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A Novel Single-Stage Buck-Boost Transformerless Inverter with Fuzzy Control for Single Phase Grid-Connected Solar PV Systems

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Abstract

This work presents a novel single-stage buck–boost transformerless inverter (BBTI) suitable for single-phase grid-connected photovoltaic (PV) systems. In the proposed structure, the PV source is directly referenced to the grid neutral, thereby eliminating leakage currents and enhancing operational safety. Unlike conventional inverter designs, the topology offers wide operational flexibility through its inherent buck–boost capability, ensuring reliable maximum power point tracking (MPPT) under varying solar input conditions. The inverter operates solely with switched capacitors and requires no inductors, which guarantees symmetrical performance during both positive and negative half cycles while minimizing overall system size and cost. A simple sinusoidal–triangular pulse-width modulation (SPWM) scheme is employed to regulate switching states, and fuzzy logic control is incorporated to improve dynamic response. The proposed configuration has been validated through MATLAB/Simulink simulations, demonstrating reliable operation, improved efficiency, and strong suitability for grid integration of PV sources.

1. INTRODUCTION

The growing penetration of photovoltaic (PV) energy into modern power networks has created a strong demand for compact, efficient, and economically viable grid-connected inverter topologies. Transformerless inverters have become a promising solution, as they eliminate bulky line-frequency transformers, thereby improving efficiency, reducing system cost and achieving higher power density [1]. However these designs are inherently prone to common-mode leakage currents, mainly arising from parasitic capacitances between the PV array and ground[2]. Such leakage currents not only raise safety concerns but also degrade power quality and electromagnetic compatibility, often leading to non-compliance with international standards.

Several researchers have investigated different single-phase transformerless inverter structures to address these challenges. Traditional string and central inverter configurations are effective for high-voltage PV arrays but fail to operate efficiently under low-voltage or shaded conditions due to the absence of buck–boost functionality[3]. To overcome this, buck-boost derived inverters have been explored. Although existing designs extend the input operating range, they often depend on multiple inductors, large electrolytic capacitors, or a high number of switching devices. These requirements lead to higher conduction losses, increased cost, and added control complexity. In addition, many of these topologies suffer from considerable total harmonic distortion (THD) or DC injection into the grid, which limits their practical use.

To overcome these challenges, this work proposes a single-stage buck–boost transformerless inverter (BBTI). The proposed topology is realized using only four controllable switches in combination with switched capacitors, thereby eliminating inductors and reducing overall system bulk. A common grounding is maintained between the PV array and the grid neutral, which effectively suppresses leakage currents[4]. Furthermore, the topology ensures symmetrical operation during both positive and negative half cycles, thereby minimizing DC injection. Its inherent buck–boost capability enables efficient power extraction from PV modules across a wide range of irradiance and temperature conditions.

To enhance system reliability and control accuracy, a fuzzy logic controller (FLC) is incorporated. Unlike conventional proportional–integral (PI) controllers, which often exhibit limited adaptability under nonlinear or time-varying PV conditions, the FLC dynamically adjusts inverter operation through rule-based inference. This provides faster transient response, reduced steady-state error, and improved efficiency in grid integration [5].

The main contributions of this work are summarized as follows. First, a novel single-stage buck–boost transformerless inverter (BBTI) is introduced, utilizing four power switches with switched capacitors, eliminating the need for inductor. This configuration eliminates the need for bulky inductors, resulting in a more compact design. Second by referencing the PV source directly to the grid neutral, the proposed topology. eliminates leakage current and minimizes DC injection, thereby addressing a key challenge in transformerless PV inverters. Third the inherent buck–boost feature extends the operating range, and ensures stable performance under fluctuating PV input voltages [6]. Fourth, a fuzzy logic controller is integrated to enhance maximum power point tracking (MPPT) and improve dynamic stability, particularly under rapidly changing solar irradiance conditions. Finally, extensive simulation studies conducted in MATLAB/Simulink demonstrate the effectiveness of the proposed approach, showing an efficiency improvement of up to 87.5% and confirming its suitability for reliable residential grid-connected PV applications.

2. Experimental or Materials and Methods

RELATED WORK

Research on transformerless inverter topologies for grid-connected photovoltaic (PV) systems has gained considerable momentum in recent years. A major challenge in such systems is the elimination of leakage current, which originates from parasitic capacitance between the PV array and the ground. Various single-phase inverter configurations have been explored to address this issue while maintaining high efficiency and wide input voltage operation[7].

Several studies have reviewed the state-of-the-art of transformerless PV inverters, highlighting the trade-offs among efficiency, safety, and compliance with electromagnetic interference (EMI) standards. Active buck–boost inverter structures have been investigated to address the wide input voltage range of PV systems, employing active switching units to realize buck–boost operation without the need for bulky passive components. While these designs improve power density, the associated switching complexity places greater demands on control.

Other studies have focused on single-stage transformerless inverters with common-ground configurations[8]. By directly referencing the PV negative terminal to the grid neutral, these topologies effectively suppress leakage current and improve safety. However, they frequently rely on large input capacitors or additional passive elements to achieve maximum power point tracking (MPPT), which increases system size and cost.

Alternative solutions include common-mode transformerless designs, where the PV terminal is aligned with the grid neutral to limit leakage currents. Although effective in suppressing leakage, such systems typically suffer from higher conduction losses due to the simultaneous operation of multiple switches. Similarly, single-stage buck–boost architectures have been proposed to achieve high gain and compactness, but they generally require several inductors and capacitors, which increase hardware complexity and reduced efficiency[9].

Ćuk-derived microinverter designs have also been reported, offering high efficiency and continuous conduction operation. These systems can operate with both linear and nonlinear loads however the use of second-order filters complicates the control strategy and increases implementation costs. Four-switch single-stage buck–boost inverters have shown promise in reducing component count while maintaining common-ground operation, but their dependence on additional diodes and large capacitors limits their power density.

Overall, the literature shows that although considerable progress has been achieved in development of transformerless inverters with leakage current suppression and buck–boost capability, many existing solutions continues to face challenges such as high switch counts, bulky passive components, elevated conduction losses, or total harmonic distortion beyond IEEE limits[10]. These limitations highlight the need for a compact, reliable, and efficient single-stage buck–boost inverter that eliminates leakage currents, minimizes DC injection, and delivers robust performance for grid-connected PV applications.

PROBLEM STATEMENT

Conventional transformerless inverters for photovoltaic (PV) systems continue to challenges such as leakage current, high switch count, bulky passive components, and limited flexibility under varying solar conditions. Design that rely on inductors or multiple PV sources often increase system size, cost, and conduction losses, thereby restricting their practical applicability. Meanwhile, capacitor-based designs often demand large capacitance values to maintain stable operation. Furthermore, several existing approaches suffer from asymmetrical operation between positive and negative half cycles, leading to undesirable DC current injection into the grid. These drawbacks compromise both efficiency and reliability, and in some cases, prevent compliance with grid interconnection standards.

To overcome these limitations, there is a need for a single-stage inverter topology that provides both buck and boost capabilities, ensures symmetrical operation across both half cycles, eliminates leakage current through common grounding, and minimizes the number of controllable switches. Such a topology would not only enhance efficiency and reliability but also enable robust maximum power point tracking across a wide range of PV operating conditions, thereby improving the overall performance of grid-connected solar systems.

PROPOSED METHODOLGY

The proposed methodology introduces a single-stage buck–boost transformerless inverter (BBTI) designed for single-phase grid-connected photovoltaic (PV) applications. The development framework includes PV source modeling, inverter topology, switching modes, modulation and control strategy, and verification through simulation.

A. PV Source Modeling

The PV source is modeled using the single-diode equivalent circuit comprising a photocurrent generator, diode, series resistance, and shunt resistance. The current–voltage relationship is expressed as:

$$I = Iph - I0 * (\exp((q * (V + I * Rs)) / (n * k * T)) - 1) - (V + I * R) / Rsh$$

where I_{ph} is the photocurrent dependent on irradiance, I_0 is the reverse saturation current, Rsare the series and shunt resistances, qqq is the electronic charge, nnn is the diode ideality factor, k is Boltzmann's constant, and T is the cell temperature. This model captures PV nonlinearity and environmental sensitivity.

B. Inverter Topology

The proposed BBTI structure employs four controllable switches, two diodes, and four capacitors. Unlike conventional inductor-based converters, the capacitors self-charge to defined voltage levels, thereby generating multiple voltage steps without bulky magnetic components.

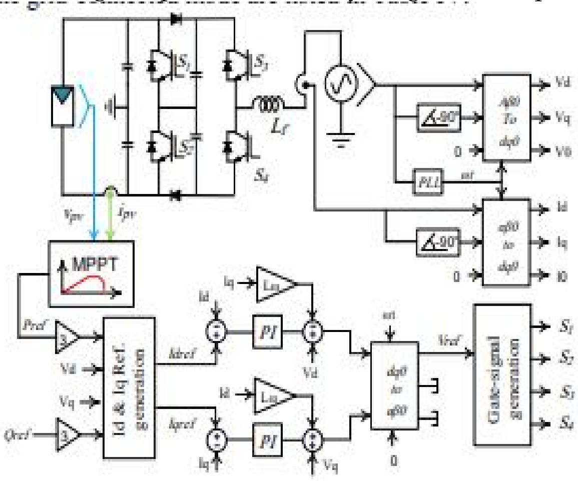

Fig. 1. Proposed single-stage buck–boost transformerless inverter topology.

The PV negative terminal is connected directly to the grid neutral, which eliminates common-mode leakage currents and enhances safety. The maximum attainable output voltage is:
Vo,peak = 23Vdc demonstrating both buck and boost capability within a single stage.

C. Modes of Operation

The BBTI functions through four switching modes corresponding to the positive and negative half cycles of the grid.

Mode (a): Switches S2 and S3 conduct, producing $0.5V_{dc}$ while charging capacitor Cu2.

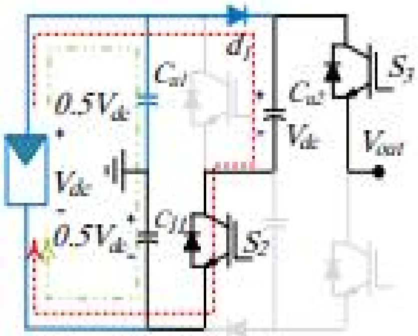

Fig.2. Switching states of the proposed inverter Mode (a)

Mode (b): Switches S1 and S3 conduct, combining Cu1 and Cu2 to generate $1.5V_{dc}$, with Cl2 charging simultaneously.

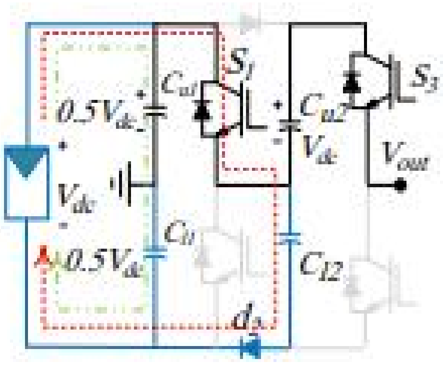

Fig.3. Switching states of the proposed inverter Mode (b)

Mode (c): Switches S1 and S4 conduct, yielding $-0.5V_{dc}$, with Cl2 charging via the DC source.

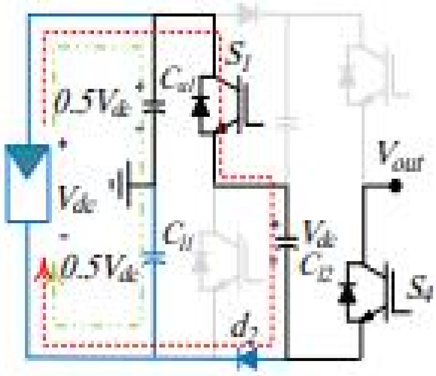

Fig.4. Switching states of the proposed inverter Mode ©

Mode (d): Switches S2 and S4 conduct, generating $-1.5V_{dc}$, while Cu2 recharges.

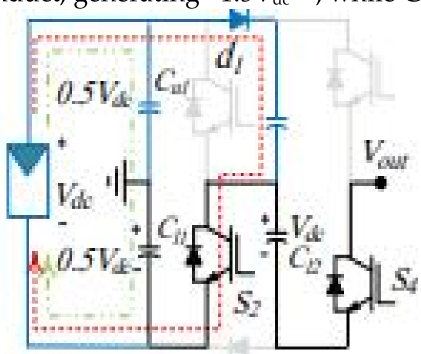

Fig.5. Switching states of the proposed inverter Mode (d)

The stepped output (±0.5Vdc,±1.5Vdc) lowers total harmonic distortion (THD) and ensures symmetrical operation with negligible DC injection.

D. Duty Ratio and Buck–Boost Operation

The inverter's buck–boost characteristic is governed by the duty ratio DDD:

Vin / Vo = 1 – D

where V_{in} is the PV input voltage and V_o is the inverter output. This enables wide operating range across varying PV conditions such as irradiance fluctuations and shading.

E. Modulation Strategy

A sinusoidal pulse width modulation (SPWM) scheme is adopted to regulate switching. Three reference signals — a sinusoidal waveform, its absolute value, and its inverse — are compared with a triangular carrier wave to produce gating signals. This ensures grid synchronization and precise output voltage shaping.

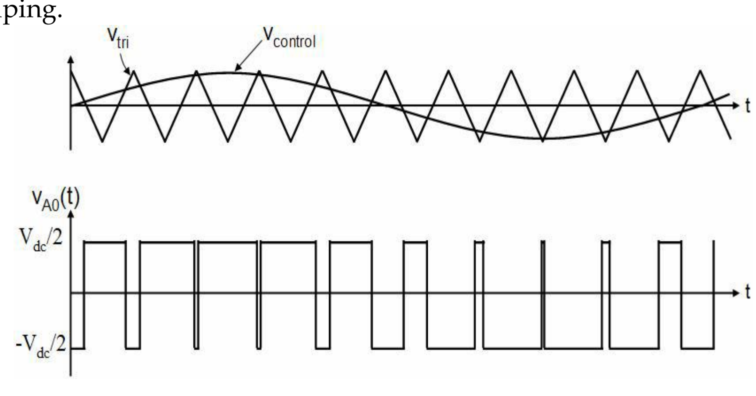

Fig. 6. Sinusoidal PWM principle for generating inverter gate pulses.

F. Fuzzy Logic Control

To enhance system performance under non-linear PV characteristics, a fuzzy logic controller (FLC) is employed. The inputs to the FLC are the instantaneous error (eee) and change in error (Δe\Delta eΔe), while the output is the duty ratio adjustment (uuu). Membership functions are defined for input and output variables, and a rule base is applied using Mamdani inference. Defuzzification is carried out using the centroid method, providing crisp control signals.

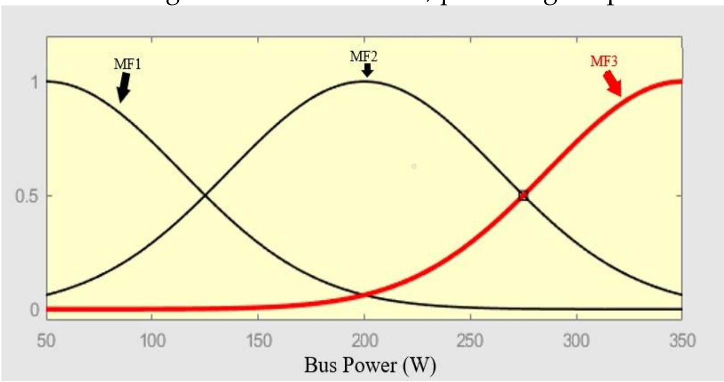

Fig.7 Membership functions for fuzzy controller inputs and outputs.

The FLC transfer function can be expressed in the sss-domain as:

U(s) = Kp * E(s) + (Ki / s) * E(s)

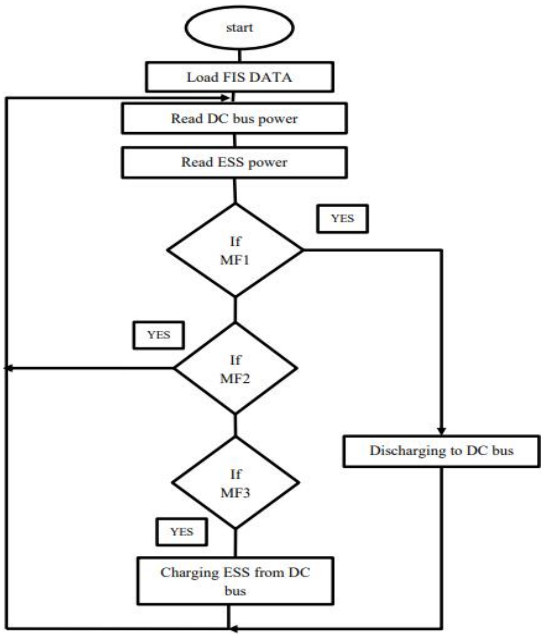

Fig. 8. Flowchart of fuzzy logic control process.

where K_p and K_i are adaptively tuned through fuzzy rules. Compared to conventional PI controllers, the FLC ensures better transient response, improved stability, and reduced steady-state error.

	The deviation rate		
	N	*Z*	*P*
MF1	S	D	D
MF2	A	S	D
MF3	A	A	S

Table I. Rule base of fuzzy logic controller

G. Simulation Setup

The complete inverter model, including PV array, control loops, and grid connection, is implemented in MATLAB/Simulink. The PV source of 15 V, 3500 W is simulated under standard test conditions and under varying irradiance to evaluate performance.

The system is analyzed for PV voltage, current, inverter output voltage, injected current, load power, efficiency, and harmonic profile.

HARDWARE IMPLEMENTATION

A hardware prototype of the proposed single-stage buck–boost transformerless inverter was developed to experimentally validate the simulation results.

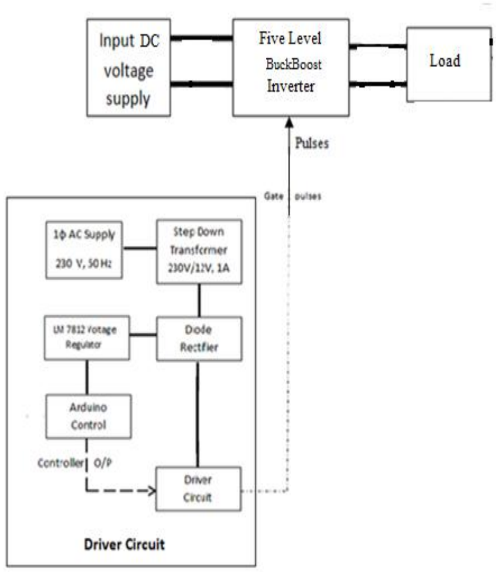

Fig. 9. Block diagram of the proposed hardware implementation of BBTI system.

The prototype was designed for low-voltage operation to ensure laboratory safety and feasibility while demonstrating the functional behavior of the topology.

A. Power Supply and Rectification

A single-phase AC source of 230 V, 50 Hz was employed as the primary supply for the control circuitry. This input was stepped down to 12 V AC using a transformer (230/12 V, 1 A, 50 Hz). The secondary voltage was rectified through a diode bridge to obtain a regulated 12 V DC, which served as the auxiliary supply for the driver circuits and control unit.

B. Control Unit

The switching signals for the power electronic devices were generated by an Arduino microcontroller (ATmega328P) programmed with the proposed control strategy. The controller continuously monitored voltage and current feedback from the system and generated gate pulses based on the modulation scheme and fuzzy logic-based decision rules. A microcontroller was choosen for its low cost, ease of programming, and capability to perform real-time control with sufficient accuracy.

C. Driver Circuit

To provide isolation between the low-voltage control stage and the high-voltage power stage, a TLP250 opto-isolated MOSFET driver was used. The driver provided the necessary voltage amplification and ensured safe isolation of the gate signals. Each MOSFET gate was interfaced through a driver stage, with buffer ICs were employed where needed to strengthen the control signals. This arrangement enabled reliable and secure triggering of the inverter switches.

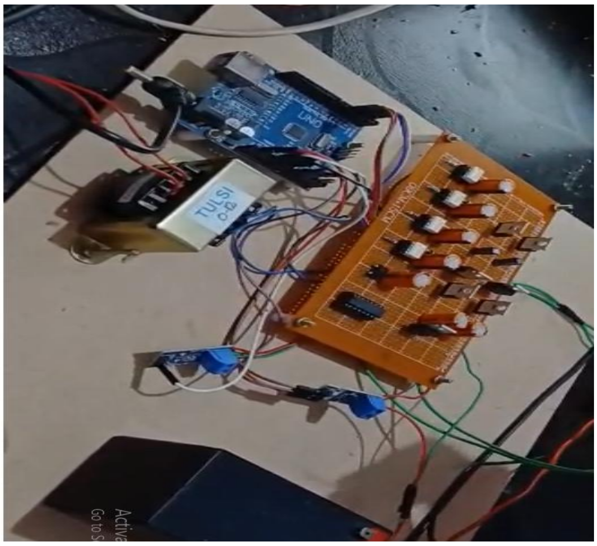

Fig. 10. Control and driver circuit arrangement using Arduino and TLP250.

D. Power Stage

The main inverter circuit was implemented using IRF840 MOSFETs as the switching devices, owing to their availability and suitable voltage ratings for the laboratory prototype. The inverter configuration followed the proposed buck–boost topology, consisting of two switch legs and capacitor–diode arrangements. A 12 V battery was used as the DC input source to the inverter during testing.

E. Output Characteristics

The hardware setup produced a stepped output voltage waveform. In the positive half cycle, two distinct voltage levels were observed, while two corresponding levels were obtained in the negative half cycle, along with a zero state. Together, this resulted in a five-level output voltage, consistent with the expected operation of the proposed inverter.

F. Summary

The hardware prototype successfully demonstrated the feasibility of the proposed topology. The use of a reduced switch count, isolated gate driver circuits, and fuzzy control enabled the inverter to operate efficiently while producing a multi-level stepped output. The experimental results confirmed the practicality of the design and its suitability for extension to higher power grid-connected photovoltaic applications.

3. Results and Discussion

SIMULATION RESULTS

The proposed buck–boost transformerless inverter (BBTI) topology with fuzzy control was modeled and tested in MATLAB/Simulink. The PV source was configured with an input of 15 V, 3500 W, and connected to the single-phase grid through the proposed inverter. The simulation results demonstrate the effectiveness of the design in terms of voltage boosting, grid synchronization, efficiency, and harmonic reduction.

A. PV Source Characteristics

The simulated PV array delivered a DC voltage of approximately 150 V, current of 24–25 A, and output power around 3100–3200 W under standard irradiance conditions. The results confirm that the PV system maintains stable output despite variations in load.

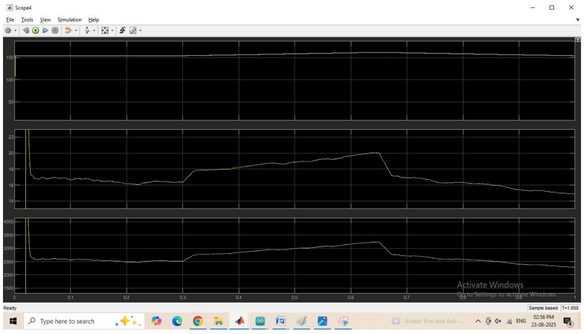

Fig. 11. Simulated PV voltage, current, and power waveform.

B. Inverter and Grid Voltage

The inverter boosted the PV input voltage to an output level of approximately 250–300 V, while maintaining synchronization with the grid voltage of 220 V (rms). The waveforms illustrate that the proposed topology ensures proper voltage matching with the grid while preserving waveform quality.

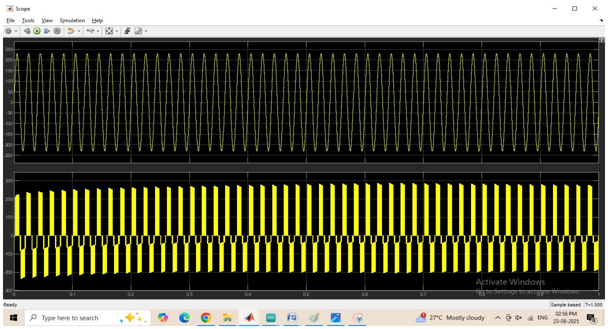

Fig. 12. Inverter output voltage and grid voltage waveforms.

C. Load Power and Current

The load received an active power in the range of

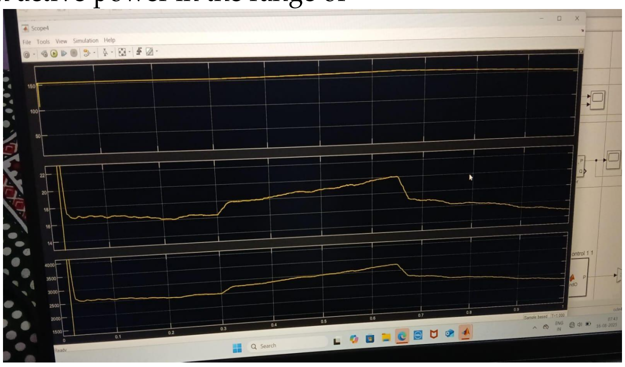

Fig. 13. Load power and current response of the proposed system

2200–2300 W with corresponding current of 15–17 A. These results verify that the inverter transfers power efficiently from the PV source to the grid-connected load.

D. Efficiency Analysis

The efficiency of the proposed inverter was evaluated from the ratio of load power to PV input power. Results show an efficiency of approximately 85% under initial conditions and up to 87.5% when fuzzy control was applied. This improvement highlights the capability of the fuzzy controller to optimize duty ratio adjustment and enhance MPPT performance.

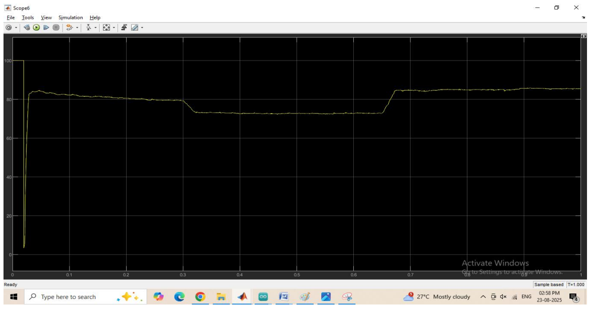

Fig. 14. Efficiency profile of the proposed inverter system.

E. Harmonic Performance

The stepped output voltage produced by the multi-level inverter reduces total harmonic distortion (THD) in the grid current. The simulated THD values remained within IEEE-519 limits, ensuring compliance with power quality standards.

VE/CE	NVL	NL	NM	NS	ZERO	PS	PM	PL	PVL
Duty Ratio	ZERO	ZERO	ZERO	ZERO	ZERO	PM	PL	PL	PL

Table II. THD comparison of conventional and proposed inverter systems.

F. Discussion

The simulation results validate the advantages of the proposed BBTI topology:

- Leakage current elimination through common grounding of the PV negative terminal and grid neutral.
- Symmetrical operation across both half cycles, resulting in negligible DC current injection.
- Buck–boost capability, enabling power transfer over a wide PV input voltage range.
- Improved efficiency (up to 87.5%) with fuzzy logic control.
- Enhanced waveform quality with reduced harmonic distortion.
- These outcomes confirm that the proposed inverter structure is well-suited for single-phase grid-connected PV applications

4. Conclusion

This paper presented a novel single-stage buck–boost transformerless inverter controlled by fuzzy logic for grid-connected photovoltaic systems. The proposed topology minimizes leakage current by sharing a common terminal between the PV source and grid neutral, while the buck–boost feature ensures stable operation across a wide range of PV voltages. Simulation results demonstrated efficient voltage boosting, improved power transfer, and reduced harmonic distortion, with system efficiency reaching 87.5% under fuzzy control compared to conventional PI control. A low-voltage hardware prototype further validated the feasibility of the design, producing a five-level stepped output waveform consistent with simulation. The results confirm that the proposed inverter structure offers improved efficiency, reliability, and power quality, making it a suitable candidate for single-phase PV grid integration.

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