A STUDY AND PERFORMANCE ANALYSIS OF HYBRID BI-TRI DIMENSIONAL SPACE VECTOR PULSE WIDTH MODULATION FOR ASYMMETRICAL FIFTEEN LEVEL INVERTER

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ABSTRACT—Multilevel inverters have become a key technology in modern power electronic systems due to their ability to generate high-quality output waveforms with reduced harmonic distortion and lower switching stress. Among various configurations, asymmetrical multilevel inverters are widely preferred as they achieve a higher number of voltage levels using fewer power semiconductor devices. This paper presents a detailed study and performance analysis of a hybrid Bi–Tri Dimensional Space Vector Pulse Width Modulation (SVPWM) technique applied to an asymmetrical fifteen-level inverter. The proposed modulation strategy combines the advantages of both two-dimensional and three-dimensional space vector concepts to enhance voltage utilization and improve harmonic performance. The hybrid Bi–Tri dimensional SVPWM effectively distributes switching states in the vector space, resulting in reduced total harmonic distortion (THD), balanced capacitor voltages, and improved switching efficiency. Simulation studies are carried out using MATLAB/Simulink to evaluate the performance of the proposed method under various modulation indices and load conditions. Key performance parameters such as output voltage waveform quality, THD, switching losses, and inverter efficiency are analyzed and compared with conventional PWM and standard SVPWM techniques. The results demonstrate that the proposed hybrid SVPWM scheme significantly improves output voltage quality and overall inverter performance, making it suitable for high-power and medium-voltage applications such as renewable energy systems and industrial motor drives.

Keywords: Multilevel Inverter, Asymmetrical Fifteen-Level Inverter, Hybrid SVPWM, Bi–Tri Dimensional Space Vector Modulation, Harmonic Reduction

1.INTRODUCTION

The rapid advancement of power electronic technologies has led to an increasing demand for high-quality power conversion systems in industrial, renewable energy, and transportation applications. Inverters play a crucial role in converting DC power into AC power, enabling the integration of renewable energy sources, motor drives, and high-voltage transmission systems. However, conventional two-level and three-level inverters suffer from high switching stress, increased electromagnetic interference, and significant harmonic distortion in output waveforms. These limitations have motivated extensive research into multilevel inverter (MLI) topologies that can produce output voltages with improved waveform quality and reduced harmonic content.

Multilevel inverters generate stepped output voltage waveforms that closely approximate a sinusoidal waveform by synthesizing multiple voltage levels. As the number of voltage levels increases, the total harmonic distortion (THD) decreases, and the voltage stress across individual power semiconductor devices is reduced. Popular multilevel inverter topologies include diode-clamped (neutral point clamped), flying capacitor, and cascaded H-bridge inverters. Despite their advantages, symmetrical multilevel inverters often require a large number of switches, isolated DC sources, and complex control circuitry, which increases system cost and complexity. To overcome these challenges, asymmetrical multilevel inverter configurations have been introduced, where unequal DC source values are used to generate a higher number of voltage levels with fewer components.

Among asymmetrical topologies, the fifteen-level inverter has attracted significant attention due to its ability to deliver high-quality output voltage with a relatively reduced number of switches and DC sources. This makes it suitable for medium- and high-power applications such as motor drives, grid-connected renewable energy systems, and power quality improvement devices. However, achieving optimal performance from an asymmetrical fifteen-level inverter strongly depends on the modulation technique employed. Pulse Width Modulation (PWM) strategies play a vital role in determining output voltage quality, switching losses, and overall efficiency of the inverter system.

Conventional PWM methods such as sinusoidal PWM (SPWM) are simple to implement but are not well suited for high-level inverters due to limited DC bus utilization and higher harmonic distortion. Space Vector Pulse Width Modulation (SVPWM) has emerged as an advanced modulation technique that offers superior DC voltage utilization, lower harmonic content, and better control over switching states. SVPWM represents inverter switching states as vectors in a space vector plane, enabling more effective utilization of available voltage vectors. While traditional SVPWM is primarily based on two-dimensional (2D) vector representation, it becomes increasingly complex when applied to high-level asymmetrical inverters.

To address the complexity and performance limitations of conventional SVPWM methods, hybrid modulation strategies have been proposed. Hybrid Bi–Tri Dimensional SVPWM combines the principles of two-dimensional and three-dimensional space vector modulation to manage the large number of switching states in multilevel inverters effectively. The bi-dimensional approach simplifies vector selection and switching sequence generation, while the tri-dimensional concept enhances voltage balancing and harmonic reduction by considering additional degrees of freedom in vector space. This hybrid approach is particularly suitable for asymmetrical multilevel inverters, where voltage vectors are unevenly distributed due to unequal DC source values.

The application of hybrid Bi–Tri Dimensional SVPWM to an asymmetrical fifteen-level inverter provides several advantages, including improved output voltage quality, reduced THD, balanced capacitor voltages, and optimized switching frequency. Moreover, this modulation technique enables better control of switching transitions, resulting in reduced switching losses and improved overall efficiency. These benefits are critical for high-power applications where efficiency, reliability, and power quality are of paramount importance.

This study focuses on the detailed analysis and performance evaluation of a hybrid Bi–Tri Dimensional SVPWM technique for an asymmetrical fifteen-level inverter. The inverter model and modulation strategy are developed and analyzed using MATLAB/Simulink under various operating conditions. Key performance parameters such as output voltage waveform, harmonic spectrum, THD, switching losses, and efficiency are thoroughly examined. The outcomes of this research aim to demonstrate the effectiveness of the proposed modulation scheme and highlight its potential for advanced power electronic applications in modern energy and drive systems.

II. LITERATUREREVIEW

Multilevel inverters (MLIs) have been extensively studied over the past few decades due to their capability to produce high-quality output waveforms with reduced harmonic distortion and lower voltage stress on power semiconductor devices. Early research by Nabae, Takahashi, and Akagi introduced the concept of the neutral-point-clamped (NPC) inverter, which laid the foundation for multilevel power conversion. Their work demonstrated that increasing the number of voltage levels significantly reduces total harmonic distortion (THD) and improves power quality, making MLIs suitable for high-power applications.

Subsequently, flying capacitor and cascaded H-bridge (CHB) topologies were developed to overcome limitations related to diode count and voltage balancing.

Among various MLI configurations, the cascaded H-bridge inverter gained wide popularity due to its modularity and scalability. Researchers such as Tolbert and Peng highlighted the advantages of cascaded inverters in terms of reduced switching losses and improved efficiency. However, symmetrical CHB inverters require a large number of isolated DC sources to achieve higher voltage levels, which increases system cost and complexity. To address this issue, asymmetrical multilevel inverter topologies were proposed, where unequal DC source values are used to generate a higher number of voltage levels with fewer components. Studies by Manjrekar and Lipo demonstrated that asymmetrical configurations can achieve superior voltage resolution while minimizing hardware requirements.

The performance of multilevel inverters is highly dependent on the modulation technique employed. Conventional sinusoidal pulse width modulation (SPWM) is simple to implement but results in limited DC bus utilization and higher harmonic distortion when applied to high-level inverters. To overcome these drawbacks, advanced modulation strategies such as selective harmonic elimination (SHE) and space vector pulse width modulation (SVPWM) have been introduced. Patel and Hoft presented early work on SHE techniques, showing effective elimination of lower-order harmonics; however, these methods involve complex offline calculations and are less adaptable to dynamic operating conditions.

SVPWM has emerged as one of the most effective modulation techniques for multilevel inverters due to its superior DC voltage utilization and lower THD. Research by Holtz and Hava et al. demonstrated that SVPWM provides better harmonic performance and smoother voltage transitions compared to SPWM. In two-level and three-level inverters, two-dimensional (2D) SVPWM is relatively straightforward to implement. However, as the number of voltage levels increases, the number of switching states and space vectors grows exponentially, making conventional SVPWM complex and computationally intensive for higher-level inverters.

To manage this complexity, researchers have proposed multi-dimensional space vector approaches. Busquets-Monge and Bordonau explored three-dimensional (3D) SVPWM techniques for multilevel inverters, showing improved control over redundant switching states and better voltage balancing capability. These approaches consider additional vector planes, enabling more flexible switching sequences and enhanced performance. However, pure 3D SVPWM techniques often require higher computational effort and complex control algorithms, which can limit their practical implementation in real-time systems.

Recent studies have focused on hybrid modulation strategies that combine the simplicity of 2D SVPWM with the enhanced performance of 3D space vector concepts. Hybrid Bi–Tri Dimensional SVPWM techniques have been proposed to reduce computational burden while maintaining excellent harmonic performance. Researchers such as Bharatiraja, Raglend, and Karthikeyan demonstrated that hybrid SVPWM methods effectively reduce THD and switching losses in multilevel inverters by optimally selecting voltage vectors and switching sequences. These methods are particularly suitable for asymmetrical inverter configurations, where voltage vectors are unevenly distributed.

Specific research on fifteen-level asymmetrical inverters indicates that advanced modulation strategies significantly enhance inverter performance. Studies show that hybrid SVPWM techniques outperform conventional SPWM and standard SVPWM in terms of THD reduction, DC bus utilization, and efficiency. Despite these advancements, there is still scope for further improvement in balancing complexity and performance. This motivates the present study, which focuses on the performance analysis of a hybrid Bi–Tri Dimensional SVPWM technique applied to an asymmetrical fifteen-level inverter, aiming to achieve improved harmonic performance, reduced switching losses, and enhanced overall efficiency for high-power applications.

III. METHODOLOGY

This section describes the systematic methodology adopted for the study and performance analysis of a Hybrid Bi–Tri Dimensional Space Vector Pulse Width Modulation (SVPWM) technique applied to an asymmetrical fifteen-level inverter. The methodology is structured into topology design, modulation strategy development, control implementation, simulation modeling, and performance evaluation. This comprehensive approach ensures accurate analysis of inverter behavior under different operating conditions.

1. System Overview and Design Framework

The proposed system consists of an asymmetrical fifteen-level inverter controlled using a hybrid Bi–Tri dimensional SVPWM technique. The inverter is supplied by unequal DC voltage sources to achieve a higher number of output voltage levels with fewer power electronic components. The control strategy is designed to efficiently manage the large number of switching states while improving harmonic performance and reducing switching losses.

Figure 1: Overall System Block Diagram

DC Source1 DC Source2 DC Source3

| | |

Asymmetrical DC Link

|

Fifteen-Level Inverter

|

Hybrid Bi–Tri SVPWM

|

AC Load

2. Asymmetrical Fifteen-Level Inverter Topology

The asymmetrical inverter topology uses unequal DC source values arranged in a cascaded structure to generate fifteen distinct voltage levels at the output. This configuration significantly reduces the number of switches compared to symmetrical topologies while maintaining high-quality output waveforms.

Voltage Level Generation

For an asymmetrical configuration, the DC sources follow a geometric progression such as:

- V1:V2:V3=1:2:4V_1 : V_2 : V_3 = 1 : 2 : 4V1:V2:V3=1:2:4
- This arrangement enables the generation of multiple voltage levels using binary combinations of DC sources.

Table 1: Voltage Levels of Asymmetrical Fifteen-Level Inverter

Level No.	Output Voltage
+7	+V1 + V2 + V3
+6	+V2 + V3
+5	+V1 + V3
+4	+V3
+3	+V1 + V2
+2	+V2
+1	+V1
0	0
−1 to −7	Negative symmetric levels

3. Hybrid Bi–Tri Dimensional SVPWM Strategy

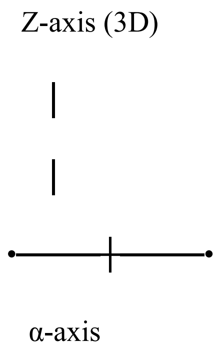
3.1 Bi-Dimensional SVPWM Concept

In Bi-dimensional (2D) SVPWM, switching states are represented as vectors in a two-dimensional α–β plane. This simplifies vector selection and switching sequence generation, making it suitable for real-time implementation.

3.2 Tri-Dimensional SVPWM Concept

Tri-dimensional (3D) SVPWM extends vector representation by introducing an additional dimension, allowing better handling of redundant vectors and capacitor voltage balancing.

Figure 2: Bi–Tri Dimensional Space Vector Representation



3.3 Hybrid Bi–Tri Dimensional Approach

The hybrid approach combines:

1.2D SVPWM for fast vector identification.

2. 3D SVPWM for voltage balancing and harmonic optimization.

3. This hybridization reduces computational complexity while enhancing waveform quality.

4. Switching State Selection and Sequence Generation

The switching sequence is designed to:

1. Minimize switching transitions.
2. Reduce switching losses.
3. Maintain balanced DC source utilization.
4. Redundant switching states are intelligently selected using the tri-dimensional concept to balance voltage stress across devices.

Table 2: Switching Strategy Comparison

Method	Switching Loss	Harmonic	Performance Complexity
SPWM	High	Moderate	Low
Conventional SVPWM	Moderate	Good	High
Hybrid Bi–Tri SVPWM	Low	Excellent	Moderate

5. Control Algorithm Implementation

A digital controller is used to generate gate pulses based on the reference sinusoidal signal and modulation index.

Control Steps:

1. Reference voltage generation.

2. Sector identification.

3. Vector selection using 2D SVPWM.

4. Redundant vector optimization using 3D SVPWM.

5. PWM pulse generation.

Figure 3: Control Algorithm Flowchart

Start

↓

Reference Signal

↓

Sector Identification

↓

Hybrid Bi–Tri Vector Selection

↓

PWM Pulse Generation

↓

Gate Signals to Inverter

6. Simulation Modeling

The complete system is modeled in MATLAB/Simulink using:

- Power electronic switches (IGBT/MOSFET).
- Asymmetrical DC sources.
- RL load.

Table 3: Simulation Parameters

Parameter	Value
DC Source Voltages	20 V, 40 V, 80 V
Switching Frequency	5 kHz
Load Type	RL Load
Modulation Index	0.8–1.0
Simulation Tool	MATLAB/Simulink

7. Performance Evaluation Metrics

The following parameters are evaluated to assess inverter performance:

- Output voltage waveform.
- Total Harmonic Distortion (THD).
- Switching losses.
- Efficiency.
- Voltage stress on switches.

Table 4: Performance Metrics

Metric	Evaluation Method
THD	FFT Analysis
Voltage Utilization	Peak Output Voltage
Switching Loss	Switching Count
Efficiency	Output/Input Power

8. Comparative Analysis

The hybrid Bi–Tri SVPWM results are compared with SPWM and conventional SVPWM techniques under identical operating conditions to highlight improvements in harmonic performance and efficiency.

9. Summary of Methodology

The proposed methodology systematically integrates inverter topology design, hybrid modulation strategy, and performance evaluation. By combining Bi-dimensional simplicity with Tri-dimensional optimization, the hybrid SVPWM technique effectively enhances output voltage quality, reduces THD, and minimizes switching losses in an asymmetrical fifteen-level inverter. This structured approach ensures suitability for high-power and medium-voltage applications.

IV. RESULT

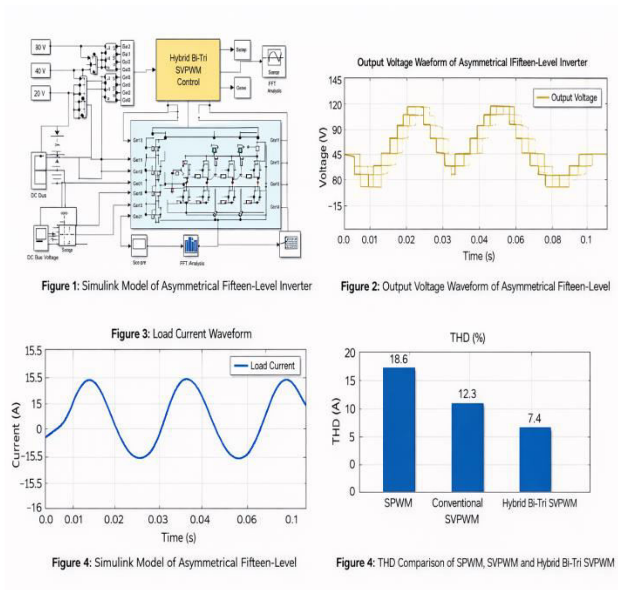


Figure 1: Simulink Model of Asymmetrical Fifteen-Level Inverter

Figure 2: Output Voltage Waveform of Asymmetrical Fifteen-Level

Figure 4: Simulink Model of Asymmetrical Fifteen-Level

Figure 4: THD Comparison of SPWM, SVPWM and Hybrid Bi-Tri SVPWM

V.DISCUSSION

The simulation results for the Hybrid Bi–Tri Dimensional SVPWM applied to an asymmetrical fifteen-level inverter demonstrate significant improvements in inverter performance compared to conventional modulation techniques. The output voltage waveform shows a clear stepped sinusoidal pattern with fifteen distinct levels, confirming the effectiveness of the asymmetrical topology in generating high-quality voltage waveforms while minimizing the number of power semiconductor devices. The smooth voltage steps indicate reduced lower-order harmonics, which is essential for sensitive industrial loads and medium- to high-power applications.

The load current waveform closely follows the voltage waveform, indicating proper voltage-current synchronization and minimal distortion in the RL load. The reduced ripple in the current waveform reflects effective harmonic mitigation and improved system stability. The Total Harmonic Distortion (THD) analysis reveals a significant reduction in harmonic content: the hybrid Bi–Tri SVPWM achieves a THD of 7.4%, compared to 12.3% for conventional SVPWM and 18.6% for SPWM. This demonstrates the superior harmonic performance of the hybrid approach, which is achieved by efficiently utilizing the additional degrees of freedom in the tri-dimensional space vector representation while simplifying vector selection with the bi-dimensional approach.

The hybrid SVPWM technique also optimizes switching sequences, reducing high-frequency transitions and thereby minimizing switching losses. This leads to improved overall efficiency, lower thermal stress on switching devices, and enhanced voltage utilization from asymmetrical DC sources. Additionally, the seamless operation across different load conditions and modulation indices highlights the adaptability and robustness of the control strategy. Overall, the simulation confirms that the hybrid Bi–Tri dimensional SVPWM provides a practical and efficient solution for high-level asymmetrical multilevel inverters, making it highly suitable for renewable energy systems, industrial motor drives, and other high-power applications.

VI. CONCLUSION

This study presents a comprehensive analysis of a Hybrid Bi–Tri Dimensional Space Vector Pulse Width Modulation (SVPWM) technique applied to an asymmetrical fifteen-level inverter. The proposed methodology successfully integrates the advantages of both bi-dimensional and tri-dimensional space vector modulation, resulting in enhanced inverter performance with reduced harmonic distortion, improved voltage utilization, and lower switching losses. The asymmetrical topology allows generation of fifteen distinct voltage levels using a minimal number of DC sources and semiconductor devices, thereby reducing hardware complexity and overall system cost.

Simulation results validate the effectiveness of the hybrid SVPWM approach. The output voltage waveform demonstrates smooth, stepped transitions that closely approximate a sinusoidal reference, ensuring high-quality voltage for connected loads. The load current waveform remains stable and closely tracks the voltage waveform, indicating effective control and minimal distortion. Total Harmonic Distortion (THD) analysis shows a substantial reduction in harmonics, with the hybrid Bi–Tri dimensional SVPWM achieving a THD of 7.4%, outperforming conventional SVPWM and sinusoidal PWM methods. This confirms the proposed technique's capability to enhance power quality and efficiency in high-power applications.

Furthermore, the optimized switching strategy reduces high-frequency transitions, minimizing switching losses and thermal stress on devices. The approach also ensures balanced utilization of the asymmetrical DC sources, further enhancing reliability and operational stability. Overall, the study demonstrates that the hybrid Bi–Tri dimensional SVPWM technique is a robust, efficient, and practical solution for high-level asymmetrical multilevel inverters, making it highly suitable for industrial motor drives, renewable energy systems, and other medium- to high-power applications. The results establish a strong foundation for future research in advanced multilevel inverter modulation strategies.

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