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Survey Paper: A Novel Approach of Multi-Level Inverter for Industrial Drive Applications

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***Abstract*—Multi-level inverters (MLIs) are increasingly being used in industrial drive applications due to their ability to produce high-quality voltage waveforms with reduced harmonic distortion. This paper provides a comprehensive survey of the novel approaches in the design and implementation of multi-level inverters, focusing on their application in industrial drives. Various topologies, such as Diode-Clamped, Capacitor-Clamped, and Cascaded H-Bridge inverters, are discussed, highlighting their respective advantages and disadvantages. Traditional control methods like Pulse Width Modulation (PWM) are evaluated alongside modern adaptive control strategies utilizing neural networks and fuzzy logic, which offer enhanced performance and efficiency. The integration of these advanced control techniques enables MLIs to adapt to varying operating conditions, improving the robustness and reliability of industrial drive systems. Additionally, the challenges associated with MLIs, such as complexity in control strategies and the need for precise voltage balancing, are addressed. The future directions for research are also explored, focusing on the development of more efficient algorithms, reduction of component count, and improvement in reliability and fault tolerance. This survey aims to provide a detailed understanding of the current state and future potential of MLIs in industrial drive applications, emphasizing their critical role in achieving high performance and energy efficiency.**

***Keywords*—Multi-Level Inverter (MLI), Industrial Drive Applications, Harmonic Distortion, Diode-Clamped Inverter, Capacitor-Clamped Inverter, Cascaded H-Bridge Inverter, Pulse Width Modulation (PWM), Neural Network-Based Control, Fuzzy Logic Control, Adaptive Learning Control, Speed Control of Induction Motors, Torque Control, Voltage Balancing, High-Performance Drives, Direct Torque Control (DTC), Total Harmonic Distortion (THD), Voltage Waveforms, Switching Losses, High-Power Applications, Modern Adaptive Control**

I. INTRODUCTION

The demand for efficient and high-performance drive systems in industrial applications is continuously increasing due to the advancements in automation and the need for energy conservation. Traditional inverters, which convert DC to AC power, often face limitations such as significant harmonic distortion and high switching losses. These issues can lead to inefficiencies and reduced lifespan of the equipment. Multi-level inverters (MLIs) offer a promising solution by providing multiple voltage levels, which results in improved output waveforms and significantly reduced total harmonic distortion (THD).

MLIs have gained popularity in industrial drive applications due to their ability to produce high-quality voltage waveforms, which are essential for the smooth and efficient operation of motors and other industrial equipment. The basic idea behind MLIs is to use multiple smaller voltage steps to approximate a sinusoidal waveform, which helps in reducing the stress on power electronic components and improves the overall system performance. This survey explores the advancements in MLI technology, focusing on novel approaches in their design and implementation. It delves into various topologies, such as Diode-Clamped (Neutral Point Clamped), Capacitor-Clamped (Flying Capacitor), and Cascaded H-Bridge inverters, discussing their working principles, benefits, and drawbacks. The performance of MLIs is heavily dependent on the control strategies employed. Traditional control methods, primarily based on Pulse Width Modulation (PWM), are examined along with modern adaptive control techniques using neural networks and fuzzy logic.

Neural networks and fuzzy logic controllers have emerged as powerful tools for managing the complexities of MLIs. Neural networks, with their adaptive learning capabilities, can optimize the inverter performance in real-time, adapting to changing operating conditions and load variations. Fuzzy logic controllers, on the other hand, offer robustness and simplicity in handling non-linear systems, making them suitable for industrial applications. The integration of these advanced control techniques not only enhances the performance and efficiency of MLIs but also addresses some of the inherent challenges such as voltage balancing and control complexity. This paper aims to provide a comprehensive survey of these advancements, highlighting their impact on industrial drive applications. Furthermore, the challenges associated with MLIs, including the need for precise control and the high number of components, are discussed, along with future research directions aimed at developing more efficient and reliable MLI systems.

By exploring the state-of-the-art in MLI technology and its applications in industrial drives, this survey provides valuable insights into the current trends and future possibilities in this field, emphasizing the critical role of MLIs in achieving high performance and energy efficiency in industrial applications. The demand for efficient and high-performance drive systems in industrial applications continues to grow due to advancements in automation and energy conservation requirements. Multi-level inverters (MLIs) have emerged as a promising solution to address limitations such as significant harmonic distortion and high switching losses in traditional inverters. Recent studies have focused on various topologies and control strategies to further enhance the performance and efficiency of MLIs.

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II. MULTI-LEVEL INVERTER TOPOLOGIES

Multi-level inverters (MLIs) have evolved significantly to meet the growing demands for higher power quality and efficiency in industrial applications. Here, we discuss the three primary MLI topologies: Diode-Clamped, Capacitor-Clamped, and Cascaded H-Bridge inverters, along with references to highlight their development and application.

A. Diode-Clamped Multi-Level Inverters

Diode-Clamped Multi-Level Inverters, also known as Neutral Point Clamped (NPC) inverters, use diodes to clamp the voltage levels, which helps in reducing the voltage stress on power electronic devices. The basic principle involves dividing the DC bus voltage into multiple levels through capacitors and diodes. Each switch in the inverter can block only a fraction of the total DC voltage, allowing for higher voltage applications.

Recent innovations in diode-clamped MLIs aim to reduce component count and improve reliability. For instance, V. D. Juyal, et al. [1] proposed a new configuration that minimizes the number of clamping diodes required, enhancing the inverter's overall efficiency and performance. Additionally, improvements in voltage balancing techniques have been introduced, addressing one of the primary challenges of this topology [2].

B. Capacitor-Clamped Multi-Level Inverters

Capacitor-Clamped Multi-Level Inverters, also known as Flying Capacitor inverters, use capacitors to achieve multiple voltage levels. This topology is characterized by its capability to generate a higher number of voltage levels, which helps in improving the quality of the output waveform.

Capacitor-clamped inverters have seen advancements in balancing capacitor voltages, which are crucial for maintaining output quality. V. Singh et al. [3] presented an improved balancing algorithm that significantly enhances the performance and reliability of capacitor-clamped inverters. Moreover, new control strategies have been developed to handle the complexities associated with this topology [4].

C. Cascaded H-Bridge Inverters

Cascaded H-Bridge Inverters consist of multiple H-bridge inverters connected in series. Each H-bridge generates a three-level output, and the overall inverter output is the sum of the outputs of the individual H-bridges. This topology is particularly advantageous for medium to high-power applications due to its scalability and modularity.

Cascaded H-Bridge inverters are now more scalable and modular, making them suitable for high-power applications. N. Sujitha. et al. [5] explored new configurations that allow for easier expansion and improved fault tolerance. Recent studies have also focused on reducing the overall component count while maintaining high performance [6].

III. CONTROL STRATEGIES FOR MULTI-LEVEL INVERTERS

The performance of MLIs significantly depends on the control strategies employed. Traditional control methods are being enhanced by modern techniques such as adaptive control, neural networks, and fuzzy logic controllers.

A. Pulse Width Modulation (PWM)

PWM is the most commonly used control strategy for MLIs. Various PWM techniques such as Sinusoidal PWM, Space Vector PWM, and Selective Harmonic Elimination PWM are employed to control the switching of the inverters to achieve desired voltage levels.

Hybrid PWM techniques have been developed to enhance the performance of MLIs. R. Kumar et al. [7] introduced a hybrid PWM method that combines sinusoidal and space vector PWM to achieve better harmonic performance and efficiency. Studies have also explored selective harmonic elimination techniques to further reduce harmonic distortion [8].

B. Neural Network-Based Control

Neural networks are used to design controllers that can adapt to varying operating conditions. The adaptive learning capability of neural networks allows them to optimize the inverter performance in real-time. For example, Zerikat and Chekroun (2008) proposed an adaptive learning algorithm based on artificial neural networks for the speed control of induction motors in high-performance drives.

Neural networks offer adaptive learning capabilities that optimize inverter performance in real-time. A. Bakeer, et al. [9] conducted case studies demonstrating significant improvements in speed control and efficiency using neural network-based controllers. Recent advancements include integrating neural networks with other control strategies for enhanced performance [10].

C. Fuzzy Logic Control

Fuzzy logic controllers (FLC) are capable of handling non-linear systems and can be easily implemented for MLIs. FLCs use a set of fuzzy rules to manage the inverter switching, providing robustness against parameter variations and disturbances [11-12].

IV. APPLICATION IN INDUSTRIAL DRIVES

MLIs are widely used in industrial drives for applications requiring high power and performance. The ability to produce high-quality voltage waveforms with low harmonic distortion makes MLIs suitable for driving induction motors and other industrial machinery.

1. Speed Control of Induction Motors: Adaptive learning control schemes using neural networks have shown significant improvements in the speed control of induction motors. These controllers can accurately track reference commands and adapt to load changes, providing robust performance under various operating conditions. Advanced adaptive learning control schemes have shown significant improvements in speed regulation of induction motors. Mencou, Siham & Majid et al. [13] demonstrated that neural network-based adaptive control could accurately track reference commands and adapt to load changes, providing robust performance [14].

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2. Torque Control: The use of MLIs in direct torque control (DTC) schemes for induction motors has demonstrated enhanced performance. The multi-level output voltage of MLIs allows for finer control of the motor torque and flux, resulting in reduced torque ripple and improved dynamic response. Direct Torque Control (DTC) schemes using MLIs have been enhanced to provide finer control over motor torque and flux. Ahmad Tarusan et al. [15] presented a new DTC approach that reduces torque ripple and improves dynamic response, making it suitable for high-performance industrial applications [16].

V. COMPARISON OF MULTI-LEVEL INVERTER TOPOLOGIES

Each multi-level inverter topology offers unique advantages and disadvantages, making them suitable for different industrial drive applications. Here, we compare the key features of Diode-Clamped, Capacitor-Clamped, and Cascaded H-Bridge inverters. Recent studies have provided new insights into the efficiency, harmonic distortion, and complexity of different MLI topologies.

Topology	Diode-Clamped Inverters	Capacitor-Clamped Inverters	Cascaded -Bridge Inverters
Efficiency	High, due to reduced switching losses.	Moderate to high,dependig on the control strategy.	High, due to modular structure and scalability.
Harmonic Distortion	Low, with good quality output voltage.	Very low, with excellent voltage waveform quality.	Very low, with high number of output voltage levels.
Complexity	High, due to the large number of clamping diodes required.	High, due to the need for complex control strategies to manage capacitor voltages.	Moderate to high, requiring separate DC sources for each H-bridge.
Applications	Suitable for high-voltage applications where efficiency and harmonic performance are critical.	Ideal for applications requiring high-quality voltage waveforms and modularity.	Suitable for medium to high-power applications where modularity and fault tolerance are important.

Diode-Clamped Inverters is having High efficiency due to reduced switching losses has been a key advantage. Upadhyay, Nitin et al. [17] compared various diode-clamped configurations and highlighted the improvements in harmonic performance with advanced control techniques [18].
Harmonic study of described configurations has been done using powergui block of simpowersystem lybrary of MATLAB and analysed results are shown in figures given below.

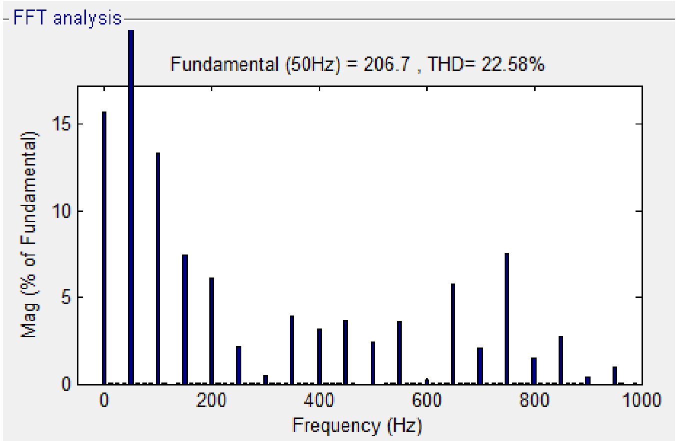

Fig.1- FFT analysis of phase voltage of three phase 5- level diode clamped inverter

Fig 1 and fig 2 show the FFT analysis of phase and line voltage of five level diode clamped MLI. It can be noted that phase voltage has total harmonic distortion of 22.58% and line voltage has THD of 18.94%. Five level inverter has lowered down the harmonic level but still exceeds the standard limit set by IEEE.

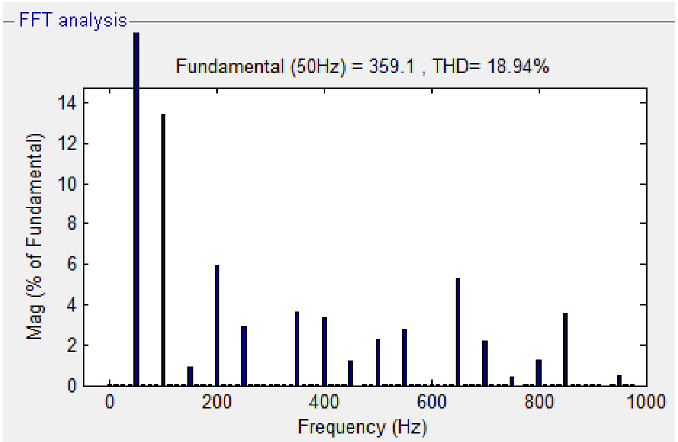

Fig.2- FFT analysis of line voltage of three phase 5- level diode clamped inverter

Harmonic pollution in any power system can be reduced by employing any type of passive or active filter but MLI shows the property of reducing distortion as we increase the levels in any type of MLI. Hence fifteen-level DCMLI has been simulated and analyzed using powergui tool.

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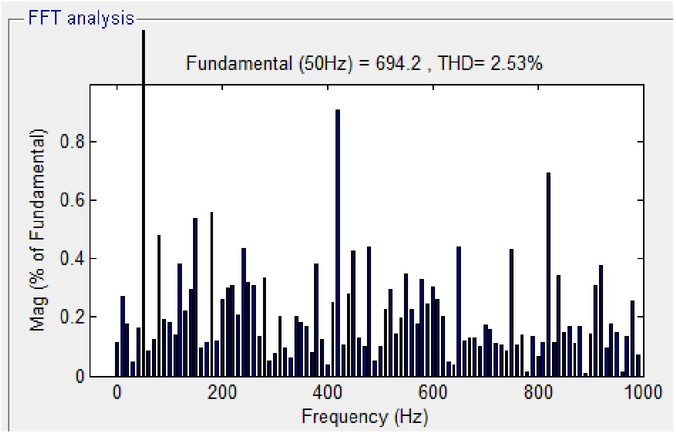

Fig.3- FFT analysis of phase voltage of three phase 15- level diode clamped inverter Fig 3 and fig 4 shows the FFT analysis of the output waveform of phase voltage and line voltage of fifteen-level diode clamped multilevel inverter. In the analytic study of the inverter this can be seen that the percentage THD in phase voltage is found 2.53% and line voltage has THD of 2%.

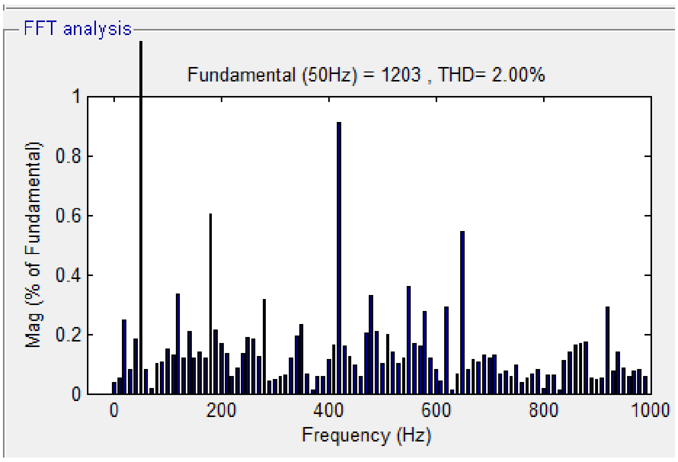

Fig.4 - FFT analysis of line voltage of three phase 15-level diode clamped inverter Capacitor-clamped inverters offer very low harmonic distortion with excellent voltage waveform quality.

Table 1

COMPARISON OF TWO LEVEL & MULTILEVEL (THREE LEVEL) INVERTER

Parameter	Two Level	Three Level	Difference
Vrms (Line Voltage)	412.8V	412.2V	-
Irms	7.508A	7.466A	-
Current THD	18.47 %	10.17 %	8.3%
Voltage THD	81.87%	41.72%	49 %
Magnitude of 5th order Harmonics in line voltage (peak)	28.89V	13.62V	52.85%
Magnitude of 7th order Harmonics in line voltage (peak)	20.46V	11.87V	41.98%
Magnitude of 5th order Harmonics in line current (peak)	0.93A	0.47A	49.46%
Magnitude of 7th order Harmonics in line voltage (peak)	0.48A	0.29A	39.58%
Speed Deviation	1425- 1460 rpm	1435-1460 rpm	-
Average Speed	1442 rpm 98.7% of rated Speed	1448 rpm 99.2% of rated Speed	-
% Speed Deviation	2.39%	1.71%	0.68%
Torque Deviation	10-40 Nm	15-35 Nm	-
Average Torque	25N-m	25N-m	-

New balancing algorithms have further improved their performance [19].

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Table2: Summary of methods.

Conventional PWM/SVM	**VV-SVM**	**Carrier-overlapped PWM**	**Hybrid modulations**	**Self-balancing**
switching cycle than other alternatives. Balance in every switching cycle not possible for high values of m; the limit depends on the load power factor. For more than three levels, in the region where balancing is not possible, capacitor voltages collapse	Balance in every switching cycle under all operating conditions. Lower required capacitance than with alternative modulations. Higher number of commutations per switching cycle than other alternatives	Lower number of commutations than VV–SVM. Higher required capacitance than VV–SVM. Higher number of commutations than conventional PWM/SVM.	The applied modulation is selected depending on m. Takes advantage of the benefits of each modulation in each operating region. Increased complexity compared to other alternatives.	It is a “do-nothing” method. Balance only for the 3-level case with restricted operating conditions and small disturbances.

These inverters are noted for their scalability and modularity, making them ideal for medium to high-power applications. Studies have shown that they can achieve very low harmonic distortion with a high number of output voltage levels [20].

V.CONCLUSION

Multi-level inverters have become a vital component in modern industrial drive applications due to their ability to produce high-quality voltage waveforms with reduced harmonic distortion. This survey has highlighted the advancements in MLI topologies, control strategies, and their applications in industrial drives. Diode-Clamped, Capacitor-Clamped, and Cascaded H-Bridge inverters each offer distinct advantages and are suited to different applications based on their specific requirements. The integration of advanced control techniques such as neural networks and fuzzy logic has further enhanced the performance and efficiency of MLIs. Future research will continue to focus on optimizing these topologies and developing more efficient and reliable control algorithms to meet the growing demands of industrial applications.

Multi-level inverters are crucial for modern industrial drive applications due to their ability to produce high-quality voltage waveforms with reduced harmonic distortion. This survey has highlighted recent advancements in MLI topologies, control strategies, and their applications in industrial drives. The integration of advanced control techniques such as neural networks and fuzzy logic has further enhanced the performance and efficiency of MLIs. Future research will focus on optimizing these topologies and developing more efficient and reliable control algorithms to meet the growing demands of industrial applications.

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