FOREX Publication
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International Journal of
Electrical and Electronics Research (IJEER)
Review Article | Volume 13, Issue 1 | Pages 62-68 | e-ISSN: 2347-470X

Design and Analysis of a Transformer-Integrated Multilevel Inverters for Solar Energy Systems

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ABSTRACT- This work presents the design and implementation of a transformer-integrated multilevel inverter for photovoltaic (PV) power applications. The proposed topology combines the benefits of multilevel inverters and transformer integration to enhance efficiency, reliability, and power quality in PV systems. Traditional multilevel inverters often encounter issues such as complex control schemes, high component count, and significant harmonic distortion. This innovative design addresses these challenges by incorporating a transformer, which simplifies the control strategy and provides galvanic isolation, improving system safety and grid compatibility. The system uses a PV array as the input supply, directly generating DC power, which is then converted to AC through the multilevel inverter. The transformer integration facilitates effective voltage boosting and harmonic reduction, resulting in a cleaner, more stable output. The detailed simulations results demonstrate the proposed inverter's effectiveness, showcasing improved performance metrics, including higher efficiency, reduced total harmonic distortion (THD), and enhanced power quality compared to conventional inverter topologies. This study also delves into design considerations, control algorithms, and implementation challenges associated with the transformer-integrated multilevel inverter. The findings indicate that the proposed system is a viable and advantageous solution for modern PV power applications, offering substantial improvements in performance and reliability.

Keywords: Transformer based Multilevel Inverter, PV Source, Seven Level Inverter, Output Voltage, THD

ARTICLE INFORMATION
Author(s): B. Vinoda, and Satish Kumar.P;
Received: 07/01/2025; **Accepted**: 28/03/2025; **Published**: 30/03/2025;
e-ISSN: 2347-470X;
Paper Id: IJEER 0701-04;
Citation: 10.37391/ijeer.120318
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-12/ijeer-120318.html

crossref member CROSSREF.ORG THE CITATION LINKING BACKBONE

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1. INTRODUCTION

The growing global emphasis on renewable energy systems from the pressing need to develop sustainable and environmentally friendly power generation solutions. Among the diverse renewable energy sources, solar energy stands out as a leading option due to its widespread availability and scalability. Photovoltaic (PV) systems, which directly convert sunlight into electricity, have gained significant traction worldwide as a cornerstone of clean energy generation. The performance and reliability of these systems are heavily influenced by the power electronics interfacing the PV modules with the grid or load [1].

Multilevel inverters have emerged as a transformative technology in the realm of power electronics, offering considerable advantages over conventional two-level inverters. These benefits include reduced harmonic distortion, lower electromagnetic interference, enhanced voltage handling capability, and improved overall system efficiency. Despite these advantages, the integration of multilevel inverters into PV systems poses challenges related to system complexity, higher cost, and efficiency optimization [2].

In response to these challenges, this paper proposes a novel transformer-integrated multilevel inverter designed specifically for solar energy systems. The integration of a transformer within the inverter architecture provides significant benefits, including improved voltage regulation, enhanced efficiency, and galvanic isolation between the PV source and the load. This innovative design addresses critical issues such as voltage imbalance and common-mode voltage—common challenges in traditional multilevel inverter systems—while simplifying the overall system configuration [6].

2. PROPOSED TRANSFORMER-INTEGRATED SEVEN LEVEL INVERTER

The proposed transformer-integrated multilevel inverter employs state-of-the-art modulation techniques and carefully optimized component selection to achieve superior performance and reliability. The proposed Transformer-integrated multilevel inverter has more advantages compare to transformer less multilevel inverter and two-level inverter. The proposed inverter circuit has the following advantages [3].

Advantages of the transformer-integrated multilevel inverter are given below

- A reduced number of power semiconductors and driver circuits.
- Fewer transformers are needed with the proposed topology.

- The inverter provides the benefit of galvanic isolation.
- A single PV source is used.
- The load voltage can be adjusted by varying the transformer's turns ratio.

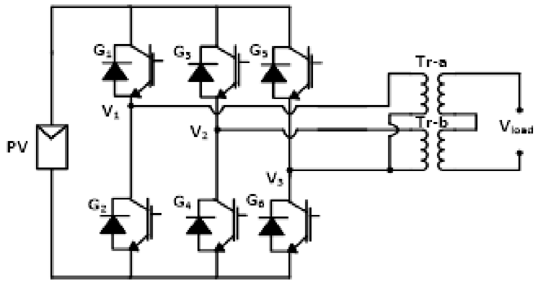

Figure1. Proposed Seven Level Inverter Configuration

2.1 MODES OF OPERATION

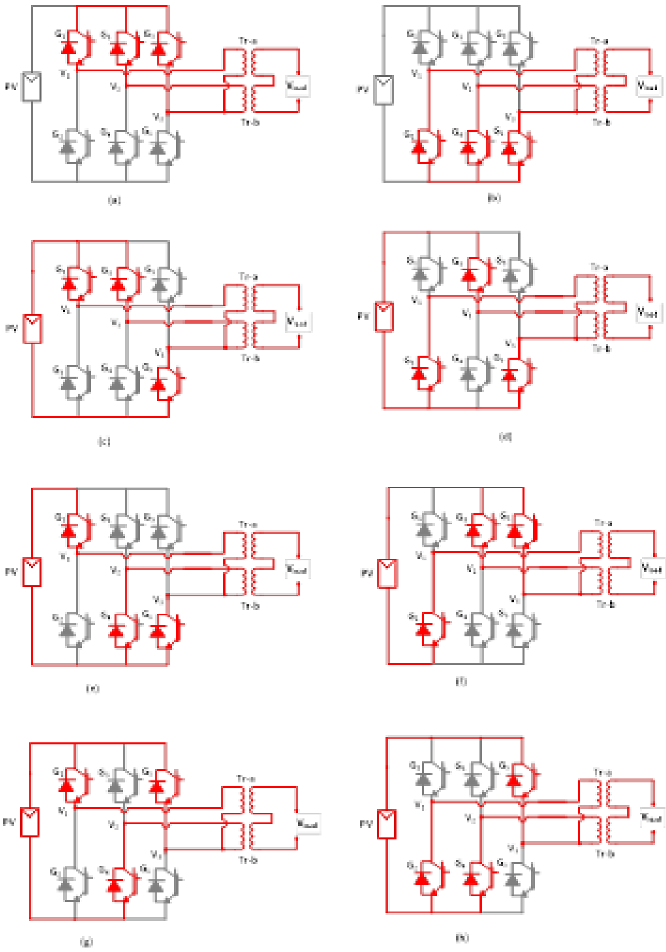

Figure 2. Mode of Operation of proposed Seven Level Inverter

An outline of the suggested 7-level circuit, which has a common arm powered by a PV source. Two transformers and three half-bridges make up the recommended topology. A multilayer output waveform is produced by connecting the terminals of the three half-bridges to the primary sides of the two transformers. The galvanic isolation created by the inverter is easily obvious. Furthermore, higher order harmonics in the load voltage are automatically filtered out by the proposed inverter's usage of transformers [18].

To help comprehend the functioning of the proposed seven-level (7L) inverter, the states of its positive modes are shown. The several voltage-level switching modes are shown in *Figure 2*. Table II displays the various switching configurations of the suggested circuit.

2.2 SWITCHING MODES OF OPERATION OF INVERTER

While the other switching devices are held in the OFF state, power electronic switches G_2, G_4 and G_6 are activated to provide a zero level (0PVDC). The load is cut off from the input source by short-circuiting the primary sides of the two transformers. In *Fig. 2(b)*, the precise route for producing this voltage level is displayed.

$$V_o = V_a + V_b$$
$$V_a = (V_1 - V_2)$$
$$V_b = 2(V_2 - V_3)$$
$$V_a = 0$$
$$V_b = 0$$
$$V_o = V_a + V_b = 0PV_{DC} \tag{1}$$

Power electronic switches G_1, G_4 and G_6 must be activated in order to create the initial positive level (PVDC), with the other switching devices being held in the OFF state. The input source provides PVDC to transformer Tr-a's primary side, while the primary sides of the other transformer are short-circuited. In *Fig. 2(c)*, the precise pathway for producing this voltage level is illustrated.

$$V_a = PV_{DC}$$
$$V_b = 0$$
$$V_o = V_a + V_b = PV_{DC} \tag{2}$$

To generate $2PV_{DC}$, power electronic switches G_2, G_3 and G_6 must be activated; otherwise, all other switching devices stay in the OFF state. Transformer Tr-b's primary side receives $2PV_{DC}$ from the input source, while the primary side of the other transformer is short-circuited. *Fig. 2(d)* shows the precise pathway for producing this voltage level.

$$V_a = 0$$
$$V_b = 2PV_{DC}$$
$$V_o = V_a + V_b = 2PV_{DC} \tag{3}$$

To generate 3PVDC, power electronic switches G_1, G_3 and G_6 must be activated; otherwise, all other switching devices stay in the OFF state. Transformer Tr-a receives PVDC on its primary side, whereas Transformer Tr-b receives 2PVDC from the input source *Fig. 2(e)* depicts the precise pathway for producing this voltage level.

$$V_a = PV_{DC}$$
$$V_b = 2PV_{DC}$$
$$V_o = V_a + V_b = 3PV_{DC} \tag{4}$$

Power electronic switches G_2, G_3, G_5, and G_7 must be activated in order to produce the initial negative level (−PVDC), while the other switching devices must stay in the OFF-state. Transformer Tr-a's primary side receives −PVDC from the input source, while the primary side of the other transformer is short-circuited. The entire process for producing this voltage level is shown *in fig. 2(f).*

$$V_a = -PV_{DC}$$
$$V_b = 0$$
$$V_o = V_a + V_{bc} = -PV_{DC} \tag{5}$$

Power electronic switches G_1, G_4 and G_5 must be activated in order to produce -2PVDC; all other switching devices must stay in the OFF state. While the other transformer primary sides are short-circuited, transformer Tr-b's primary side receives -2PVDC from the input source. This voltage level's detailed journey is shown graphically in *figure 2(k).*

$$V_a = 0$$
$$V_b = -2PV_{DC}$$
$$V_o = V_a + V_b = -2PV_{DC} \tag{6}$$

Power electronic switches G_2, G_4 and G_5 must be activated in order to produce -3PVDC, while the remaining switching devices must remain in the OFF position. Transformer Tr-a's primary side delivers −PVDC, while transformer Tr-b's primary side receives −2PVDC from the input source. *Fig. 2(l)* shows the schematic depiction of this voltage level creation.

$$V_a = -PV_{DC}$$
$$V_b = -2PV_{DC}$$
$$V_o = V_a + V_b = -3PV_{DC} \tag{7}$$

Table 1. Switching States

PV_{DC}	G_1	G_2	G_3	G_4	G_5	G_6
$3PV_{DC}$	1	0	1	0	0	1
$2PV_{DC}$	0	1	1	0	0	1
PV_{DC}	1	0	0	1	0	1
$0PV_{DC}$	1	0	1	0	1	0
$0PV_{DC}$	0	1	0	1	0	1
$-PV_{DC}$	0	1	1	0	1	0
$-2PV_{DC}$	1	0	0	1	1	0
$-3PV_{DC}$	0	1	0	1	1	0

3. SIMULATION OF PROPOSED TRANSFORMER-INTEGRATED MULTILEVEL INVERTER

In this work, we propose a novel transformer-integrated multilevel inverter for solar power applications that utilizes a Pulse Width Modulation (PWM)) technique to enhance performance. The PWM technique plays a crucial role in controlling the inverter's output voltage and improving its efficiency. By modulating the width of the pulses applied to the inverter switches, the proposed design can achieve a more precise and stable output. This results in reduced harmonic distortion and better power quality [7].

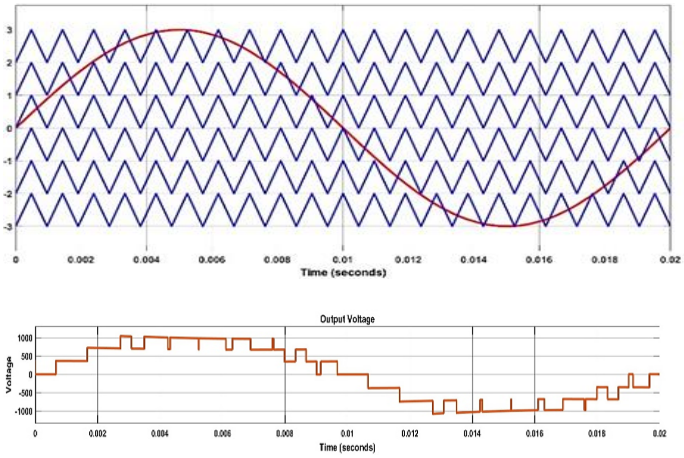

Figure 3. PWM Technique

Furthermore, the PWM technique helps in minimizing switching losses and improving the overall efficiency of the inverter. The integration of this technique with the transformer-based design ensures that the inverter operates efficiently under varying load conditions, making it ideal for solar power applications where reliability and efficiency are paramount.

In a multilevel inverter, multiple voltage levels are synthesized using several power switches and DC sources. To generate the required switching signals, Level Shift PWM compares a reference signal (sinusoidal or other waveform) with multiple carrier signals. The carrier signals are phase-shifted to generate multiple switching pulses for different levels of the inverter.

Advantages of Level Shift PWM in Multilevel Inverters

- Lower Total Harmonic Distortion (THD)
- Better voltage balancing (especially in NPC inverters)
- Reduced switching losses compared to conventional PWM
- Improved efficiency and power quality

3.1 Simulation

To evaluate the performance and functionality of the proposed seven-level transformer-integrated multilevel inverter, extensive simulation studies were carried out using MATLAB/Simulink. These simulations aimed to analyse the inverter's operation under various conditions and compare its performance with traditional inverter designs.

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Review Article | Volume 13, Issue 1 | Pages 62-68 | e-ISSN: 2347-470X

The first set of simulations focused on the inverter's basic operational characteristics, examining key parameters such as output voltage, current waveforms, and total harmonic distortion (THD). The results confirmed that the proposed design achieved the desired seven-level output with significantly reduced THD compared to traditional inverters. This reduction in harmonic distortion enhances the efficiency and extends the lifespan of the connected solar power systems.
Another important aspect of the simulations was evaluating the inverter's efficiency and power losses. The proposed design, featuring fewer switches and transformers, showed a marked improvement in efficiency [8]. The reduced number of switching components led to lower conduction and switching losses, thereby improving the overall energy conversion efficiency of the system. Additionally, the simulations confirmed that the proposed inverter could maintain stable operation and high efficiency across a wide range of load conditions. The galvanic isolation provided by the transformer was also tested in the simulations. This feature is essential for safety and reliability in solar power applications. The results indicated that the proposed inverter effectively isolated the DC source from the AC load, preventing potential electrical hazards and ensuring safe operation. Furthermore, the simulations included stress testing of the inverter under fault conditions and sudden load changes. The proposed inverter demonstrated robust performance, quickly adapting to changes and maintaining output stability. This resilience is particularly important for solar power applications, where environmental conditions can cause rapid fluctuations in power generation [11].

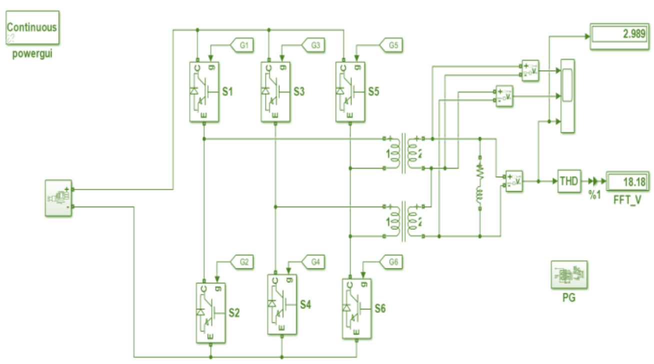

Figure 4. Simulation diagram of Proposed Seven Level Inverter

The simulation output for the proposed novel transformer-integrated multilevel inverter for solar power applications demonstrates its effectiveness and performance. The results validate the inverter's ability to produce a seven-level output voltage waveform with reduced harmonic distortion.

Key findings from the simulation studies include:

- ***Reduced Switch Count:*** The proposed inverter uses fewer switches compared to conventional designs, as evidenced by the simplified circuit topology in the simulation.
- ***Efficiency and Energy Savings:*** The simulation shows that the inverter operates with higher efficiency due to reduced switching losses, contributing to lower overall energy consumption.
- ***Voltage Regulation:*** By adjusting the transformer's turn ratio, the load voltage can be finely controlled, as illustrated by the stable and adjustable output voltage in the simulation results.
- ***Galvanic Isolation:*** The inverter provides effective galvanic isolation, ensuring safe and reliable operation, which is confirmed by the isolation tests conducted in the simulation environment.
- ***Harmonic Performance:*** The output voltage waveform exhibits low total harmonic distortion (THD), indicating superior power quality. The simulation results include harmonic analysis, which shows significant improvement over traditional inverters.

Overall, the simulation studies corroborate the proposed inverter's design benefits, including reduced component count, improved efficiency, adjustable voltage levels, and enhanced power quality, making it a promising solution for solar power applications [10-12].

3.2 RESULTS

The simulation results validate the proposed inverter's effectiveness demonstrating its ability to deliver a seven-level output with reduced harmonic the proposed design as a promising and cost-effective solution for solar power applications, addressing critical challenges in renewable energy systems.

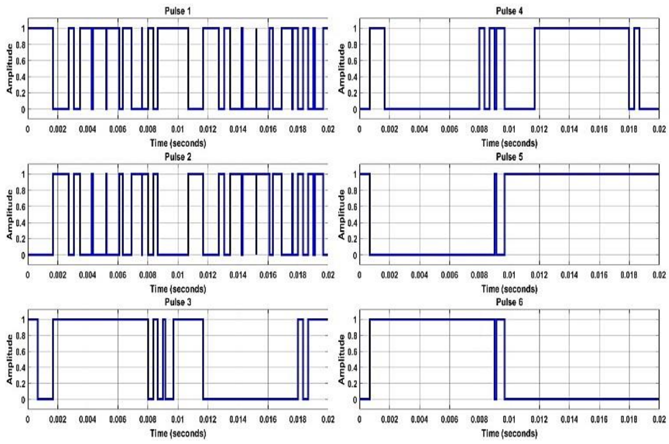

Figure 5. Amplitude of the 6 Pulses

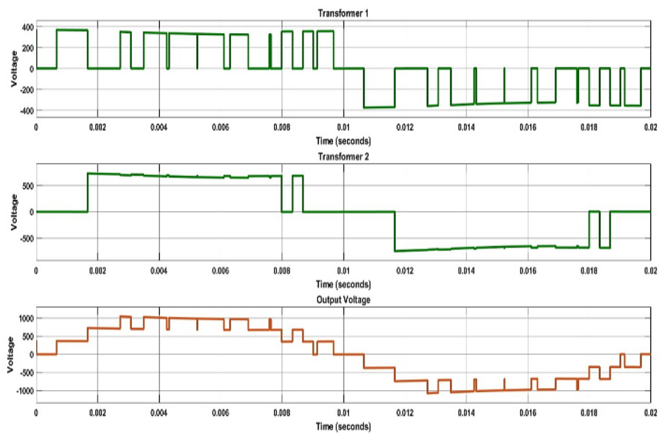

Figure 6. Output Voltages of the transformers at RL Load

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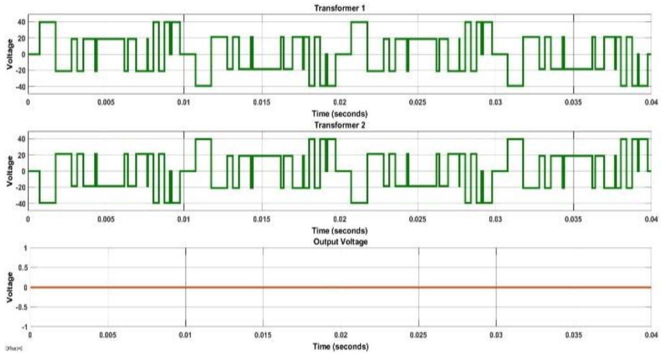

Figure 7. Output voltage of the transformers at no load

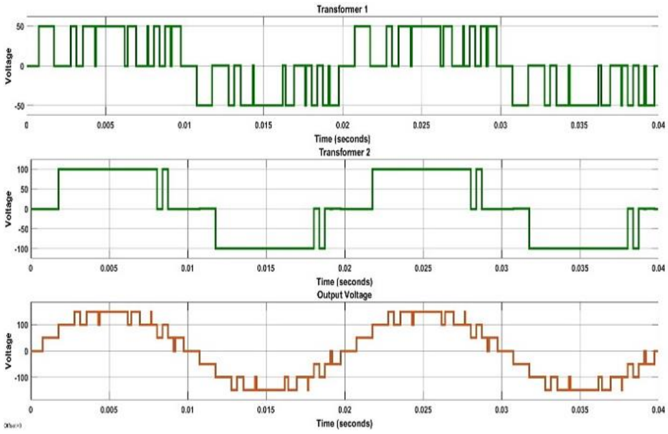

Figure 8. Output voltages of the transformers at R load

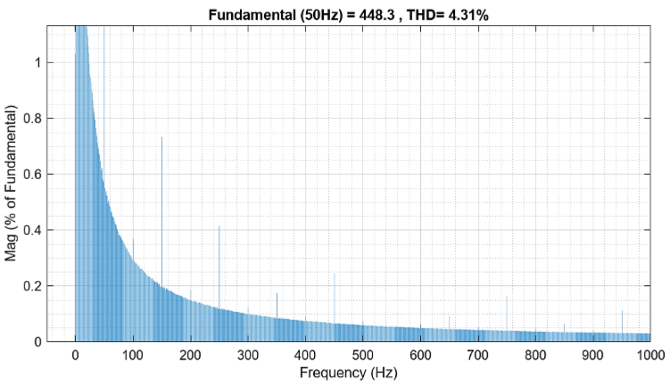

Figure 9. FFT Spectrum for load current

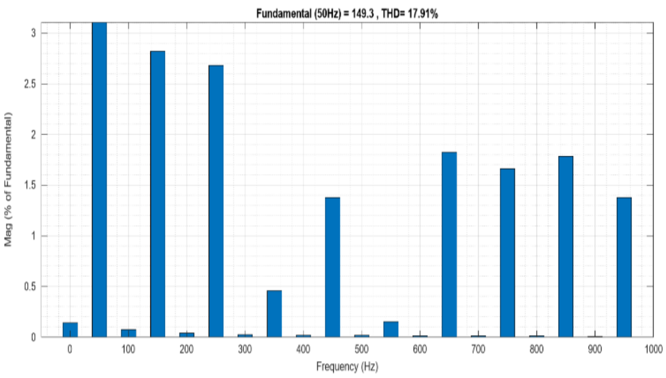

Figure 10. FFT Spectrum for load voltage

3.3 Comparison of Topology

Comparative study of the proposed transformer-integrated multilevel inverter for solar power applications. Traditional inverters typically require four switches per module, leading to increased complexity, higher energy consumption, and greater space requirements. In contrast, the proposed design reduces the number of switches to two per module, simplifying the overall system. This design also minimizes the number of required power semiconductors and driver circuits, further reducing component count and associated costs. Additionally, the proposed inverter topology requires fewer transformers and offers galvanic isolation, enhancing safety and reliability [13-20]. The ability to adjust load voltage by varying the transformer's turn ratio provides greater flexibility and control. Comparative analysis with existing inverter designs demonstrates that the proposed inverter not only achieves improved efficiency and reduced costs but also occupies less space and uses fewer resources, making it a highly advantageous solution for solar power applications. A Genetic Algorithm Based Solar Photovoltaic (SPV) System with a Cascaded H-Bridge Multilevel Inverter offers an innovative approach to maximizing the efficiency and performance of solar energy systems [20-23].

The implementation of a genetic algorithm in the management and optimization of a Solar Photovoltaic system integrated with a cascaded H-bridge multilevel inverter brings several power systems.

Table 2. Comparisons on features basis

Feature	Transformer-Integrated Multilevel Inverter (TI-MLI)	Conventional Inverter
Voltage Levels	Generates multiple voltage levels, reducing harmonics	Typically, two or three voltage levels
Harmonics & THD	Lower Total Harmonic Distortion (THD) due to multiple levels	Higher THD, requires extra filtering
Size & Weight	Bulky due to transformer	Compact, no transformer
Efficiency	Slightly lower due to transformer losses	Higher without transformer losses
Isolation	Provides galvanic isolation, enhancing safety	No inherent isolation, requires extra components
Complexity	More complex due to transformer and multilevel control	Simpler, fewer components
Cost	Higher due to transformer and control circuits	Lower due to simpler design
Applications	High-power industrial, renewable energy, grid integration	General-purpose drives, solar inverters, motor control

Table 3. Component Comparison Analysis

Topology	Switches	Drives	Transformers	Sources
Conventional (2 LEVEL)	12	12	3	1
Proposed (15 LEVEL)	8	8	3	1
Proposed (7 LEVEL)	6	6	2	1
Conventional (2 LEVEL)	12	12	3	1

4. CONCLUSION

The proposed transformer-integrated multilevel inverter offers a transformative solution for solar power applications. By adopting a unique seven-level design and integrating transformers, the inverter achieves a simplified architecture with a reduced component count. This innovative approach minimizes the number of switches required, resulting in lower energy consumption, reduced space requirements, and significant cost savings. The galvanic isolation provided by the integrated transformer ensures safety and reliability, making the system compatible with a wide range of load conditions. Additionally, the ability to finely regulate load voltage through the transformer's turn ratio adds a layer of flexibility, enhancing the inverter's adaptability for diverse applications. Simulation studies have validated the inverter's functionality, showcasing its ability to produce a high-quality seven-level output with significantly reduced harmonic distortion. Key performance metrics, including improved efficiency, reduced power losses, and robust operation under dynamic conditions, underscore the practical viability of this design. This innovative transformer-integrated multilevel inverter represents a significant advancement in solar energy conversion.

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