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A REVIEW OF HARMONIC MITIGATION-ORIENTED DESIGN OF A MODIFIED CASCADED MULTILEVEL INVERTER FOR MEDIUM-POWER INDUSTRIAL DRIVE SYSTEMS

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Abstract - *The increasing demand for high-performance medium-power industrial drive systems has intensified the need for power electronic converters capable of delivering high-quality output voltage with minimal harmonic distortion. Multilevel inverters (MLIs) have emerged as an effective solution for improving power quality due to their ability to synthesize staircase-like voltage waveforms with reduced switching stress and lower total harmonic distortion (THD). Among various MLI topologies, the cascaded H-bridge multilevel inverter (CHB-MLI) has gained significant attention because of its modular structure, scalability, and suitability for medium-voltage and medium-power industrial applications. However, conventional CHB inverters still face several challenges, including a high number of power semiconductor devices, multiple isolated DC sources, and increased control complexity. To address these limitations, researchers have proposed several modified cascaded multilevel inverter (MCMLI) configurations focused on reducing component count while maintaining or improving harmonic performance. This review paper presents a comprehensive survey of harmonic mitigation-oriented design strategies for modified cascaded multilevel inverters used in medium-power industrial drive systems. The paper discusses the fundamental principles of multilevel inverter technology, conventional and modified CHB topologies, and various harmonic mitigation techniques such as pulse width modulation methods, selective harmonic elimination, and optimization-based control approaches. Furthermore, the paper summarizes recent research developments, compares different inverter configurations in terms of harmonic performance and structural complexity, and highlights emerging trends and research gaps. The review aims to provide a consolidated understanding of harmonic mitigation strategies in modified cascaded multilevel inverters for improving efficiency, reliability, and power quality in modern industrial drive applications..*

Key Words: Multilevel Inverter, Cascaded H-Bridge Inverter, Harmonic Mitigation, Industrial Drive Systems, Pulse Width Modulation, Total Harmonic Distortion.

1. INTRODUCTION

1.1 Background of Industrial Drive Systems

Industrial drive systems play a crucial role in modern manufacturing and processing industries by enabling precise control of electric motors used in applications such as pumps, compressors, conveyors, fans, and machine tools. These drives are responsible for regulating speed, torque, and operational efficiency of industrial machinery, which directly affects productivity and energy consumption. Medium-power industrial drives, typically ranging from a few kilowatts to several hundred kilowatts, are widely employed in sectors such as chemical processing, water treatment, mining, and automated production systems. The integration of power electronic converters in these drives has significantly improved motor control performance and energy efficiency compared with traditional electromechanical control methods (Bose, 2002).

1.1.1 Power Quality Requirements in Industrial Environments

In industrial environments, maintaining high power quality is essential for ensuring reliable and efficient operation of electrical equipment. Power quality refers to the stability and purity of electrical voltage and current supplied to loads. Poor power quality can lead to overheating of motors, malfunction of sensitive electronic devices, and increased system losses. Industrial facilities often contain nonlinear loads such as variable speed drives, rectifiers, and switching converters, which can introduce voltage distortion and current harmonics into the electrical network. Therefore, modern industrial drive systems must be designed with appropriate power electronic configurations and control strategies that minimize distortion and maintain stable operation under varying load conditions (Arrillaga and Watson, 2003).

1.2 Harmonics and Their Impact on Industrial Drives

Harmonics are sinusoidal components of voltage or current whose frequencies are integer multiples of the fundamental frequency of the power system. In inverter-based motor drives, harmonics are primarily generated due to the switching action of power semiconductor devices and nonlinear characteristics of loads. Harmonic distortion is typically quantified using Total Harmonic Distortion (THD), which represents the ratio of harmonic components to the fundamental component of the waveform. Excessive harmonic distortion can degrade the quality of electrical power and negatively affect the performance of industrial drive systems (Akagi, 2017).

1.2.1 Effects on Motors, Transformers, and Grid Stability

The presence of harmonics in industrial power systems can cause several adverse effects on electrical equipment. In electric motors, harmonic currents lead to additional copper and iron losses, resulting in increased heating and reduced efficiency. Harmonics can also produce torque pulsations that cause vibration and acoustic noise in motor drives. In transformers, harmonic currents increase core losses and may lead to insulation stress and premature failure. Furthermore, harmonics injected into the utility grid can cause voltage distortion, interference with communication systems, and instability in power distribution networks. As a result, effective harmonic mitigation techniques are essential for maintaining reliable operation of industrial drive systems and ensuring compliance with power quality standards such as IEEE 519 (Akagi, 2017).

1.3 Multilevel Inverters as a Solution

Multilevel inverters have emerged as an important power electronic solution for reducing harmonic distortion in medium- and high-power applications. Unlike conventional two-level inverters that produce only two voltage levels, multilevel inverters generate multiple discrete voltage levels by combining several power semiconductor devices and DC sources. This capability enables them to produce output waveforms that more closely resemble sinusoidal signals. Consequently, multilevel inverters can achieve lower harmonic distortion, reduced voltage stress across switching devices, and improved overall efficiency compared with traditional inverter topologies (Rodriguez, Lai and Peng, 2002).

1.3.1 Advantages over Conventional Two-Level Inverters

One of the major advantages of multilevel inverters is their ability to reduce switching losses and electromagnetic interference due to lower voltage step changes in the output waveform. The staircase voltage waveform generated by multilevel inverters approximates a sinusoidal waveform with smaller harmonic components, thereby reducing the need for bulky output filters. Additionally, these inverters distribute voltage stress across multiple semiconductor switches, which enhances reliability and allows the use of lower-rated devices in high-power applications. Because of these benefits, multilevel inverters have become widely adopted in industrial drives, renewable energy systems, and high-voltage power conversion applications (Rodriguez, Lai and Peng, 2002).

1.4 Modified Cascaded Multilevel Inverters

Among the various multilevel inverter topologies, the cascaded H-bridge (CHB) inverter has gained considerable attention due to its modular structure and ease of control. In a conventional CHB inverter, multiple H-bridge cells are connected in series, each supplied by an isolated DC source, to produce multiple voltage levels at the output. Although this configuration provides high-quality output waveforms and improved harmonic performance, it also introduces several practical challenges. Specifically, the requirement for multiple isolated DC sources increases system complexity, cost, and design difficulty. In addition, a large number of power semiconductor devices and gate driver circuits may increase switching losses and control complexity (Malinowski, Gopakumar and Rodriguez, 2010).

To overcome these limitations, researchers have proposed modified cascaded multilevel inverter (MCMLI) topologies that aim to reduce the number of switches, minimize DC source requirements, and improve harmonic suppression performance. These modified configurations often employ hybrid structures, asymmetric voltage sources, or optimized switching strategies to enhance system efficiency while maintaining high-quality output voltage waveforms. As a result, MCMLIs are increasingly considered promising candidates for medium-power industrial drive systems where reliability, efficiency, and power quality are critical design considerations.

1.5 Scope and Organization of the Review Paper

This review paper aims to provide a comprehensive overview of harmonic mitigation-oriented design approaches for modified cascaded multilevel inverters used in medium-power industrial drive systems. The paper begins by discussing the fundamentals of multilevel inverter technology and the operational characteristics of cascaded inverter topologies. Subsequently, different modified cascaded multilevel inverter configurations proposed in the literature are analyzed with emphasis on their harmonic mitigation capabilities and structural advantages. The review further examines various harmonic reduction techniques, including modulation strategies and optimization-based switching methods. Finally, the paper presents a comparative analysis of existing approaches, identifies research gaps, and outlines potential future directions for improving the performance and practical implementation of modified cascaded multilevel inverter systems in industrial applications.

2. FUNDAMENTALS OF MULTILEVEL INVERTER TECHNOLOGY

2.1 Overview of Multilevel Inverter Topologies

Multilevel inverter (MLI) technology has become an important advancement in power electronics for medium- and high-power applications. Unlike conventional two-level inverters that generate only two voltage states, multilevel inverters produce multiple discrete voltage levels by combining several switching devices and DC voltage sources. This capability allows the inverter to synthesize a stepped output voltage waveform that more closely approximates a sinusoidal waveform. As a result, multilevel inverters significantly reduce harmonic distortion, switching losses, and voltage stress across semiconductor devices. Because of these advantages, MLIs are widely applied in industrial motor drives, renewable energy systems, high-voltage direct current transmission, and flexible AC transmission systems (Rodriguez, Lai and Peng, 2002). Over the years, several multilevel inverter topologies have been developed, among which the Neutral Point Clamped (NPC), Flying Capacitor (FC), and Cascaded H-Bridge (CHB) inverters are considered the most prominent structures.

2.1.1 Neutral Point Clamped (NPC) Inverter

The Neutral Point Clamped (NPC) inverter, also known as the diode-clamped multilevel inverter, was one of the earliest multilevel converter topologies introduced for high-power applications. In this configuration, clamping diodes are used to connect the midpoint of the DC bus to the switching devices, thereby enabling the generation of multiple voltage levels. A typical three-level NPC inverter divides the DC-link voltage into two equal parts using capacitors and uses clamping diodes to control the voltage across the switching devices. The main advantage of the NPC topology is its ability to share voltage stress among multiple switches, allowing the use of lower-rated semiconductor devices in high-voltage applications. However, as the number of voltage levels increases, the number of clamping diodes required grows significantly, which increases circuit complexity and makes voltage balancing more challenging (Nabae, Takahashi and Akagi, 1981).

2.1.2 Flying Capacitor (FC) Inverter

The Flying Capacitor (FC) inverter is another widely studied multilevel topology that replaces clamping diodes with capacitors connected between switching nodes. These capacitors act as floating voltage sources that enable the generation of multiple output voltage levels. One of the key advantages of the FC inverter is its flexibility in controlling voltage levels and the ability to provide redundant switching states, which can be used to balance capacitor voltages. This feature improves the reliability and control capability of the system. However, the major limitation of this topology is the requirement of a large number of capacitors as the number of voltage levels increases. The additional capacitors increase system cost, physical size, and control complexity, which may limit its practical implementation in some industrial applications (Peng, 2001).

2.1.3 Cascaded H-Bridge (CHB) Inverter

The Cascaded H-Bridge (CHB) inverter consists of multiple single-phase H-bridge cells connected in series, with each cell powered by an independent DC source. By combining the outputs of individual H-bridge modules, the inverter can generate multiple voltage levels at the output. The CHB topology offers several advantages, including modular structure, simple control strategy, and the ability to expand the number of voltage levels by adding additional H-bridge cells. Due to its modularity and scalability, the cascaded H-bridge topology is widely adopted in medium- and high-power motor drive systems, particularly in applications such as electric drives, renewable energy integration, and high-voltage power conversion. Furthermore, the modular design simplifies maintenance and improves system reliability compared with other multilevel inverter structures (Malinowski, Gopakumar and Rodriguez, 2010).

2.2 Advantages of Multilevel Inverters in Industrial Drives

Multilevel inverters offer several advantages that make them highly suitable for industrial drive applications. These advantages primarily arise from their ability to generate multiple voltage levels, which improves the quality of the output waveform and reduces electrical stress on system components. As industrial processes increasingly demand efficient and reliable motor control systems, multilevel inverter technology has become a preferred choice for medium- and high-power drive applications. The improved waveform quality reduces the need for bulky filters, enhances system efficiency, and ensures compliance with power quality standards in industrial power systems (Bose, 2002).

2.2.1 Reduced Harmonic Distortion

One of the most significant advantages of multilevel inverters is their ability to reduce harmonic distortion in the output voltage waveform. Because the output voltage is generated through multiple small voltage steps rather than large transitions between two levels, the resulting waveform closely approximates a sinusoidal signal. This reduction in harmonic components decreases the Total Harmonic Distortion (THD) of the system and improves the overall power quality supplied to the motor drive. In practical implementations, increasing the number of voltage levels significantly decreases harmonic distortion; for instance, THD may reduce from approximately 34% in a three-level inverter to nearly 17% in a seven-level inverter under similar operating conditions. This improvement enhances motor performance and reduces thermal stress on electrical components.

2.2.2 Lower Switching Losses

Multilevel inverters also contribute to reduced switching losses in power electronic devices. In conventional two-level inverters, switches must handle the full DC-link voltage, resulting in higher switching stress and greater energy loss during switching transitions. In contrast, multilevel inverter structures divide the DC-link voltage across multiple devices, reducing the voltage stress on individual switches. Because the voltage change during switching is smaller, the associated switching losses are reduced. This characteristic allows multilevel inverters to operate efficiently at higher power levels while maintaining acceptable thermal conditions for semiconductor devices (Rodriguez, Lai and Peng, 2002).

2.2.3 Improved Electromagnetic Compatibility

Another important advantage of multilevel inverters is improved electromagnetic compatibility (EMC) in industrial environments. The smaller voltage steps produced by multilevel inverters lead to lower rates of voltage change (dv/dt) compared with conventional inverters. Lower dv/dt reduces electromagnetic interference (EMI), minimizes insulation stress on motor windings, and decreases the likelihood of bearing currents in motor drives. As a result, multilevel inverter-based drive systems provide more reliable operation and longer equipment lifespan. These benefits are particularly important in industrial applications where sensitive electronic systems and communication equipment operate alongside high-power motor drives (Bose, 2002).

3. CASCADED MULTILEVEL INVERTER TOPOLOGY

3.1 Structure and Operating Principle of CHB Inverters

The Cascaded H-Bridge (CHB) multilevel inverter is one of the most widely used multilevel converter topologies for medium- and high-power applications. It is particularly suitable for industrial motor drive systems because of its modular design, simple control structure, and capability to produce high-quality output voltage waveforms. In this topology, multiple H-bridge power cells are connected in series on the AC side, and each cell is supplied by an independent DC voltage source. By properly controlling the switching states of individual H-bridge cells, the inverter can generate multiple voltage levels that approximate a sinusoidal waveform. The modular nature of CHB inverters allows easy expansion of voltage levels by adding additional H-bridge modules, making the topology highly scalable for different power ratings and voltage requirements (Rodriguez, Lai and Peng, 2002).

3.1.1 Basic H-Bridge Cell Configuration

The fundamental building block of a cascaded multilevel inverter is the H-bridge power cell. Each H-bridge consists of four power semiconductor switches arranged in a bridge configuration along with appropriate gate driver circuits. The H-bridge cell is supplied by a DC voltage source and can produce three different output voltage levels: positive DC voltage (+Vdc), zero voltage (0), and negative DC voltage (−Vdc). These voltage levels are generated by activating specific pairs of switches in the bridge. For example, turning on one diagonal pair of switches produces a positive output voltage, while activating the opposite diagonal pair produces a negative voltage. When the two switches on the same leg are turned on simultaneously, the output voltage becomes zero. This switching capability allows each H-bridge cell to contribute a controlled voltage level to the overall inverter output (Bose, 2002).

3.1.2 Cascaded Connection of H-Bridge Modules

In a cascaded multilevel inverter, multiple H-bridge cells are connected in series to form a multilevel output voltage waveform. Each module contributes its individual voltage level to the total output voltage of the inverter. If n H-bridge cells are connected in series, the inverter can generate 2n + 1 voltage levels. For example, two cascaded H-bridge modules can produce a five-level output waveform, while three modules can generate a seven-level waveform. By increasing the number of modules, the output voltage waveform becomes smoother and more closely approximates a sinusoidal signal. This modular architecture also improves system reliability because faulty modules can sometimes be bypassed or replaced without affecting the entire system. Due to these advantages, cascaded H-bridge inverters are widely applied in medium-voltage motor drives, static synchronous compensators, and renewable energy systems (Malinowski, Gopakumar and Rodriguez, 2010).

3.2 Mathematical Representation of Output Voltage

The output voltage of a cascaded multilevel inverter is obtained by summing the voltage contributions from each individual H-bridge module. The mathematical representation of the inverter output voltage is useful for analyzing waveform characteristics, harmonic components, and modulation strategies used in practical implementations. Understanding the mathematical formulation of the CHB inverter output helps engineers design appropriate control algorithms for harmonic reduction and efficient operation of industrial drive systems.

3.3 Limitations of Conventional CHB Inverters

Although cascaded H-bridge multilevel inverters provide several advantages such as modularity and improved harmonic performance, conventional CHB configurations also exhibit certain practical limitations. These limitations mainly arise from the requirement of multiple DC voltage sources, increased hardware complexity, and sophisticated control strategies needed for proper operation. Addressing these challenges has motivated researchers to develop modified cascaded multilevel inverter topologies that reduce component count and simplify system implementation.

3.3.1 Requirement of Multiple DC Sources

One of the primary limitations of the conventional CHB inverter is the requirement for multiple isolated DC voltage sources, one for each H-bridge module. In many industrial applications, obtaining several independent DC sources is difficult and may require additional power conversion stages such as rectifiers or isolated transformers. This requirement increases system complexity, cost, and installation space. In renewable energy applications, separate DC sources may be available naturally (such as photovoltaic modules), but in typical industrial motor drive systems this requirement can pose a significant design challenge (Rodriguez, Lai and Peng, 2002).

3.3.2 Increased Component Count

Another limitation of the conventional cascaded multilevel inverter is the increased number of power semiconductor switches and associated gate driver circuits required as the number of voltage levels increases. Each additional H-bridge cell requires four switching devices, which increases hardware complexity and overall system cost. The large number of components may also reduce system reliability due to the higher probability of component failure. Furthermore, increased device count leads to higher conduction losses and larger system size, which can limit the practical deployment of high-level CHB inverters in certain industrial applications (Malinowski, Gopakumar and Rodriguez, 2010).

3.3.3 Control Complexity

Control complexity is another challenge associated with conventional CHB inverter systems. As the number of cascaded modules increases, the control algorithm must manage multiple switching states and ensure proper voltage balancing among the DC sources. In addition, advanced modulation techniques are often required to minimize harmonic distortion and optimize switching performance. Implementing these control strategies requires sophisticated digital controllers and complex gating signal generation schemes. Consequently, developing efficient and simplified control techniques remains an active research area in multilevel inverter technology for industrial drive systems (Holmes and Lipo, 2003).

4. MODIFIED CASCADED MULTILEVEL INVERTER TOPOLOGIES

4.1 Modified Topologies

Although conventional cascaded H-bridge (CHB) multilevel inverters offer several advantages such as modular design, improved waveform quality, and scalability for medium- and high-power applications, practical implementation often reveals several technical limitations. These limitations include the requirement of multiple isolated DC voltage sources, a high number of semiconductor switching devices, and increased control complexity. As the number of voltage levels increases, these challenges become more pronounced, resulting in higher system cost and reduced practicality for industrial applications. To overcome these issues, researchers have proposed modified cascaded multilevel inverter (CMLI) topologies that aim to achieve similar or improved performance while reducing hardware complexity and improving harmonic suppression capability. These modified structures often integrate innovative circuit configurations and advanced modulation strategies to optimize inverter performance for industrial drive systems (Rodriguez et al., 2010).

4.1.1 Reduction in DC Sources

One of the major motivations for developing modified cascaded multilevel inverter topologies is to reduce the number of required DC voltage sources. In conventional CHB inverters, each H-bridge module requires a separate isolated DC source. While this arrangement is suitable for applications such as photovoltaic systems where multiple DC sources naturally exist, it becomes a challenge in industrial drive systems where only a single DC supply may be available. Modified CMLI structures attempt to address this issue by using techniques such as switched capacitor networks, diode clamping arrangements, or shared DC-link configurations. By minimizing the number of required DC sources, these topologies simplify system design and reduce the need for additional power conversion stages (Gupta and Jain, 2014).

4.1.2 Improved Harmonic Performance

Another important motivation behind modified cascaded inverter topologies is the need for improved harmonic performance. Industrial drive systems require high-quality output voltage waveforms with minimal harmonic distortion to ensure efficient motor operation and compliance with power quality standards. Modified CMLI designs often employ optimized switching configurations, additional voltage levels, or advanced modulation techniques to reduce Total Harmonic Distortion (THD). By increasing the effective number of voltage levels or optimizing switching angles, these topologies can generate output waveforms that more closely resemble sinusoidal signals, thereby reducing harmonic currents and associated losses in motors and power systems (Holmes and Lipo, 2003).

4.1.3 Reduced Power Semiconductor Devices

The reduction of power semiconductor devices is another key objective in the development of modified cascaded multilevel inverter topologies. Conventional CHB inverters require four switches per H-bridge module, which means that the number of switching devices increases rapidly as more voltage levels are added. A higher number of switches not only increases the cost of the inverter but also complicates gate driver circuits and increases switching losses. Modified topologies aim to generate more voltage levels using fewer switches by employing alternative circuit configurations such as switched capacitor cells, diode-assisted structures, or integrated bridge arrangements. Reducing the number of switching devices improves system efficiency, decreases control complexity, and enhances overall reliability (Saba et al., 2018).

4.2 Classification of Modified CMLI Topologies

Modified cascaded multilevel inverter topologies can be broadly classified based on their circuit configuration and operating principles. Researchers have proposed several innovative designs that improve performance while addressing the limitations of conventional CHB inverters. These modified configurations typically focus on reducing component count, improving harmonic performance, or enabling operation with fewer DC voltage sources. Among the most commonly studied modified structures are reduced switch count inverters, hybrid multilevel inverters, and asymmetric cascaded inverter configurations.

4.2.1 Reduced Switch Count Inverters

Reduced switch count multilevel inverters are designed to produce multiple voltage levels using a smaller number of power semiconductor devices compared with conventional CHB structures. These topologies often utilize special switching arrangements or auxiliary components such as diodes or capacitors to generate additional voltage levels without significantly increasing hardware complexity. The main objective of these designs is to reduce cost and improve efficiency while maintaining acceptable harmonic performance. Such configurations are particularly beneficial in industrial applications where compact design and reduced system cost are important considerations (Gupta and Jain, 2014).

4.2.2 Hybrid Multilevel Inverters

Hybrid multilevel inverter topologies combine features of different multilevel inverter structures to achieve improved performance characteristics. For example, hybrid configurations may integrate cascaded H-bridge cells with diode-clamped or flying capacitor structures to reduce the number of DC sources and improve voltage balancing capabilities. By combining different topological principles, hybrid inverters can achieve higher voltage levels, lower harmonic distortion, and improved efficiency compared with conventional designs. These systems are increasingly being investigated for applications in medium-voltage industrial drives and renewable energy systems where flexibility and efficiency are essential design requirements (Rodriguez et al., 2010).

4.2.3 Asymmetric Cascaded Inverters

Asymmetric cascaded multilevel inverters represent another important class of modified CMLI topologies. In these configurations, the DC voltage sources connected to different H-bridge modules have unequal voltage magnitudes. By selecting appropriate voltage ratios, such as binary or trinary progression, asymmetric cascaded inverters can generate a larger number of output voltage levels using fewer inverter cells. This approach significantly improves the voltage resolution and reduces harmonic distortion without requiring a large number of switching devices. Asymmetric cascaded structures are particularly attractive for applications where higher voltage levels are required with minimal hardware complexity (Lezana and Rodriguez, 2009).

4.3 Comparison Between Conventional and Modified Topologies

To better understand the advantages of modified cascaded multilevel inverter topologies, it is useful to compare them with conventional CHB structures in terms of design complexity, component count, and harmonic performance. Conventional CHB inverters provide excellent modularity and scalability but often require a large number of switches and isolated DC sources. Modified CMLI topologies aim to address these limitations by optimizing circuit configuration and reducing component requirements while maintaining or improving harmonic performance.

Table 1 Comparison Between Conventional CHB and Modified CMLI Topologies

Feature	Conventional CHB	Modified CMLI
Number of DC sources	High	Reduced
Switch count	High	Optimized
Harmonic distortion	Moderate	Lower
System complexity	High	Moderate

5. HARMONIC GENERATION AND MITIGATION TECHNIQUES

5.1 Sources of Harmonics in Inverter-Based Drives

Harmonics in inverter-based industrial drive systems primarily arise due to the switching nature of power electronic converters and the nonlinear characteristics of electrical loads. When inverters convert DC power into AC using semiconductor switching devices, the resulting voltage waveform is typically non-sinusoidal and contains multiple frequency components. These harmonic components can propagate through the electrical system, affecting motor performance, increasing losses, and degrading power quality. Understanding the sources of harmonic generation is essential for designing effective mitigation techniques in multilevel inverter-based industrial drives (Arrillaga and Watson, 2003).

5.1.1 Switching Harmonics

Switching harmonics are generated as a direct consequence of the high-frequency switching operations of semiconductor devices such as IGBTs and MOSFETs used in power electronic inverters. During the switching process, the output voltage waveform changes abruptly between discrete voltage levels, producing harmonic components at multiples of the switching frequency and its sidebands. Although high switching frequencies help reduce low-order harmonics, they may introduce higher-frequency components that can cause electromagnetic interference and additional switching losses. Proper selection of switching frequency and modulation strategies is therefore essential to minimize these undesirable harmonic effects (Holmes and Lipo, 2003).

5.1.2 Motor-Load Interaction

Another significant source of harmonics in inverter-driven systems arises from the interaction between the inverter output and the electrical characteristics of the motor and mechanical load. Induction motors and other electric machines possess nonlinear magnetic properties that can introduce additional distortion in current waveforms when supplied with non-sinusoidal voltage. These harmonic currents may lead to torque pulsations, increased vibration, and acoustic noise in the motor drive system. Additionally, the interaction between inverter switching patterns and motor impedance can amplify certain harmonic components, further affecting system performance (Bose, 2002).

5.1.3 Nonlinear Loads

Nonlinear loads connected to industrial power systems also contribute to harmonic generation. Devices such as rectifiers, switching power supplies, and variable speed drives draw non-sinusoidal currents even when supplied with sinusoidal voltage. These nonlinear current waveforms contain harmonic components that propagate through the electrical network and interact with inverter-generated harmonics. As a result, the combined harmonic distortion in industrial power systems may increase significantly if appropriate filtering or mitigation techniques are not implemented (Akagi, 2017).

5.2 Pulse Width Modulation Techniques

Pulse Width Modulation (PWM) is one of the most widely used techniques for controlling power electronic inverters and mitigating harmonic distortion in output voltage waveforms. In PWM-based control, the switching states of semiconductor devices are modulated according to a reference signal to produce a desired AC waveform. By adjusting parameters such as modulation index and switching frequency, PWM techniques can significantly influence the harmonic performance of the inverter. Properly designed PWM strategies can reduce total harmonic distortion (THD), improve waveform quality, and enhance the efficiency of inverter-based industrial drive systems (Holmes and Lipo, 2003).

5.2.1 Sinusoidal PWM (SPWM)

Sinusoidal Pulse Width Modulation (SPWM) is one of the simplest and most commonly used modulation techniques in inverter control. In SPWM, a sinusoidal reference signal representing the desired output voltage is compared with a high-frequency triangular carrier signal. The intersection points between these two signals determine the switching instants of the inverter switches. As a result, the width of the generated pulses varies in proportion to the sinusoidal reference waveform, producing an output voltage that approximates a sinusoidal waveform. SPWM is widely used because of its simplicity and ease of implementation, although it may not always provide optimal harmonic performance for high-level multilevel inverter systems.

5.2.2 Space Vector PWM (SVPWM)

Space Vector Pulse Width Modulation (SVPWM) is an advanced modulation technique that utilizes the space vector representation of three-phase voltages to control inverter switching states. Instead of directly comparing reference and carrier signals, SVPWM determines the appropriate switching vectors within the inverter voltage space to synthesize the desired output waveform. This method allows better utilization of the DC bus voltage and typically produces lower harmonic distortion compared with conventional SPWM techniques. SVPWM is widely used in high-performance motor drives and multilevel inverter applications because of its improved efficiency and enhanced control flexibility (Rodriguez, Lai and Peng, 2002).

5.2.3 Carrier-Based PWM Techniques

Carrier-based PWM techniques are widely applied in multilevel inverter systems where multiple carrier signals are used to generate switching patterns for different voltage levels. In these techniques, several triangular carrier waveforms are compared with a single sinusoidal reference signal to produce the required switching pulses. Depending on the relative phase arrangement of the carriers, different strategies such as phase-disposition (PD), phase-opposition disposition (POD), and alternate phase-opposition disposition (APOD) can be implemented. These techniques are particularly suitable for multilevel inverter configurations because they enable efficient generation of multiple voltage levels while maintaining acceptable harmonic performance (Kouro et al., 2010).

5.3 Selective Harmonic Elimination (SHE)

Selective Harmonic Elimination (SHE) is a widely used harmonic mitigation technique in multilevel inverter systems. Unlike conventional PWM methods that rely on high switching frequencies, SHE focuses on eliminating specific harmonic components by carefully selecting switching angles within each voltage cycle. This approach allows significant reduction of low-order harmonics, which are typically the most harmful to power systems and motor drives. SHE is particularly effective in multilevel inverters where multiple switching angles are available for optimization (Patel and Hoft, 1973).

5.3.1 Principle of SHE

The fundamental principle of selective harmonic elimination is based on the mathematical representation of the inverter output voltage using Fourier series expansion. By selecting appropriate switching angles within a quarter cycle of the output waveform, certain harmonic components can be forced to zero while maintaining the desired fundamental voltage magnitude. The switching angles are determined by solving a set of nonlinear equations derived from the Fourier series coefficients of the inverter output voltage. This technique allows the elimination of specific lower-order harmonics such as the 5th and 7th harmonics, which significantly improves overall power quality.

5.3.2 Switching Angle Optimization

Determining the optimal switching angles for SHE requires solving nonlinear transcendental equations, which becomes increasingly complex as the number of voltage levels increases. Traditional numerical techniques such as Newton–Raphson methods have been used for solving these equations; however, they may suffer from convergence issues for higher-level inverters. Therefore, modern approaches often employ computational algorithms to determine optimal switching angles that minimize harmonic distortion while maintaining the required output voltage magnitude (Holmes and Lipo, 2003).

5.4 Optimization-Based Harmonic Reduction

In recent years, optimization-based techniques have gained significant attention for harmonic reduction in multilevel inverter systems. These techniques utilize computational algorithms to determine optimal switching parameters that minimize total harmonic distortion and improve inverter performance. Optimization-based methods are particularly useful for complex inverter topologies where analytical solutions for switching angles may be difficult to obtain. By applying intelligent search algorithms, researchers can identify optimal solutions for harmonic elimination in high-level multilevel inverter structures (Sivanagaraju and Srinivasa Rao, 2010).

5.4.1 Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is a population-based optimization algorithm inspired by the collective behavior of birds and fish. In the context of multilevel inverters, PSO can be used to determine optimal switching angles that minimize harmonic distortion while maintaining the desired fundamental voltage component. Each particle in the swarm represents a potential solution, and the algorithm iteratively updates particle positions based on individual and collective experiences. PSO is widely used because of its fast convergence and ability to handle nonlinear optimization problems effectively.

5.4.2 Genetic Algorithms (GA)

Genetic Algorithms (GA) are another popular optimization technique used for harmonic elimination in inverter systems. GA is based on principles of natural selection and genetic evolution, where candidate solutions evolve over successive generations to achieve optimal results. In harmonic mitigation applications, GA can optimize switching angles or modulation parameters to minimize THD in multilevel inverter output voltage. The algorithm employs processes such as selection, crossover, and mutation to generate improved solutions in each iteration (Goldberg, 1989).

5.4.3 Other Metaheuristic Methods

In addition to PSO and GA, several other metaheuristic optimization algorithms have been explored for harmonic mitigation in multilevel inverters. These include techniques such as ant colony optimization, differential evolution, simulated annealing, and firefly algorithms. Such methods are capable of solving complex nonlinear optimization problems and can effectively determine optimal switching parameters for high-level inverter topologies. The application of these advanced optimization techniques has significantly improved the harmonic performance of modern multilevel inverter systems used in industrial drive applications (Kouro et al., 2010).

6. LITERATURE REVIEW

The development of multilevel inverter technology has attracted significant attention from researchers due to its ability to improve power quality and efficiency in medium- and high-power applications. Over the past few decades, numerous studies have focused on inverter topologies, harmonic mitigation techniques, and advanced control strategies to enhance inverter performance in industrial drive systems. The literature reveals continuous progress in designing efficient multilevel inverter structures with improved harmonic performance, reduced hardware complexity, and optimized control methods. This section reviews major research contributions related to conventional multilevel inverter structures, harmonic mitigation techniques, modified cascaded multilevel inverter designs, optimization-based harmonic reduction approaches, and their applications in industrial motor drive systems.

6.1 Review of Conventional Multilevel Inverter Research

Early research on multilevel inverter technology primarily focused on the development of three fundamental inverter topologies: the Neutral Point Clamped (NPC), Flying Capacitor (FC), and Cascaded H-Bridge (CHB) inverters. One of the earliest contributions was the introduction of the diode-clamped multilevel inverter, which utilized clamping diodes to generate multiple voltage levels from a split DC bus. This topology enabled improved voltage handling capability and reduced harmonic distortion in high-power applications. Later studies explored the flying capacitor inverter, which uses floating capacitors to generate additional voltage levels and provide flexible voltage balancing capabilities. Although the FC topology offers redundant switching states and improved voltage control, its practical implementation requires a large number of capacitors, which increases system complexity (Nabae, Takahashi and Akagi, 1981).

Subsequent research emphasized the cascaded H-bridge multilevel inverter due to its modular structure and scalability. In this topology, multiple H-bridge cells are connected in series, each supplied by an independent DC source. The modular design allows easy expansion of voltage levels by adding additional cells, making the CHB inverter particularly suitable for medium-voltage motor drives and renewable energy systems. Because of its advantages such as reduced harmonic distortion, improved efficiency, and ease of control, the CHB topology has become one of the most widely studied multilevel inverter configurations in power electronics research (Rodriguez, Lai and Peng, 2002).

6.2 Review of Harmonic Mitigation Techniques

A significant portion of multilevel inverter research has focused on harmonic mitigation techniques to improve output waveform quality. Pulse Width Modulation (PWM) strategies have been widely investigated for controlling inverter switching operations and reducing harmonic distortion. Conventional modulation methods such as sinusoidal PWM and carrier-based PWM techniques have been extensively studied due to their simplicity and ease of implementation. These techniques generate switching signals by comparing reference signals with carrier waveforms, thereby producing voltage waveforms that approximate sinusoidal signals. Research has demonstrated that appropriate selection of modulation index and switching frequency can significantly reduce total harmonic distortion in inverter output voltage (Holmes and Lipo, 2003).

In addition to PWM methods, selective harmonic elimination (SHE) techniques have been widely explored for harmonic reduction in multilevel inverters. SHE focuses on eliminating specific lower-order harmonic components by carefully selecting switching angles within the inverter switching cycle. Researchers have developed various analytical and numerical methods to determine optimal switching angles that minimize harmonic distortion while maintaining the desired fundamental voltage magnitude. These methods have proven particularly effective for multilevel inverter systems where multiple switching angles are available for optimization (Patel and Hoft, 1973).

6.3 Review of Modified Cascaded Multilevel Inverter Topologies

With the increasing demand for efficient and cost-effective inverter systems, several researchers have proposed modified cascaded multilevel inverter topologies aimed at reducing component count and improving system performance. Conventional cascaded H-bridge inverters require multiple isolated DC sources and a large number of switching devices, which increases system complexity and cost. To address these limitations, researchers have developed modified structures that use fewer switches or shared DC sources while still generating multiple voltage levels. These reduced component designs help improve system efficiency and simplify inverter implementation in practical applications (Gupta and Jain, 2014).

Another important development in this area is the introduction of hybrid multilevel inverter configurations that combine features of different inverter topologies. Hybrid structures integrate characteristics of cascaded, diode-clamped, and flying capacitor inverters to achieve improved voltage level generation and harmonic performance. These configurations are particularly useful in medium-voltage industrial applications where both high efficiency and reliable operation are required. Studies have shown that hybrid inverter structures can significantly reduce switching losses and improve output waveform quality compared with conventional inverter designs (Kouro et al., 2010).

6.4 Review of Optimization-Based Harmonic Reduction Methods

Recent advancements in computational techniques have led to the development of optimization-based approaches for harmonic mitigation in multilevel inverter systems. Traditional analytical methods for determining switching angles become increasingly complex as the number of voltage levels increases. To overcome this limitation, researchers have applied artificial intelligence and metaheuristic optimization algorithms to determine optimal switching parameters. Techniques such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Differential Evolution have been widely used to minimize total harmonic distortion in inverter output waveforms.

These algorithms search for optimal switching angles by iteratively evaluating candidate solutions and improving them based on predefined objective functions. The application of such optimization techniques has significantly improved harmonic performance and control flexibility in multilevel inverter systems. Moreover, these methods are capable of solving complex nonlinear optimization problems that cannot be easily addressed using conventional numerical techniques (Sivanagaraju and Srinivasa Rao, 2010).

6.5 Research Trends in Industrial Drive Applications

Recent research trends indicate a growing interest in integrating multilevel inverter technology with industrial motor drive systems, particularly induction motor drives used in medium-power applications. Multilevel inverters provide improved voltage waveform quality and reduced harmonic distortion, which enhance motor efficiency and reduce thermal stress on machine components. As a result, these inverter systems are increasingly used in applications such as pumps, compressors, conveyors, and high-power industrial automation systems. The improved voltage control capability of multilevel inverters allows precise regulation of motor speed and torque, leading to higher operational efficiency and improved process control in industrial environments (Bose, 2002).

Furthermore, researchers are focusing on improving the performance of medium-power industrial drive systems by combining advanced inverter topologies with intelligent control strategies. The integration of optimized modulation techniques, reduced-switch inverter designs, and AI-based control algorithms is expected to enhance the efficiency, reliability, and power quality of industrial drive systems in the future. These advancements demonstrate the growing importance of multilevel inverter technology in modern industrial power conversion systems.

7. APPLICATIONS IN MEDIUM-POWER INDUSTRIAL DRIVE SYSTEMS

Multilevel inverter (MLI) technology has become increasingly important in medium-power industrial drive systems due to its ability to improve power quality, efficiency, and reliability. Industrial processes often require precise control of motor speed and torque while maintaining high energy efficiency and low harmonic distortion. Traditional two-level inverter drives can produce significant harmonic distortion and switching losses, which negatively affect motor performance and system reliability. In contrast, multilevel inverters generate stepped voltage waveforms that more closely approximate sinusoidal signals, resulting in lower harmonic distortion and improved power quality. Consequently, MLIs have been widely adopted in industrial applications such as induction motor drives, automated manufacturing systems, and energy-intensive industrial equipment (Bose, 2002).

7.1 Induction Motor Drives

Induction motors are the most widely used electrical machines in industrial environments because of their simple construction, robustness, and cost-effectiveness. These motors are commonly used in applications such as conveyors, pumps, compressors, and machine tools. The performance of induction motor drives strongly depends on the quality of the voltage supplied by the inverter. Multilevel inverter technology provides significant advantages in this context by delivering high-quality output voltage with reduced harmonic distortion. This improvement leads to smoother motor operation, reduced electromagnetic interference, and improved efficiency in industrial motor drive systems (Kouro et al., 2010).

7.1.1 Performance Improvement with MLIs

The integration of multilevel inverters with induction motor drives significantly enhances overall system performance. Because MLIs generate multiple voltage levels, the resulting output waveform closely resembles a sinusoidal waveform, which reduces voltage stress on motor windings and minimizes torque ripple. Reduced torque ripple improves mechanical stability and decreases vibration in industrial machines. Additionally, multilevel inverters allow better utilization of the DC bus voltage and provide improved control over motor speed and torque. These advantages make MLIs particularly suitable for medium-voltage and medium-power motor drive applications where high efficiency and precise control are required (Rodriguez et al., 2010).

7.1.2 Harmonic Impact on Motor Efficiency

Harmonics present in the inverter output voltage can significantly affect the efficiency and reliability of induction motors. Harmonic currents generated by distorted voltage waveforms produce additional copper losses and core losses in the motor, leading to increased heating and reduced efficiency. Furthermore, harmonic components may cause pulsating electromagnetic torque, resulting in vibration, acoustic noise, and mechanical stress on motor components. The use of multilevel inverters helps mitigate these effects by producing output voltage waveforms with lower total harmonic distortion (THD). As a result, motor efficiency improves, operating temperature decreases, and overall system reliability is enhanced (Akagi, 2017).

7.2 Industrial Automation Systems

Modern industrial automation systems rely heavily on variable speed motor drives for controlling production processes and improving operational efficiency. These systems include automated manufacturing lines, material handling equipment, and precision control mechanisms that require reliable and efficient motor drive technology. Multilevel inverter-based drive systems are increasingly used in such applications because they provide improved voltage waveform quality, lower switching losses, and enhanced power handling capability. These features make MLIs highly suitable for automated industrial environments where precise motion control and energy efficiency are critical (Kouro et al., 2010).

7.2.1 Conveyor Systems

Conveyor systems are widely used in industries such as mining, manufacturing, logistics, and food processing for material transportation and handling. These systems typically operate continuously and require reliable motor drive systems capable of handling varying load conditions. Multilevel inverter-based drives provide smooth voltage waveforms that reduce torque pulsations and mechanical stress on conveyor motors. This leads to smoother operation, reduced maintenance requirements, and longer equipment lifespan. Additionally, the improved efficiency of multilevel inverter drives helps reduce overall energy consumption in large-scale conveyor systems (Bose, 2002).

7.2.2 Pumps and Compressors

Pumps and compressors are essential components in many industrial processes, including water supply systems, chemical processing plants, and oil and gas industries. These applications often require variable speed operation to maintain precise control of flow rate and pressure. Multilevel inverter drives provide efficient and reliable speed control for pump and compressor motors by delivering high-quality voltage waveforms with minimal harmonic distortion. Reduced harmonic content improves motor efficiency and reduces thermal stress, which enhances the reliability and operational lifespan of these critical industrial machines (Rodriguez, Lai and Peng, 2002).

7.3 Renewable-Integrated Industrial Drives

With the increasing emphasis on sustainable energy systems, many industrial facilities are integrating renewable energy sources such as solar photovoltaic systems and wind energy into their power infrastructure. Multilevel inverters play a crucial role in enabling this integration because they can efficiently convert DC power generated by renewable sources into high-quality AC power suitable for industrial loads. In renewable-integrated industrial drive systems, multilevel inverters not only provide harmonic reduction but also facilitate efficient power conversion and grid synchronization. Their ability to operate at higher voltage levels with reduced switching losses makes them well suited for hybrid energy systems that combine renewable energy generation with industrial motor drive applications (Kouro et al., 2010).

Furthermore, the use of modified cascaded multilevel inverter topologies in renewable-integrated systems allows better utilization of multiple DC sources, such as photovoltaic panels or battery storage units. This capability improves energy utilization efficiency and reduces dependence on conventional power sources. As industries move toward more sustainable and energy-efficient operation, the role of multilevel inverter technology in renewable-integrated industrial drive systems is expected to become increasingly significant.

8. CONCLUSION

This review paper has presented a comprehensive overview of harmonic mitigation-oriented design approaches for modified cascaded multilevel inverters (CMLIs) used in medium-power industrial drive systems. The study first discussed the fundamentals of multilevel inverter technology and highlighted the major inverter topologies, including Neutral Point Clamped (NPC), Flying Capacitor (FC), and Cascaded H-Bridge (CHB) inverters. Among these, the CHB topology has received considerable attention due to its modular structure, scalability, and suitability for medium-voltage industrial drive applications. However, conventional CHB inverters suffer from several limitations, such as the requirement of multiple isolated DC sources, increased component count, and complex control strategies.

To address these challenges, various modified cascaded multilevel inverter topologies have been proposed in the literature. These modified designs focus on reducing the number of switches and DC sources while maintaining high-quality output voltage waveforms. In addition, the review discussed different harmonic mitigation techniques including pulse width modulation methods, selective harmonic elimination strategies, and optimization-based algorithms such as particle swarm optimization and genetic algorithms. These techniques play a crucial role in minimizing total harmonic distortion and improving the overall efficiency and reliability of inverter-based drive systems.

Furthermore, the review highlighted the application of multilevel inverter technology in medium-power industrial systems such as induction motor drives, conveyor systems, pumps, compressors, and renewable-integrated industrial drives. Overall, the findings indicate that modified cascaded multilevel inverter structures combined with advanced control and optimization techniques offer significant potential for improving power quality and operational efficiency in modern industrial drive systems.

8.1.Limitations of the Review

Although this review provides a broad overview of harmonic mitigation-oriented modified cascaded multilevel inverter designs, several limitations should be acknowledged. First, the review primarily focuses on widely studied inverter topologies and harmonic mitigation strategies reported in existing literature, and therefore may not include all recently proposed inverter configurations or emerging control techniques. Second, the discussion mainly emphasizes theoretical concepts and comparative analysis rather than detailed experimental validation or hardware implementation results. Additionally, variations in system parameters, switching strategies, and application-specific requirements across different studies make direct performance comparison challenging. Future reviews may incorporate a larger dataset of experimental studies and real-time industrial implementations to provide a more comprehensive evaluation of multilevel inverter performance in practical applications.

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