

HARMONIC PERFORMANCE COMPARISON OF MMC AND CHB MULTILEVEL CONVERTERS FOR HVDC SYSTEMS UNDER PSPWM CONTROL

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Abstract

High-voltage direct current (HVDC) transmission systems have become a key technology for efficient long-distance power transfer and integration of renewable energy resources. The performance of such systems is significantly influenced by the harmonic behavior of power electronic converters. This paper presents a comparative harmonic performance analysis of two widely used multilevel converter topologies, namely the Modular Multilevel Converter (MMC) and the Cascaded H-Bridge (CHB) converter, under Phase-Shifted Pulse Width Modulation (PSPWM) control.

Detailed simulation models of both converters are developed in MATLAB/Simulink using identical operating conditions and a 13-level configuration to ensure a fair comparison. The harmonic performance is evaluated using Fast Fourier Transform (FFT) analysis of the output voltage waveforms.

The results demonstrate that both converters are capable of generating high-quality multilevel output voltages; however, the MMC exhibits superior harmonic performance. The total harmonic distortion (THD) is reduced from 5.52% in the CHB converter to 3.38% in the MMC, corresponding to an improvement of approximately 38.7% under identical operating conditions.

The improved performance of the MMC is attributed to its modular structure, distributed energy storage, and enhanced voltage synthesis capability. The findings of this study provide a clear benchmark for selecting appropriate multilevel converter topologies for HVDC applications under PSPWM control, where stringent harmonic performance and high power quality are critical requirements.

1. INTRODUCTION

A. Background of HVDC Transmission

The rapid growth in electrical energy demand and the expansion of interconnected power networks have significantly increased the need for efficient long-distance power transmission technologies. Conventional high-voltage alternating current (HVAC) transmission systems face several

technical limitations over long distances, including reactive power losses and voltage stability issues [1].

High-voltage direct current (HVDC) transmission has emerged as an effective solution for bulk power transfer over long distances. HVDC systems offer several advantages, such as reduced transmission losses, improved controllability of

power flow, and the capability to interconnect asynchronous power systems [2]. These features make HVDC technology highly suitable for applications such as offshore wind integration and long-distance energy transmission corridors.

B. Role of Power Electronic Converters in HVDC Systems

Power electronic converters are fundamental components in HVDC transmission systems, as they enable efficient conversion between alternating current (AC) and direct current (DC). Advances in power semiconductor devices and converter topologies have significantly enhanced the efficiency, controllability, and reliability of HVDC systems [3].

Voltage source converters (VSCs) based on multilevel converter technology have become particularly attractive for modern HVDC applications due to their superior controllability and dynamic performance. Multilevel converters are capable of generating stepped voltage waveforms that closely approximate sinusoidal signals, thereby reducing harmonic distortion and minimizing the requirement for filtering components [4], [5].

C. Multilevel Converter Technology

Multilevel converters synthesize output voltages using multiple discrete voltage levels derived from several DC sources or capacitor modules. Compared with conventional two-level converters, multilevel converters offer several advantages, including reduced voltage stress on switching devices, improved harmonic performance, and higher power handling capability [6], [7].

Various multilevel converter topologies have been developed for high-power applications, including neutral-point-clamped (NPC), flying capacitor, cascaded H-bridge (CHB), and modular multilevel converter (MMC) structures [4], [8].

The cascaded H-bridge (CHB) converter has been widely adopted due to its modular configuration and its ability to generate multiple voltage levels using separate DC sources, making it suitable for medium- and high-power applications [5], [9].

The modular multilevel converter (MMC) has emerged as a key topology for high-voltage

applications due to its modular structure, scalability, and superior harmonic performance. Its operational characteristics and control flexibility make it highly suitable for modern HVDC transmission systems [3], [10], [11].

Recent advancements in multilevel converter technology have focused on improving efficiency, reducing switching losses, and enhancing waveform quality. These developments have significantly contributed to the widespread adoption of multilevel converters in HVDC and renewable energy applications [12], [13].

2. LITERATURE REVIEW

Numerous studies have investigated the performance of multilevel converters in high-power applications. A comprehensive review of multilevel converter topologies, control strategies, and applications has been presented in the literature, highlighting their effectiveness in improving power quality and reducing harmonic distortion [4], [8].

The cascaded H-bridge (CHB) converter has been extensively studied due to its modular configuration and its capability to generate multiple voltage levels using separate DC sources. Several studies have demonstrated that CHB converters can achieve low harmonic distortion when appropriate modulation techniques are employed [5], [9], [14].

In recent years, the modular multilevel converter (MMC) has gained significant attention in HVDC transmission systems due to its scalability, modular structure, and superior harmonic performance. Detailed investigations on MMC operation, control strategies, and performance optimization have been reported in the literature [3], [10], [11], [15].

Further research has focused on modulation techniques, loss analysis, and dynamic performance improvement of MMC systems. Advanced control approaches, such as model predictive control and optimized PWM techniques, have been proposed to enhance converter efficiency and reduce harmonic distortion [11], [15], [16].

In addition to converter design and control, harmonic analysis and power quality assessment

have become critical research areas in power electronic systems. Classical harmonic evaluation techniques, including fast Fourier transform (FFT), have been widely used to analyze converter performance [6], [17].

More recently, advanced signal processing techniques such as wavelet transform and artificial intelligence have been introduced for accurate detection and classification of power quality disturbances. These techniques provide improved time-frequency resolution and have been successfully applied in various electrical power system applications [18]–[27].

3. RESEARCH GAP AND PROBLEM STATEMENT

Despite the extensive research on multilevel converters, existing studies lack a direct comparative evaluation of modular multilevel converter (MMC) and cascaded H-bridge (CHB) converter topologies under identical operating conditions. In particular, comparisons under the same phase-shifted pulse width modulation (PSPWM) control strategy are limited, which is essential for a fair and consistent assessment of harmonic performance. As a result, it is difficult to directly compare the harmonic characteristics of different converter structures.

Moreover, harmonic distortion remains a critical issue in power electronic converters, as excessive harmonics can adversely affect power quality and system stability in HVDC transmission networks [6]. Therefore, a systematic and controlled comparison of the harmonic performance of widely used converter topologies under identical operating conditions is required.

This study addresses this gap by developing MATLAB/Simulink models of the modular multilevel converter and cascaded H-bridge converter under similar operating conditions and

evaluating their harmonic performance using FFT analysis under PSPWM control.

4. SYSTEM MODELING OF MODULAR MULTILEVEL CONVERTER (MMC)

4.1 Structure of the Modular Multilevel Converter

The modular multilevel converter (MMC) is considered one of the most advanced converter topologies employed in modern voltage source converter (VSC)-based HVDC transmission systems. The MMC topology consists of multiple identical submodules connected in series within each converter arm, enabling the generation of several discrete voltage levels at the output terminal [4].

Each phase of the MMC consists of two arms:

- (i) upper arm
- (ii) lower arm

Each arm is composed of a number of submodules along with an arm inductor. The submodules are typically half-bridge circuits consisting of two switching devices and a capacitor. By appropriately controlling the switching states of these submodules, different voltage levels can be synthesized, resulting in an output waveform that closely approximates a sinusoidal signal.

The modular structure of the MMC offers several advantages, including improved scalability, reduced harmonic distortion, and lower switching losses. Owing to these characteristics, MMC technology has become a preferred choice for modern HVDC transmission applications [4], [9]. The diagram includes the following components:

- (i) DC link
- (ii) upper arm submodules
- (iii) lower arm submodules
- (iv) arm inductors
- (v) three-phase AC output

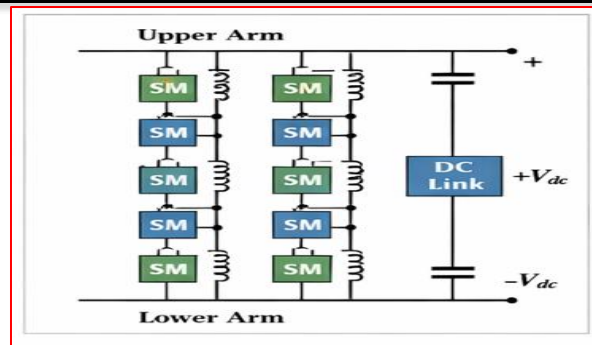


Fig. 1. Simplified configuration of a modular multilevel converter (MMC)

4.2 Operating Principle of MMC

The fundamental operating principle of the MMC is based on the insertion or bypassing of submodules within each arm of the converter. When a submodule capacitor is inserted into the circuit, it contributes its voltage to the arm voltage. Conversely, when the submodule is bypassed, it does not contribute to the output voltage.

By appropriately controlling the number of inserted submodules in each arm, the converter is able to generate a stepped output voltage waveform with multiple voltage levels. As the number of submodules increases, the output waveform becomes smoother, resulting in reduced harmonic distortion.

This voltage synthesis mechanism enables the MMC to generate high-quality AC output waveforms, making it highly suitable for HVDC transmission applications.

4.3 Advantages of MMC in HVDC Systems

The MMC topology offers several advantages compared with conventional two-level converters and other multilevel converter structures, including:

- (i) improved harmonic performance
- (ii) reduced switching losses
- (iii) modular and scalable structure
- (iv) lower filtering requirements
- (v) high efficiency in high-voltage applications

Due to these features, MMC technology has become widely adopted in modern HVDC systems and large-scale renewable energy integration projects [3], [4].

5. MODELING OF CASCADED H-BRIDGE CONVERTER (CHB)

5.1 Structure of Cascaded H-Bridge Converter

The cascaded H-bridge (CHB) converter is another important multilevel converter topology used in medium- and high-power applications. In this topology, multiple H-bridge cells are connected in series to generate several voltage levels at the output terminal [5].

Each H-bridge cell consists of four power electronic switches arranged in a bridge configuration. The switches are controlled such that each cell can produce three possible output voltage levels:

- (i) positive voltage
- (ii) zero voltage
- (iii) negative voltage

By connecting multiple H-bridge cells in series, the converter is capable of synthesizing a stepped voltage waveform that closely resembles a sinusoidal waveform.

For example, a converter with six cascaded cells can produce 13 voltage levels.

5.2 Operating Principle of CHB Converter

The CHB converter operates by controlling the switching states of individual H-bridge cells, where each cell contributes a discrete voltage level to the overall output waveform.

By combining the voltages of multiple H-bridge cells, the converter produces a stepped voltage waveform with improved harmonic characteristics. The modular nature of the CHB converter allows the number of voltage levels to be increased by adding additional H-bridge cells.

However, one of the limitations of the CHB converter is the requirement for multiple isolated DC sources, which can increase system complexity in certain applications [5], [8].

5.3 Applications of CHB Converter

The cascaded H-bridge converter has been widely used in several power electronic applications, including:

- (i) renewable energy systems
- (ii) electric motor drives
- (iii) flexible AC transmission systems (FACTS)
- (iv) high-voltage power conversion systems

Several studies have demonstrated that CHB converters can achieve acceptable harmonic performance when appropriate modulation strategies are applied [8], [13].

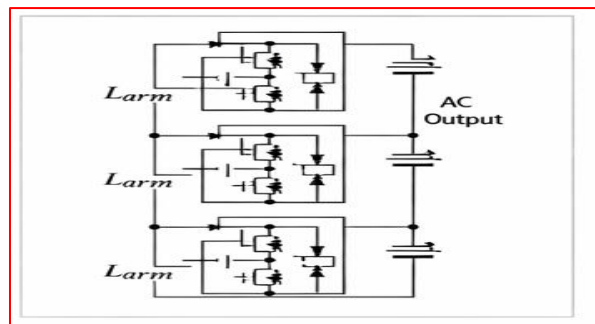


Fig. 2. Configuration of a cascaded H-bridge (CHB) multilevel converter illustrating multiple series-connected H-bridge cells for generating stepped output voltage.

6. MODULATION STRATEGY: PHASE-SHIFTED PULSE WIDTH MODULATION (PSPWM)

6.1 Principle of PSPWM

Pulse width modulation (PWM) techniques are widely used for controlling switching devices in multilevel converters. Among these techniques, phase-shifted pulse width modulation (PSPWM) is commonly adopted due to its simplicity and its ability to achieve low harmonic distortion.

In PSPWM, multiple carrier signals with identical frequency and amplitude are utilized, while each carrier signal is phase shifted relative to the others. These carrier signals are compared with a sinusoidal reference waveform to generate switching signals for the power electronic devices. The phase-shifting mechanism ensures that switching events are uniformly distributed across the converter modules, thereby reducing harmonic distortion and improving the overall waveform quality [1].

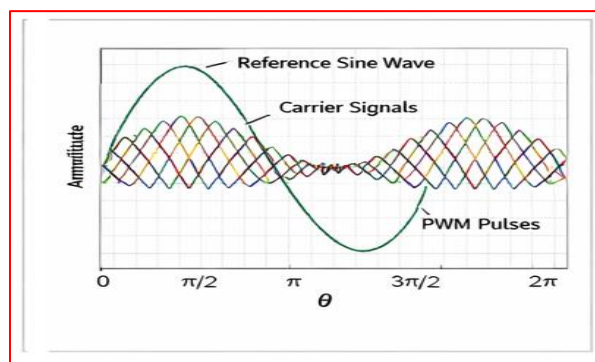


Fig. 3. Phase-shifted pulse width modulation (PSPWM) showing sinusoidal reference signal, compared with multiple phase-shifted triangular carrier signals, and resulting PWM switching pulses.

6.2 Implementation in Multilevel Converters

In multilevel converters such as MMC and CHB, PSPWM enables each module to operate with balanced switching patterns. As a result, the output voltage waveform consists of multiple

discrete levels that closely approximate a sinusoidal waveform.

This modulation technique is particularly suitable for high-power converters, as it effectively reduces harmonic distortion without significantly increasing switching losses.

TABLE I

Simulation Parameters Used for MATLAB/Simulink Modeling of MMC and CHB Converters

Parameter	Value
DC link voltage	2 kV
Switching frequency	2 kHz
Number of voltage levels	13
Modulation technique	PSPWM
Load type	RL load

7. MATLAB/Simulink Simulation Model

7.1 Simulation Environment

To evaluate the harmonic performance of the converter topologies, detailed simulation models of the Modular Multilevel Converter (MMC) and Cascaded H-Bridge (CHB) converter were developed using the MATLAB/Simulink environment.

Both converters were designed under identical operating conditions to ensure a fair, accurate, and consistent comparison of their harmonic characteristics. A 13-level configuration was implemented for both topologies, and control was achieved using the Phase-Shifted Pulse Width

Modulation (PSPWM) technique described in the previous section [1].

The developed simulation model consists of a DC voltage source, converter subsystems (MMC and CHB), a PWM generation unit, a load model, and measurement blocks.

To assess the harmonic performance, the output voltage waveform was analyzed using the Fast Fourier Transform (FFT) tool available within MATLAB. This analysis enabled the extraction of the harmonic spectrum and the calculation of Total Harmonic Distortion (THD), providing a quantitative basis for performance comparison between the two converter topologies.

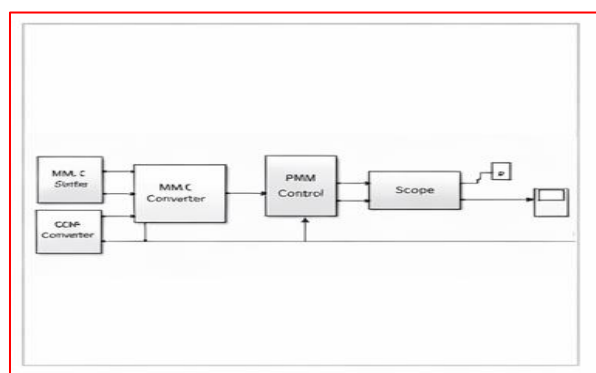


Fig. 4. MATLAB/Simulink implementation of the multilevel converter system for harmonic performance evaluation of MMC and CHB converters under PSPWM control.

7.2 Simulation Parameters

To maintain consistency between both converter models, identical simulation parameters were used during the analysis.

TABLE II
Simulation Parameters Used in MATLAB/Simulink

Parameter	Value
DC link voltage	2 kV
Number of voltage levels	13
Switching frequency	2 kHz
Load resistance	20 Ω
Load inductance	30 mH
Modulation technique	PSPWM
Simulation time	0.5 s

8. OUTPUT VOLTAGE WAVEFORM ANALYSIS

8.1 Output Voltage of Modular Multilevel Converter

The output voltage waveform generated by the modular multilevel converter exhibits a stepped profile due to the combination of multiple submodule voltages. As the number of voltage

levels increases, the output waveform more closely approximates a sinusoidal waveform.

The simulation results show that the MMC topology produces smoother voltage transitions and improved waveform quality. The modular structure of the converter distributes switching operations among several submodules, which contributes to improved harmonic performance [4].

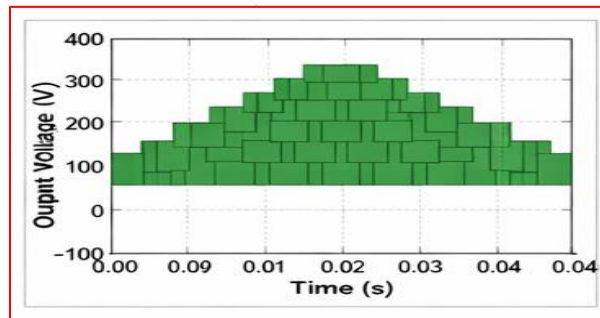


Fig. 5. Simulated 13-level output voltage waveform of the MMC obtained from MATLAB/Simulink showing a multi-level stepped voltage profile approximating a sinusoidal waveform with smooth transitions and reduced harmonic distortion.

8.2 Output Voltage of Cascaded H-Bridge Converter

The cascaded H-bridge converter also generates a stepped voltage waveform by combining the outputs of several H-bridge cells connected in series. Each H-bridge cell contributes a discrete voltage level to the overall output waveform.

The simulation results indicate that the CHB converter can generate multiple voltage levels with relatively simple control implementation. However, the harmonic performance depends on the modulation strategy and the number of cascaded cells [5], [8].

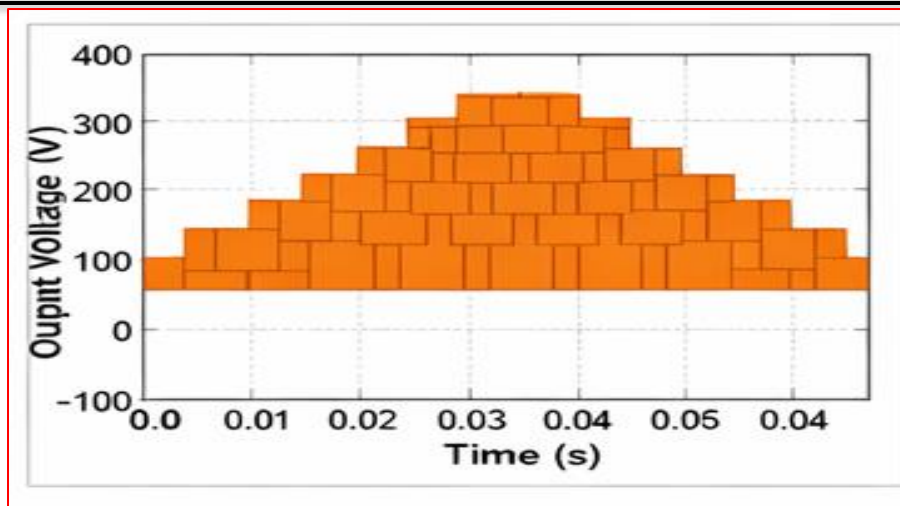


Fig. 6. Output voltage waveform of the CHB converter obtained from MATLAB/Simulink simulation showing stepped voltage levels with comparatively higher harmonic content.

9. HARMONIC ANALYSIS USING FFT

Harmonic distortion is one of the most important performance indicators for power electronic converters used in HVDC systems. Excessive harmonic components can negatively affect power quality and system stability.

To evaluate harmonic performance, the output voltage waveforms of both converters were analyzed using the fast Fourier transform (FFT) tool in MATLAB. FFT analysis provides the

harmonic spectrum and allows the calculation of total harmonic distortion (THD) [6].

$$THD = \sqrt{(V_2^2 + V_3^2 + \dots + V_n^2)} / V_1$$

Recent research has shown that advanced signal processing techniques such as wavelet transform can provide more detailed time-frequency analysis of power quality disturbances [10], [11]. These techniques have been widely used for harmonic detection and classification in electrical power systems.

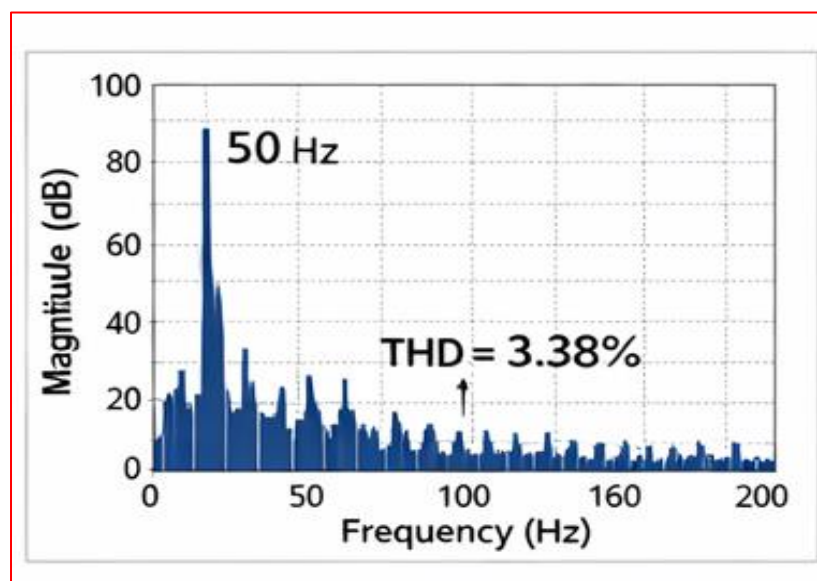


Fig. 7. Harmonic spectrum obtained from FFT based analysis of the MMC output voltage, showing reduced harmonic components.

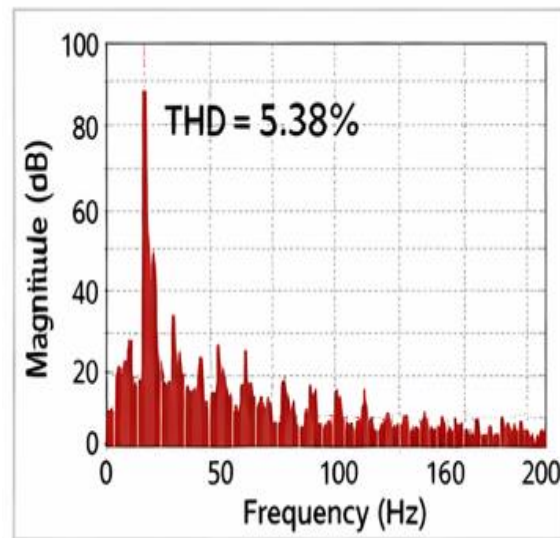


Fig. 8. FFT analysis of cascaded H-bridge converter output voltage waveform with THD = 5.52%.

10. COMPARATIVE HARMONIC PERFORMANCE

The harmonic performance of both converters was evaluated by comparing the total harmonic distortion values obtained from FFT analysis.

TABLE III

Comparison of Total Harmonic Distortion (THD) Obtained from FFT Analysis of MMC and CHB Converters

Converter Type	Total Harmonic Distortion
Modular Multilevel Converter	3.38 %
Cascaded H-Bridge Converter	5.52 %

It is observed that the output voltage waveform of the Modular Multilevel Converter (MMC) is significantly smoother, exhibiting lower harmonic content compared to the Cascaded H-Bridge (CHB) converter. This behavior confirms the effectiveness of the MMC topology for high-voltage applications.

Quantitative analysis shows that the MMC reduces total harmonic distortion (THD) by approximately 38.7% compared to the CHB converter under identical operating conditions. This significant reduction quantitatively confirms the superior harmonic performance and improved waveform quality of the MMC topology.

11. DISCUSSION OF RESULTS

The comparative analysis demonstrates that both converter topologies are capable of generating

multilevel voltage waveforms suitable for HVDC transmission systems. However, the MMC exhibits superior harmonic performance due to its modular architecture, distributed capacitor energy storage, and continuous voltage synthesis capability, which collectively enable smoother voltage transitions and reduced harmonic distortion.

In contrast, the CHB converter, although effective, exhibits relatively higher harmonic components due to its discrete voltage level generation mechanism.

Furthermore, recent advancements in signal processing—such as wavelet transform and artificial intelligence techniques—have been widely applied for power quality disturbance detection and harmonic analysis in electrical systems [10]–[17]. The integration of these techniques with

multilevel converter systems presents a promising direction for enhancing harmonic monitoring, fault detection, and adaptive control strategies in future HVDC networks.

12. CONCLUSION

This study presented a comparative harmonic performance analysis of two prominent multilevel converter topologies: the Modular Multilevel Converter (MMC) and the Cascaded H-Bridge (CHB) converter for HVDC transmission applications. Detailed simulation models were developed in the MATLAB/Simulink environment under identical operating conditions using a 13-level configuration. The converters were controlled using the Phase-Shifted Pulse Width Modulation (PSPWM) technique.

The harmonic performance of both converters was evaluated using Fast Fourier Transform (FFT) analysis to determine the harmonic spectrum and Total Harmonic Distortion (THD). The results confirm that both topologies are capable of producing high-quality multilevel voltage waveforms. However, the MMC demonstrates significantly improved performance in terms of reduced THD and enhanced waveform smoothness.

The superior performance of the MMC is attributed to its inherent structural advantages, including modular design, distributed energy storage, and flexible voltage synthesis. These features enable better harmonic suppression and improved output voltage quality.

Therefore, the Modular Multilevel Converter can be considered a technically superior and practically preferred topology for modern VSC-based HVDC transmission systems, particularly in applications requiring stringent harmonic performance and high-power quality.

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