-MPPT algorithm, significantly improves the tracking speed and accuracy, specifically under changing PV scenarios.

- ✓ The combination of dq theory and ANN controller enhances harmonic detection and suppression, providing a faster and more adaptive response to grid variations and nonlinear loads.
- ✓ The system's d-q assisted ANN control allows for managing both active and reactive power, enhancing grid stability and improving system's ability to regulate voltage and frequency.

The paper proceeds with section II presenting the proposed methodology, section III detailing the modelling of system components, section IV covering results and discussion part and section, section V presenting comparison of proposed and existing methods, VI summarizes the conclusion.

2. Proposed System Description

The proposed system demonstrates a Three phase (3Φ) grid-tied PV system designed to efficiently transform solar energy into electrical power for integration into utility grid, shown Figure 1. The DC electricity from PV is fed to ZSBC, which supports in boosting the voltage level for grid integration connection. To ensure, PV system operates at its Maximum Power Point (MPP), Cascaded ANFIS based MPPT is integrated. Controller dynamically adjusts the operating condition of PV array, offering reference signals to control the subsequent power conversion stages.

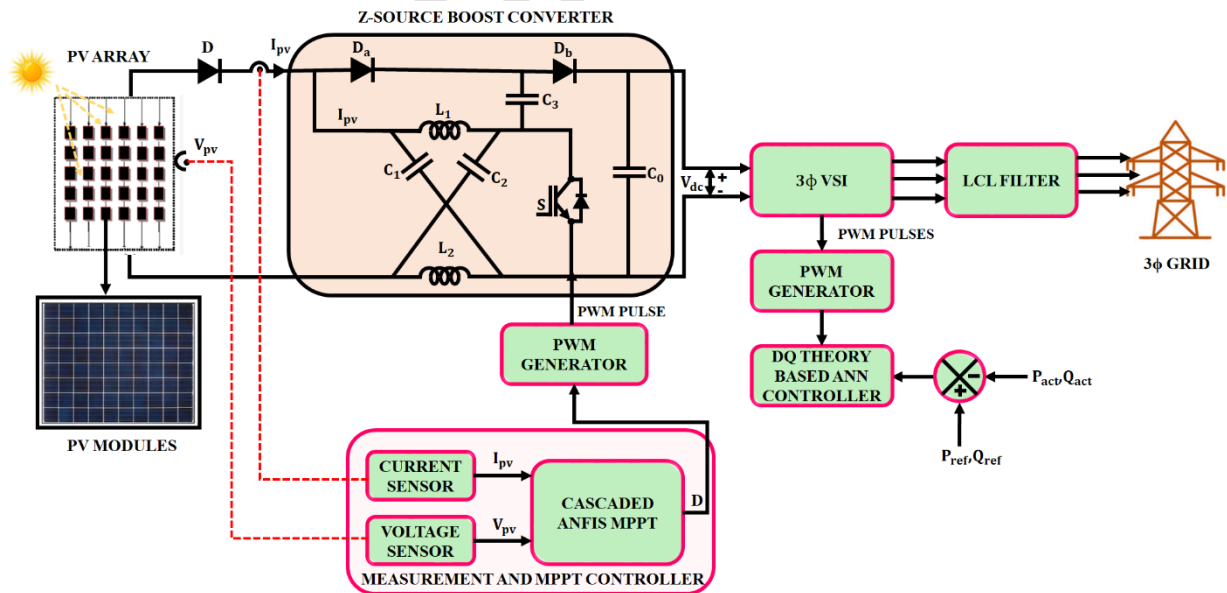


Figure. 1. Proposed System PV Grid System

The attained DC voltage is converted to AC via 3 Φ Voltage Source Inverter (VSI) to be synchronized with grid in terms of voltage, frequency and phase. To ensure the AC output is of high quality, it passes via an LCL filter, eliminating high frequency switching harmonics. The filtered AC output is fed to grid managed by a dq theory based ANN controller. The controller monitors the actual and reactive power output and adjusts the inverters PWM signals to minimize harmonics. This results in ensuring the power delivered to grid meets the desired specifications.

3. Methodology

3-1- Mathematical Modelling of PV System

The research utilizes PV as a source for generating energy. The main purpose of PV system is to stimulate electrical output based on solar irradiance and temperature. A PV cell model is illustrated in Figure 2.

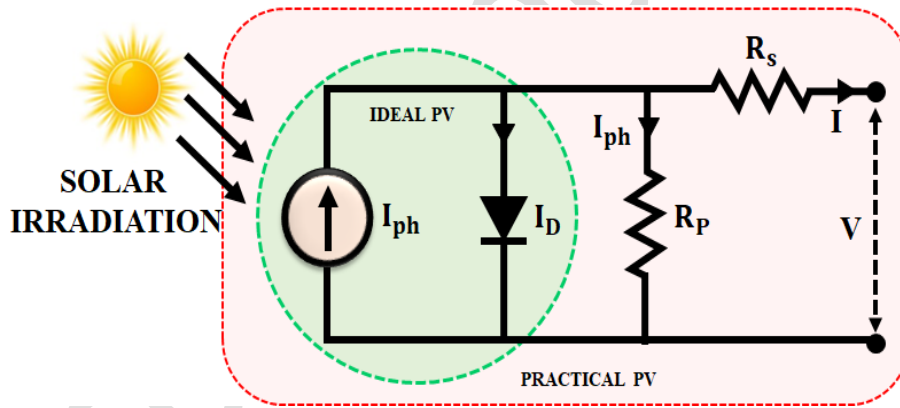


Figure 2. Circuit of Single Diode PV Module

The single diode model is widely adopted. On applying Kirchhoff's current law, the output current is mathematically expressed as Eq (1):

$$I_{out} = I_{ph} - I_0 \left\{ \left[\frac{q(V_{out} + I_{out}R_s)}{AKT_c} \right] - 1 \right\} - \frac{V_{out} + I_{out}R_s}{R_p} \quad (1)$$

Where output current is represented as I_{out} and voltage as V_{out} . The diode saturation current and photocurrent is indicated I_0 and I_{ph} . Resistance linked in series and parallel as R_s and R_p . Moreover, the

electron charge is stated as q , ideality factor by A , Boltzmann's constant as K , and absolute temperature as T_c . However, the voltage for PV source is low, and necessitates DC-DC converter for optimal boosting.

3-2- Operation of Z-Source Boost Converter

In the proposed work, a novel ZSBC is presented shown in Figure 3, which overcomes the limitations of traditional boost and Z-source converters. The developed converters offers higher voltage gain with decreased component stress. The developed converter integrates shoot-through states, resulting in short circuit avoidance and enhanced reliability.

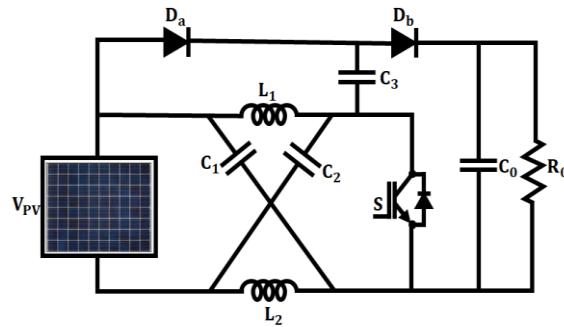


Figure 3. Proposed circuit of ZSBC

In operating mode illustrated in Figure 4(a), both the diode D_b and switch S are in ON state, while diode D_a is deactivated, allowing energy to be stored in inductors L_1 and L_2 . The diode D_a blocks the reverse current from the input, allowing to flow in one direction. And, the diode D_b blocks the current flowing to load.

$$V_{PV} - V_{L_1} + V_{C_2} = 0 \quad (2)$$

$$V_{PV} + V_{C_2} - V_{L_2} = 0 \quad (3)$$

$$V_{C_3} = 0 \quad (4)$$

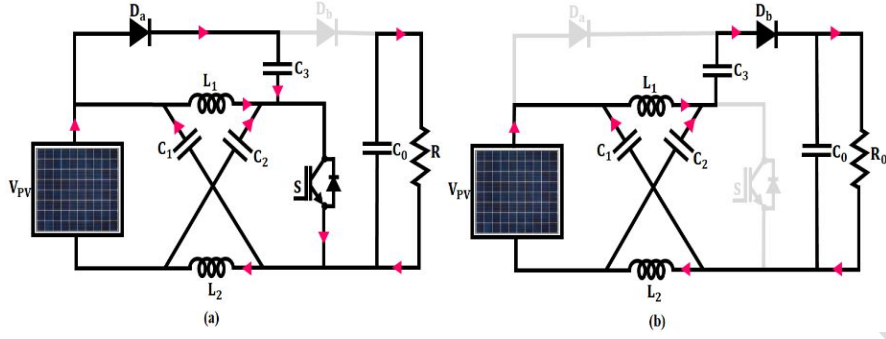


Figure 4. Operation of ZSBC (a) Switch ON State and (b) Switch OFF State

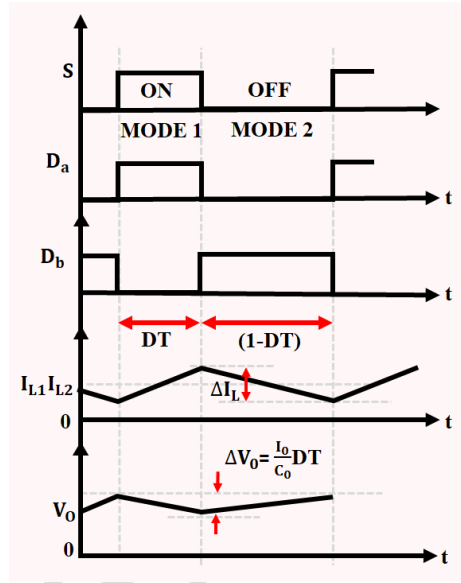


Figure 5. Switching Waveform of Proposed Converter

During this mode diode D_b and Switch S are in OFF state, displays in Figure 4(b) the stored energy in inductors L_1 and L_2 , is released to load through inductors C_3, C_0 and D_b . The Z-source network boosts the voltage, transferring energy from inductors and capacitors to output. The diode D_a is reverse-biased, blocking the input current from flowing back to the source. On applying KVL,

$$V_{L_1} = -V_{C_1} \quad (5)$$

$$V_{L_2} = -V_{C_2} \quad (6)$$

$$V_{PV} + V_{C_1} + V_{C_2} + V_{C_3} = 0 \quad (7)$$

To clearly derive voltage gain, the operation of converter is analyzed in both ON and OFF states. During the ON state, the inductor voltages are,

$$V_{L_1} = V_{in} \quad (8)$$

$$V_{L_2} = V_{in} \quad (9)$$

During the OFF state, the stored inductor energy is released, giving:

$$V_{L_1} = V_{in} - V_{C_1} \quad (10)$$

$$V_{L_2} = V_{in} - V_{C_2} \quad (11)$$

Principle of volt-second balance to inductor L_1 , using Equations (2) and (5), while assuming that $C_1 = C_2$

the expression becomes

$$(V_{C_2} + V_{PV})D - V_{C_1}(1 - D) = 0 \quad (12)$$

$$V_{C_1} = \frac{D(V_{C_2} + V_{PV})}{1 - D} \quad (13)$$

$$V_{C_1} = V_{C_2} = \frac{DV_{PV}}{1 - 2D} \quad (14)$$

$$V_o = V_{C_1} + V_{C_2} = \frac{2V_{in}}{1 - D} \quad (15)$$

On substitution of Equation (14) in (7), the voltage gain Expression becomes,

$$\frac{V_o}{V_{PV}} = \frac{2 - 2D}{1 - 2D} \quad (16)$$

Here, V_{in} is the input voltage from V_{PV} , V_o stands output voltage analog converter (V), D represents duty ratio, L_1 and L_2 are inductors, C_1 and C_2 are the capacitors, i_{L_1} and i_{L_2} represents inductor currents, V_{C_1} and V_{C_2} denotes capacitor voltages, T_s is the switching period (s). Figure 5 illustrates a timing waveform of proposed converter. The ZSBC effectively improves system stability and voltage gain, making it suitable

for PV applications. To enhance the system performance further, integration of MPPT algorithm is essential.

3-3- Cascaded ANFIS MPPT Technique

The Cascaded ANFIS MPPT, which comprises of two ANFIS structures shown in Figure 6, is modelled to optimize the power output from PV system. The system ensures the process of PV at its MPP under changing conditions. ANFIS is effective in modelling complex non-linear functions by adjusting its parameters using input-output data. Its five layers are,

Fuzzification Layer: In this layer the input membership grades are generated and for a given input x and its corresponding fuzzy set A_i , the output is estimated as,

$$O_i^1 = \mu_{A_i}(x) \quad (17)$$

Where, $\mu_{A_i}(x)$ is the membership function.

Rule Layer: Every neuron in this layer resembles to a fuzzy rule combining the input's membership values.

For two inputs x and y ,

$$O_i^2 = \omega_i = \mu_{A_i}(x) \cdot \mu_{B_i}(y) \quad (18)$$

Where, ω_i is the firing strength of rule i .

Normalization Layer: In this layer, the firing strength of the rules are normalized.

$$O_i^3 = \bar{\omega}_i = \frac{\omega_i}{\sum_{j=1}^N \omega_j} \quad (19)$$

Here, $\bar{\omega}_i$ denotes normalized firing strength. N stands total number of fuzzy rules.

Defuzzification Layer: In this layer, a linear function is applied to the inputs, which is weighted by the normalized firing strength.

$$O_i^4 = \bar{\omega}_i \cdot (p_i x + q_i y + r_i) \quad (20)$$

Where, p_i, q_i and r_i are the parameters that have to be learned. x and y are the input variables to the ANFIS.

Output Layer: In this layer, the final output is produced by combining the outputs of all rules.

$$O^5 = \sum_{i=1}^N \bar{\omega}_i \cdot (p_i x + q_i y + r_i) \quad (21)$$

In Cascaded ANFIS, two ANFIS networks act in unison to optimize duty cycle of PV fed converter to ensure MPP operation.

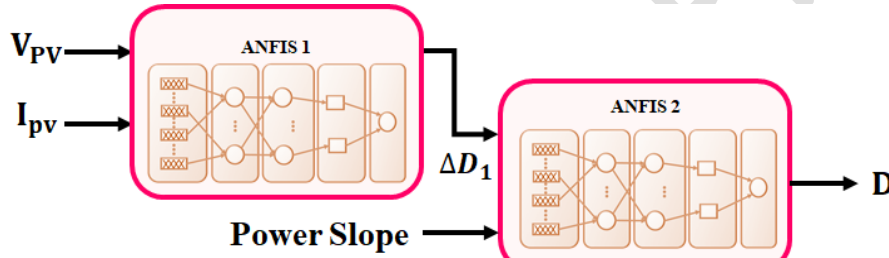


Figure 6. Structure of Cascaded ANFIS

First ANFIS Stage

The first ANFIS takes PV voltage (V_{PV}) and current (I_{PV}) as inputs to control the initial change in the duty cycle (ΔD_1). The input-output relationship for first ANFIS is modelled as,

$$\Delta D_1 = f_1(V_{PV}, I_{PV}) \quad (22)$$

Here, ΔD_1 stands change in duty cycle estimated from the first ANFIS stage based on PV voltage (V_{PV}) and PV current (I_{PV}). The output ΔD_1 is estimated as the defuzzified output from the ANFIS model,

$$\Delta D_1 = \sum_{i=1}^N \omega_i^{-1} (p_i^1 V_{PV} + q_i^1 I_{PV} + r_i^1) \quad (23)$$

Second ANFIS Stage

In second ANFIS stage, the output of first stage is refined by considering ΔD_1 and the power slope $\left(\frac{dP_{PV}}{dV_{PV}}\right)$

$$\Delta D = \sum_{i=1}^N \omega_i^{-2} \left(p_i^2 \Delta D_1 + q_i^2 \frac{dP_{PV}}{dV_{PV}} + r_i^2 \right) \quad (24)$$

Where,

$$\frac{dP_{PV}}{dV_{PV}} = I_{PV} + V_{PV} \cdot \frac{dI_{PV}}{dV_{PV}} \quad (25)$$

The power slope offers an understanding of the relationship between power and voltage, which in turn helps the system to optimize the duty cycle. To ensure replicability, the ANFIS structure is defined as follows. Each stage consists of five layers: fuzzification, rule, normalization, defuzzification, and output. In this case, triangular membership functions are used with three membership functions defined for each input variable (V_{PV} , I_{PV} , and power slope $\frac{dP_{PV}}{dV_{PV}}$). The fuzzy rule base, consisting of 9 IF-THEN rules, in each stage allows effective mapping between inputs and shift in the duty cycle. The training dataset is created from simulated PV characteristics under varying irradiance ($800-1000 \text{ W/m}^2$) and temperature ($20-40^\circ\text{C}$), producing nearly 10,000 iterations. The dataset is divided into training (70%), validation (15%), and testing (15%). The combination of least-squares assessment and gradient descent is used to fit parameters to fast convergence and tune rules effectively. This structure helps the system converge faster to the MPP by effectively using the feedback from the first ANFIS output.

3-4- DQ theory-based ANN Controller

The proposed work utilizes dq theory-based ANN controller for ensuring efficient control of both active and reactive power in developed PV-grid system. These advanced control techniques offer accurate regulation of power and mitigation of harmonics. The control process starts by sensing the 3ϕ voltage

(V_a, V_b, V_c) and current (i_a, i_b, i_c) signals from the system. These signals are then handled using a Phase Locked Loop (PLL) to produce sine and cosine signals, to ensure that the reference frame aligns with the grid voltage for optimal control.

By applying Park's transformation the 3ϕ current gets converted into dq frame. This transformation rotates the reference frame in synchronization with grid voltage. The transformation from coordinates of $\alpha\beta$ into dq frame is given by

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (26)$$

Where current components of dq frame is noted as i_d and i_q , with i_d corresponding to active power and reactive power as i_q . The system's goal is to regulate actual power output to match desired reference values for both active and reactive power. The actual power values are calculated as:

$$\Delta P = P_{ref} - P_{act} \quad (27)$$

$$\Delta Q = Q_{ref} - Q_{act} \quad (28)$$

The error signals ΔP and ΔQ are inputs to ANN controller, which uses its learning and adaptive capabilities to compute the required control actions. This is crucial for non-linear system dynamics, where conventional control methods might struggle. The ANN adapts based on historical data and real-time conditions, ensuring optimal control of the PWM signals for the VSI. Once ANN processes the control signal, reverse Park transformation is applied for conversion of dq signals back to $3\Phi abc$ reference frame for generation of appropriate reference signals for PWM generator. The reverse transformation is expressed by

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{ddc} \\ i_{qdc} \end{bmatrix} \quad (29)$$

Here, i_α , and i_β are transformed current components in the stationary $\alpha - \beta$ frame. For generation of reference current in abc frame, the following transformation is used

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1/2 & \sqrt{3}/2 \\ 1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (30)$$

The reference current signals are indicated as i_{sa}^* , i_{sb}^* and i_{sc}^* , are used to control the switching pulses of VSI. The ANN controller is based on a multi-layer feedforward neural network structure. It has an input layer with two neurons corresponding to the error signal (ΔP and ΔQ), followed by two hidden layers, which contain 15 and 10 neurons. The tansigmoid activation function is operates in hidden layers, while a linear activation function is operates in output layer to generate control signals. The Levenberg-Marquardt backpropagation algorithm is used for training, which has fast convergence properties when applied to non-linear control problems. The training dataset for the ANN controller is developed from simulation data of the PV-grid system at different loads and irradiance conditions. This simulation dataset had a total of 12,000 samples, and was split into a training (70 %), validation (15 %), and testing (15 %) set. Combination of dq theory and ANN ensures precise regulation of active and reactive power, improving power quality through reducing harmonic distortion and enhancing grid stability. The ANN controller's learning capability allows it to adapt to system changes (e.g., fluctuating solar irradiance in PV systems) more efficiently than traditional controllers.

4. Results and Discussion

This section explores, microgrid system integrating a ZSBC along with Cascaded ANFIS MPPT controller is discussed. Additionally, the system's capability to step up voltage from PV, tracking of MPPT and mitigation of harmonics is also evaluated under varying conditions. Table 1 offers the key specification of system components. A comprehensive assessment of converter's effectiveness in elimination of harmonics is also discussed.

Table 1. System Specification

Component	Symbol	Specification
PV System		
<i>Maximum Power</i>	P_{\max}	10kW
<i>No. of Cells in Series</i>	N_s	3
<i>No. of Cells in Parallel</i>	N_p	15
<i>Voltage at P_{MPP}</i>	V_{MPP}	29.95V
<i>Current at P_{MPP}</i>	I_{MPP}	8.35Amps
<i>Short Circuit Current</i>	I_{SC}	8.95Amps
<i>Open Circuit Voltage</i>	V_{OC}	37.25V
<i>Irradiance</i>	G	1000W / m ²
<i>Temperature</i>	T	35°C
ZSBC		
<i>Capcitor</i>	C_1, C_2, C_3	22 μ F
<i>Output Capcitor</i>	C_0	2200 μ F
<i>Inductor</i>	L_1, L_2	4.7mH
<i>Switching Frequency</i>	f_s	10kHz
<i>Input voltage</i>	V_{in}	80V
<i>Output voltage</i>	V_{out}	900V
Grid and filter		
<i>Grid voltage</i>	V_{grid}	415V
<i>Grid frequency</i>	f_{grid}	50Hz
<i>Filter type</i>	-	LCL filter
<i>Filter inductance</i>	Lf	2mH
<i>Filter capacitance</i>	Cf	50 μ F
Simulation Measurement		
<i>Simulation solver</i>	-	Ode45
<i>Step time</i>	-	0.2s

Table 2. Experimental/Simulation Environmental Conditions

Case	Time (s)	Irradiance (W / m ²)	Temperature (°C)	Operating condition
Case 1	0-0.5	1000	35	Constant irradiance and temperature
Case 2	0-0.2	800	25	Reduced irradiance, constant temperature
Case 2	0.2-0.3	800	35	Temperature step increase

Case 2	0.3-0.5	1000	35	Irradiance step increase
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The system is assessed under two different environmental states, as outlined in Table 2. Case 1 represents steady-state working conditions such as irradiance 1000 W/m^2 and 25°C , while case 2 represents dynamically changing conditions with step changes in irradiance and temperature, simulating realistic partial shading and atmospheric variations. These test scenarios provide comprehensive validation of the system's performance characteristics under stable and quickly changing operating environments.

Case 1: Steady State Condition

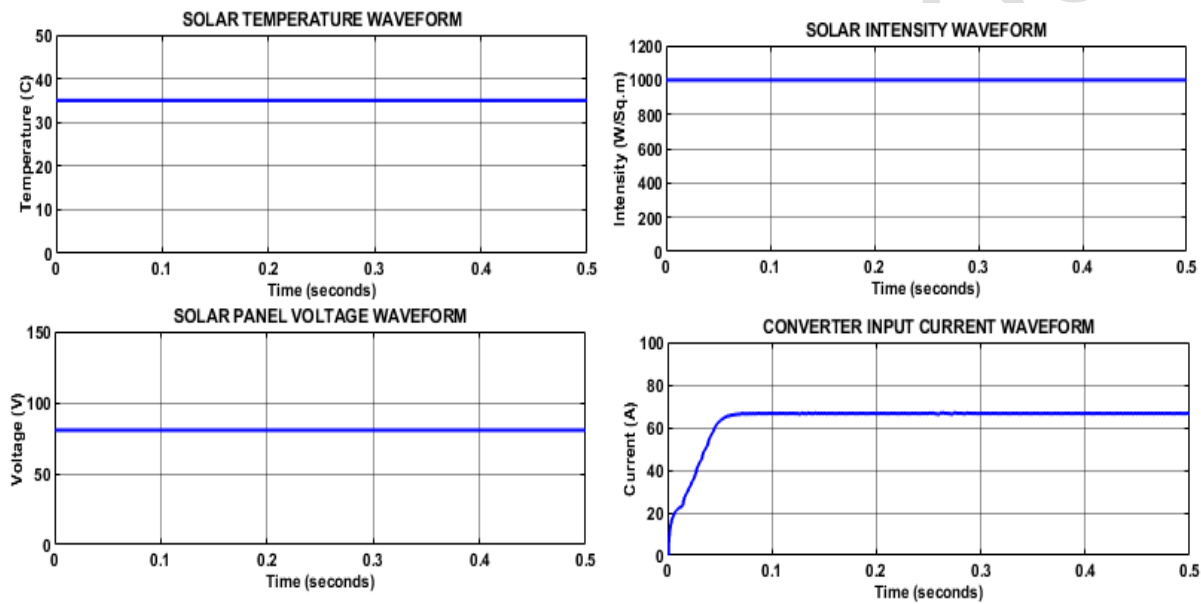


Figure 7. PV Performance at Steady State Condition

To analyse the performance of developed system, at first the performance is examined under constant condition of temperature and intensity, shown in Figure 7. It is noted that, the temperature is maintained at a constant of 35°C , with irradiance at 1000 W/m^2 . In response to this steady state condition, the PV panel continues with a constant voltage of 80 V , with current showing initial rise and maintained at 65 A , without any further oscillations. Under this condition, response of proposed converter is demonstrated in Figure 8.

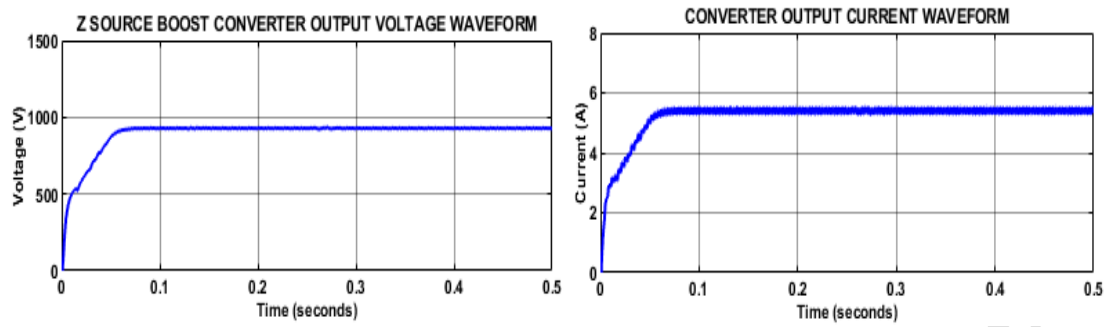


Figure 8. Proposed ZSBC Output Waveform

The proposed converter shows enhanced voltage level, from the input voltage. It is noticed that, a step up voltage of 900V is attained, after 0.1s with initial rise. Similarly, followed by initial variations a stabilized current of 5.4A is accomplished. This determines the superiority of developed converter towards boosting of voltage.

Case 2: Fluctuating condition

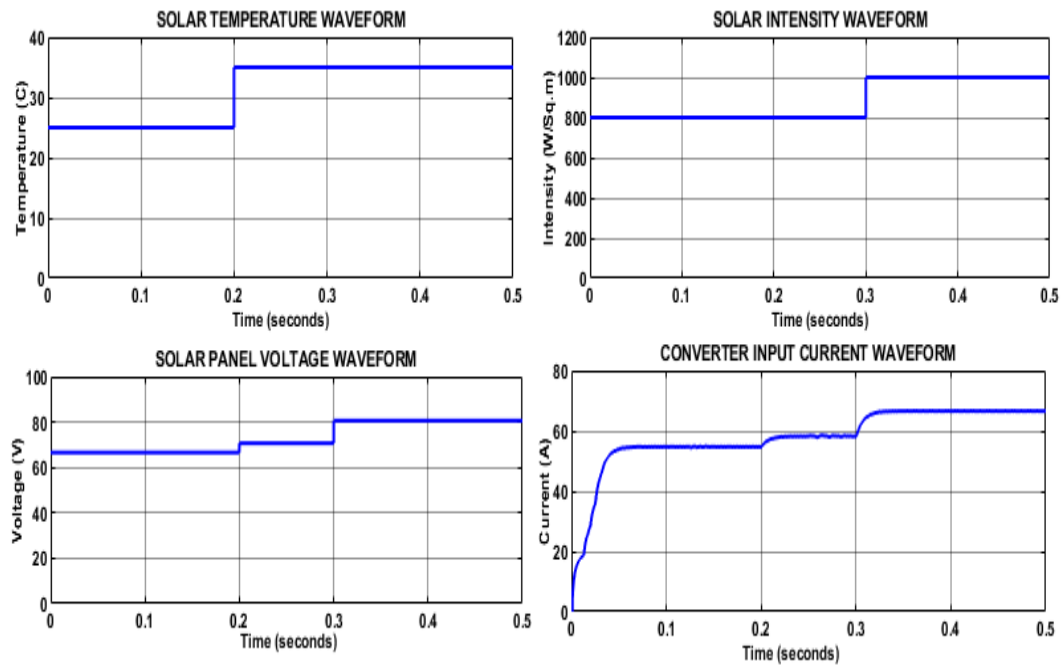


Figure 9. PV Performance at Varying Environmental Condition

Similarly, to know the effectiveness of developed system, it is also examined under varying condition shown in Figure 9. The temperature waveform shows constant performance with 25°C till 0.2s, after the

temperature rises and continues at 25°C , without any further changes. Meanwhile, the intensity is sustained at $800\text{W}/\text{m}^2$, till 0.3s, after the intensity level rises and follows as $1000\text{W}/\text{m}^2$. According to this scenario, the voltage observed by PV panel shows step response in voltage level and finally continues at 80V. In correspondence, the input current to the converter shows same, step variations and continues at 63A, after 0.32s.

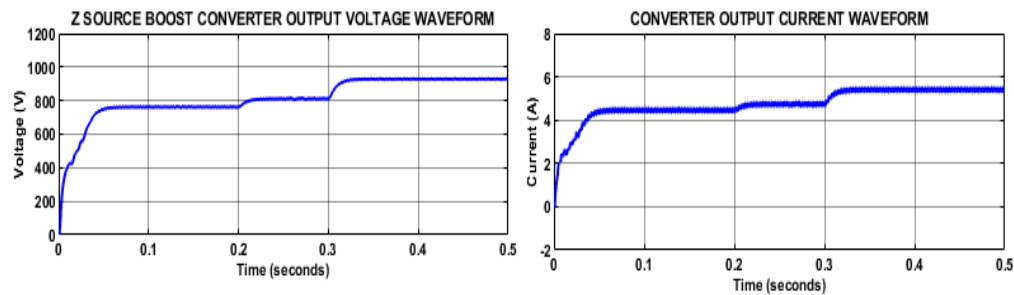


Figure 10. Converter Performance at Varying Environmental Condition

For the condition of changing temperature and intensity, the proposed converter shows step distinctions in voltage and current, shown in Figure 10. However, the converter effectively boost the level of voltage and continues at 900V after 0.33s, without any oscillations further. Whereas, the current waveform of proposed converter maintains a constant value of 5.4A after 0.33s, which initial step changes.

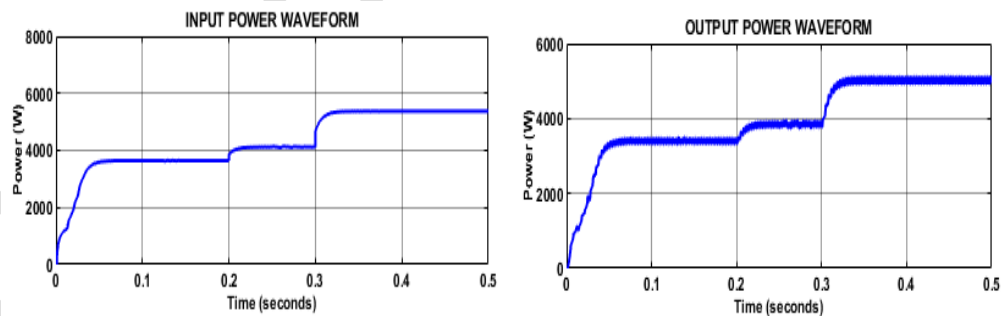


Figure 11. Power response of PV and Converter

For the developed system the power response under changing temperature and condition is shown in Figure 11. It is noticed that an input power measure of 5040W is observed followed the converter output power is 4860W, which is the MPP accomplished with the assistance of Cascaded ANFIS MPPT approach.

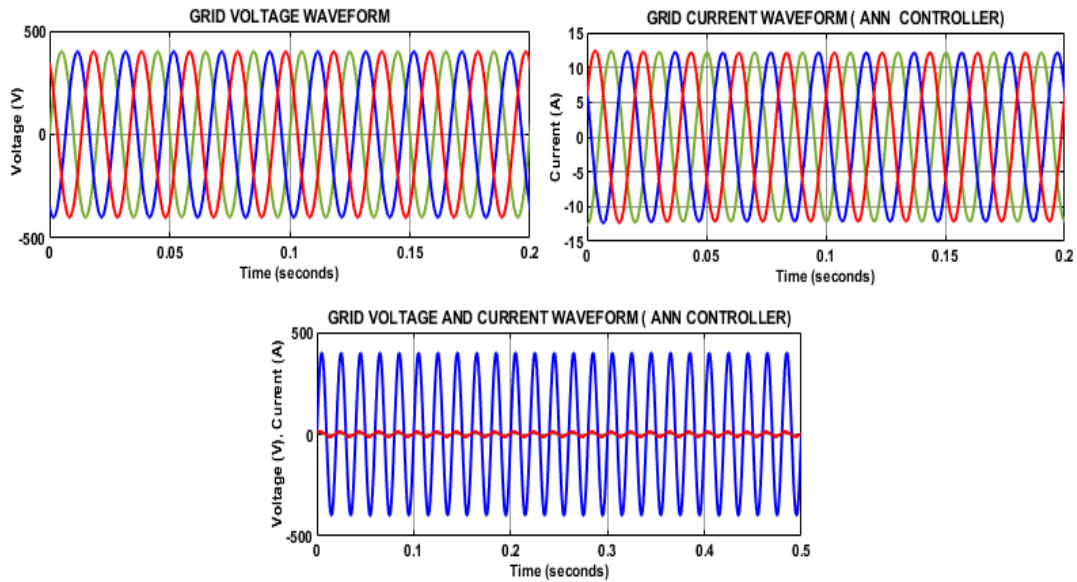


Figure 12. Grid Waveforms

For the developed 3Φ grid system, the accomplished voltage, current and in-phase response is explained in Figure 12. It is observed that, a steady voltage of 415V with current measuring 12A. This shows the performance of ANN controller is achieving stabilized grid performance. Moreover, the in-phase waveform demonstrates the synchronization of voltage and current delivered to grid.

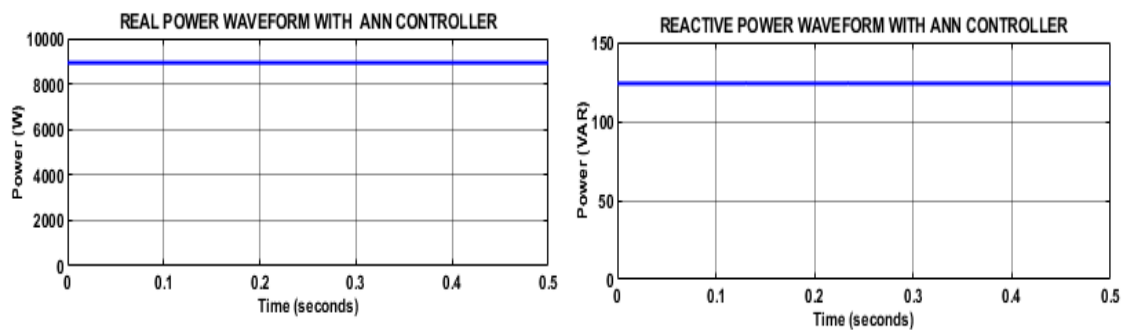


Figure 13. Real and Reactive Power Waveform with ANN Controller

In assistance with ANN based DQ theory, the proposed system maintains a stable real power output, with minimal fluctuations, demonstrating efficient system regulation. Whereas, the reactive power remains low, revealing a near unity power factor with minimized losses in energy, shown in Figure 13.

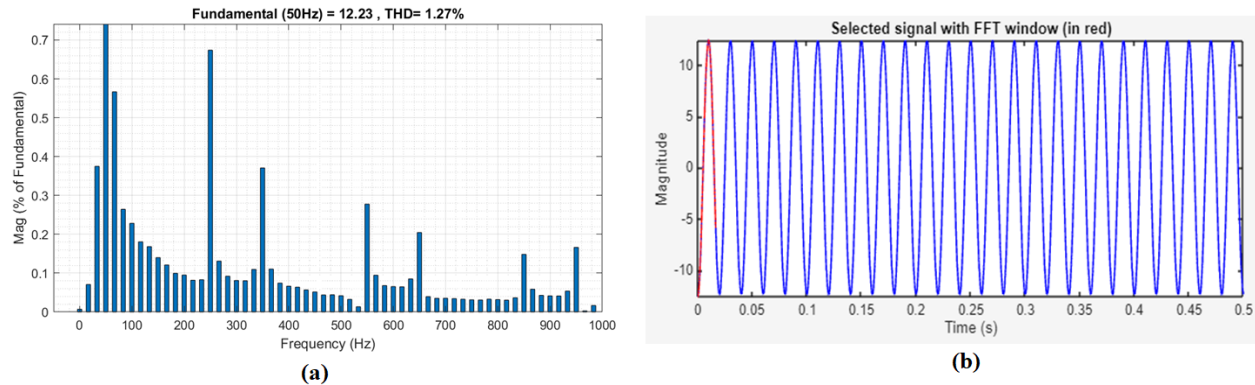


Figure 14. THD Waveform and FFT plot of Grid Current

Figure 14(a) contains the grid current waveform and the actual measured THD. The dq-ANN controller has maintain a current sinusoidal and well synchronized with the grid voltage, exhibiting limited distortion. The THD value is maintained to be 1.27%, exceeding the IEEE 519 limit of 5%, confirmation reliable grid integration with excellent power quality. Low distortion also shows superior suppression of higher-order harmonics, which means stable operations with disturbances. Figure 14 (b) indicates the segment of the grid current signal that is selected by the authors for FFT analysis. The sinusoidal shape represents the steady-state grid current and the area highlighted in red depicts the sampling window for the computation of the Fast Fourier Transform. This ensures that the harmonic spectrum is assessed while operating under steady conditions and therefore provide an accurate reading of the distortion level on current.

5. Comparative Analysis

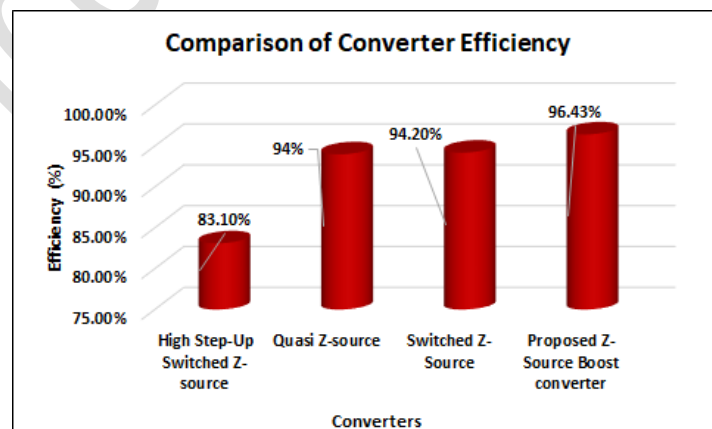


Figure 15. Comparative Analysis of Converter Efficiency

The comparison efficiency for different converter topologies is represented in Figure 15. The proposed ZSBC accomplishes highest efficiency of 96.42%, outperforming high step-up switched Z-source [20] with 83.1%, quasi Z-source converter [21] with 94%, and switched Z-source [22] with 94.2%, making it superior for renewable energy applications.

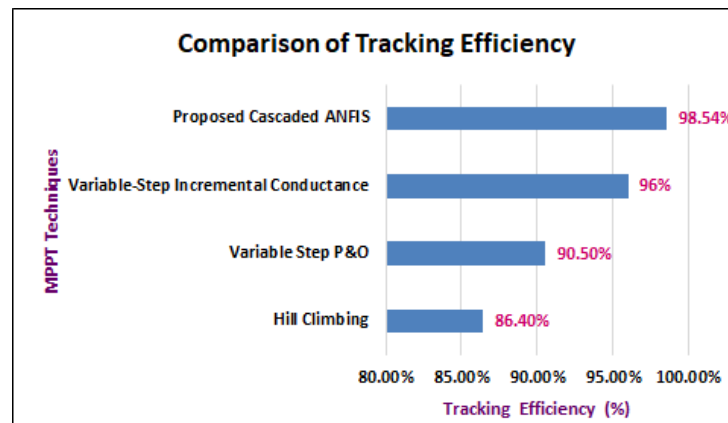


Figure 16. Comparison of MPPT Tracking Efficiency

The comparative analysis of various MPPT techniques utilized for tracking of PV power is demonstrated in Figure 16. Hill climbing [23] have the lowest tracking efficiency of 86.40%, variable step incremental conductance [24] achieves 96% and variable step P&O [25] accomplishes 90.50%. The proposed Cascaded ANFIS MPPT demonstrates the highest efficiency of 98.54%, outperforming existing techniques owing to its adaptive intelligence, enabling accurate and faster tracking MPP.

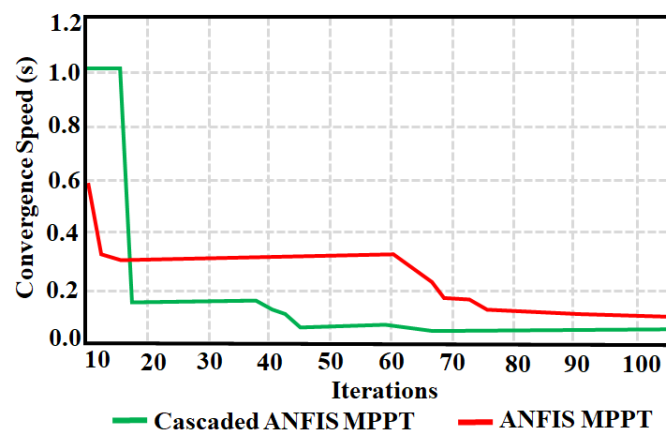


Figure 17. Comparison of Convergence Speed vs. Iteration

The convergence speed of comparison of ANFIS and Cascaded ANFIS MPPT is represented in Figure 17. The cascaded ANFIS MPPT outperforms the traditional ANFIS MPPT owing to its multi-stage structure, with fine adjustment allowing for faster tracking of MPP. Moreover, it reduces the iterations and avoids local optima, allowing for faster stabilization.

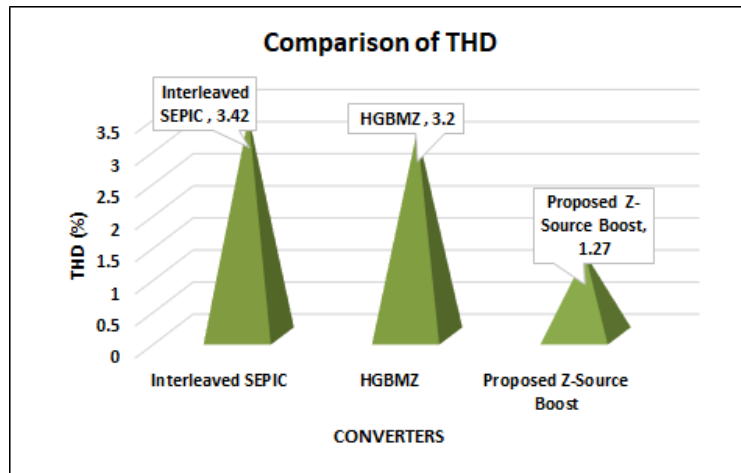


Figure 18. THD Assessment

The evaluation of THD for various converter is illustrated in Figure 18, the graph displays that the Z-source Boost converter reaches lowest THD of 1.27%, together with the assistance of ANN controller based dq theory, overtaking other converters like Interleaved SEPIC [26] with 3.42% and High Gain Bidirectional Modified Zeta (HGBMZ) [27] with 3.2%, respectively.

Table 3. Comparison of Converter's Components Count

CONVERTERS	High step-up [28]	Interleaved quadratic Boost [29]	Interleaved high gain boost [30]	Proposed
SWITCH	1	2	2	1
CAPACITOR	4	3	5	4
INDUCTOR	2	3	2	2
DIODE	4	4	5	2
TOTAL COMPONENTS	11	12	14	9
EFFICIENCY (%)	95.2%	96%	96%	96.42%

Table 3 presents a review of proposed converter with other state-of-the-art high-gain converter topologies based on components used and the efficiencies achieved. The results show that the proposed converter used fewer components (only 9) than the alternatives while also providing the greatest efficiency of 96.42%.

Fewer components achieved a benefits of lower conduction losses, low-priced, and more reliable. As well, the proposed converter utilized one switch with arranged passive components to lessen voltage stress and increase power density.

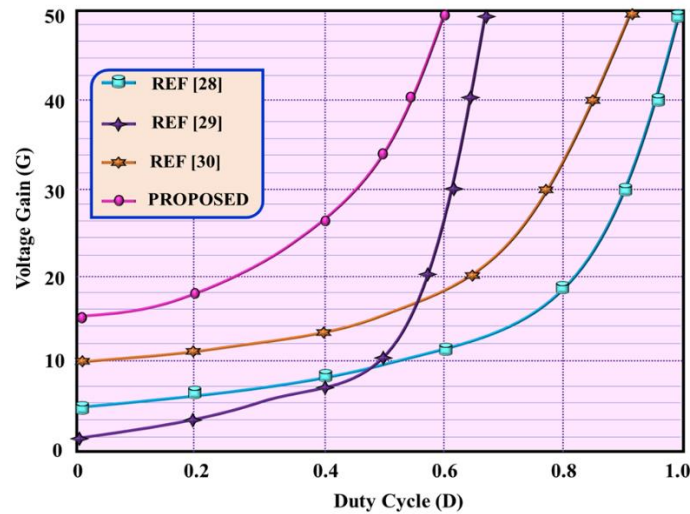


Figure 19. Comparison of converters' voltage gain

Figure 19 compares the duty cycle and voltage gain for proposed ZSBC, and three more recent high-gain designs - High Step-Up [28], Interleaved Quadratic Boost [29], and Interleaved High Gain Boost [30]. The proposed converter comparatively provides more gain at lower duty cycles than conventional topologies, but also let the application to reduce switching stress and increase efficiency. This property emphasizes the advantages of the proposed topology since PV applications require low input voltage and high boosting capability. While the voltage gain of the proposed ZSBC increases dramatically beyond duty ratios greater than 0.6, the system is intentionally kept within the stable range of 0.35-0.55. Furthermore, the Cascaded ANFIS MPPT enables seamless duty cycle transitions, while the impedance network automatically reduces current spikes, eliminating control instability while retaining dynamic robustness.

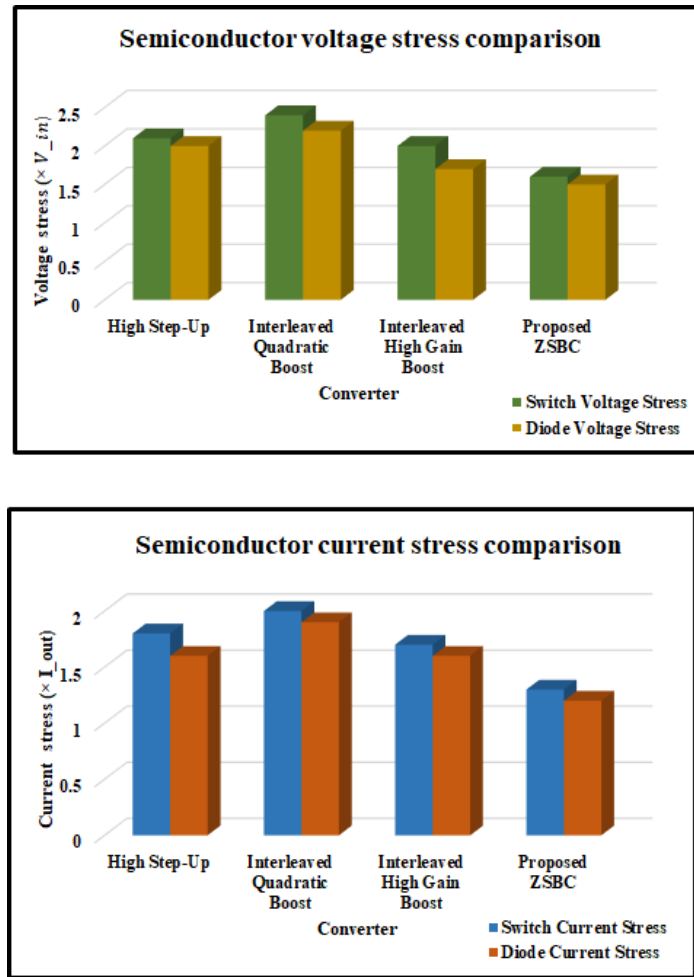


Figure 20. Comparison of voltage and current stress

Figure 20 shows switch and diode voltage stress for four converter types: High Step-Up [28], Interleaved Quadratic Boost [29], Interleaved High-Gain Boost [30], and the proposed ZSBC. Conventional converters have higher semiconductor voltage and current stress. In comparison, the Proposed ZSBC has the lowest voltage stress for both the switch and the diode, indicating increased device reliability and lower voltage rating requirements. Similarly proposed ZSBC greatly reduces switch and diode current stress. This reduced voltage and current stress helps to reduce conduction losses, improve efficiency, and increase component lifespan.

6. Conclusion

This research proposes a microgrid system, incorporating Z-Source Boost converter and cascaded ANFIS MPPT and neural network assisted dq theory for elimination of harmonics. The developed boost converter effectively boost effectively improves the voltage generated by PV system, resulting in higher voltage conversion rates, with minimal loss of energy. The Cascaded ANFIS MPPT accurately tracks the MPP, optimizing the extraction of PV energy under varying temperature and irradiance conditions. Simulation results from MATLAB demonstrate that the system achieves a notable converter efficiency of 96.42%, with tracking efficiency of 98.54% by the Cascaded ANFIS MPPT approach. The ANN based DQ theory, further enhances the system's performance by effectively managing the real and reactive power, with THD resulting as low as 1.27%, resulting in high quality of power delivered to grid. This lower THD, and minimal reactive power output demonstrate that the system operates with minimal harmonics and better power factor, making it suitable for grid integration.

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