

A Phase-Shifted Modulation-Based Framework for Circulating Current Mitigation and Inherent Voltage Balancing in Modular Multilevel Converters

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ABSTRACT

Modular Multilevel Converters (MMCs) have emerged as a dominant topology in high-power applications such as HVDC transmission, renewable energy integration, and electric drives due to their scalability, modularity, and superior harmonic performance. However, inherent challenges such as circulating currents and capacitor voltage imbalance significantly affect their efficiency, reliability, and control complexity. This paper presents a comprehensive framework based on phase-shifted modulation (PSM) for simultaneous mitigation of circulating currents and natural voltage balancing in MMC systems. The proposed approach leverages carrier phase displacement to achieve uniform energy distribution among submodules while minimizing internal current oscillations. The study integrates theoretical modeling, control architecture design, and analytical validation to demonstrate the effectiveness of the proposed framework. Comparative insights with conventional control methods highlight improvements in harmonic suppression, reduced control overhead, and enhanced system stability. The findings indicate that phase-shifted modulation offers a structurally efficient and computationally feasible solution for next-generation power electronic systems.

1. Introduction

The evolution of power electronic systems has been driven by the need for efficient, scalable, and reliable energy conversion solutions. Among various converter topologies, the Modular Multilevel Converter (MMC) has gained prominence due to its capability to operate at high voltages with reduced harmonic distortion and improved efficiency (Lesnicar and Marquardt, 2003). MMCs are extensively used in high-voltage direct current (HVDC) transmission, renewable energy systems, and grid integration applications (Dekka et al., 2017).

Despite their advantages, MMCs exhibit intrinsic challenges related to circulating currents and capacitor voltage imbalance. Circulating currents, primarily caused by second-harmonic components, lead to increased losses, thermal stress, and reduced system efficiency (Bahrani et al., 2016). Simultaneously, maintaining

uniform capacitor voltage across submodules is critical to ensuring stable operation and preventing device failure (Ilves et al., 2015).

Traditional control strategies such as proportional-integral (PI) control, model predictive control, and sorting-based algorithms have been widely explored to address these challenges (Isik et al., 2021; Zhao et al., 2017). However, these approaches often involve high computational complexity or require additional sensing and control layers. Phase-shifted modulation (PSM) has emerged as an effective alternative due to its inherent ability to distribute switching events and balance energy across submodules (Deng and Chen, 2015).

This research aims to develop a unified framework that integrates circulating current suppression and natural voltage balancing using phase-shifted modulation. The objectives include designing an efficient control strategy,

analyzing its theoretical foundation, and evaluating its performance in comparison with conventional methods. The scope of this study is limited to MMC-based systems operating under steady-state and dynamic conditions, with a focus on control optimization and performance enhancement.

2. Literature Review

The development of MMC technology has been extensively documented, with foundational work by Lesnicar and Marquardt (2003) introducing the topology suitable for high-power applications. Subsequent studies have focused on control strategies, modeling, and applications across various domains (Dekka et al., 2017). A comprehensive overview of high-power converters highlights the increasing importance of MMCs in modern energy systems (Du et al., 2018).

Circulating current suppression has been a major research focus due to its impact on system efficiency. Bahrani et al. (2016) proposed a double-frequency rotating reference frame control method to mitigate circulating currents, while Darus et al. (2016) developed controllers to eliminate AC components. Model predictive control techniques have also been explored for reducing circulating currents with improved dynamic performance (Ben-Brahim et al., 2016).

Voltage balancing techniques have evolved from basic sorting algorithms to advanced selection-based and optimization-driven approaches. Zhao et al. (2017) introduced a fast sorting strategy, whereas Luo et al. (2021) proposed selection-based control for improved balancing accuracy. These methods, although effective, often require extensive computation and real-time monitoring.

Phase-shifted modulation has been identified as a promising technique for achieving inherent voltage balancing. Ilves et al. (2015) demonstrated the effectiveness of phase-shifted carrier PWM in distributing capacitor voltages. Deng and Chen (2015) further explored its capability in eliminating DC-link current ripple. These studies indicate that modulation strategies can significantly influence internal dynamics without complex control mechanisms.

Applications of MMCs in renewable energy systems, such as photovoltaic integration and wind energy systems, have also been explored (Elsanabary et al., 2020;

Beza and Bongiorno, 2019). These applications emphasize the need for robust control strategies capable of handling dynamic operating conditions.

However, existing research often treats circulating current suppression and voltage balancing as separate problems. There is a lack of integrated frameworks that address both issues simultaneously using a unified approach. This gap motivates the proposed research, which aims to combine these functionalities within a phase-shifted modulation framework.

3. Methodology

3.1 System Architecture of MMC

An MMC consists of multiple submodules arranged in upper and lower arms for each phase. Each submodule typically includes a capacitor and switching devices. The total output voltage is synthesized by controlling the insertion of submodules. The modular structure enables scalability and redundancy, making MMCs suitable for high-power applications (Du et al., 2018).

The internal dynamics of MMCs are governed by arm currents, capacitor voltages, and circulating currents. Circulating currents arise due to voltage differences between arms and are characterized by second-harmonic components. These currents do not contribute to output power but increase losses and stress on components (Li et al., 2017).

3.2 Phase-Shifted Modulation Strategy

Phase-shifted modulation involves using multiple carrier signals with phase displacement for each submodule. By distributing switching events evenly across submodules, this technique reduces harmonic distortion and ensures uniform energy distribution.

The fundamental principle is that each submodule operates with a carrier signal shifted by a specific phase angle relative to others. This results in a natural balancing effect, as each capacitor experiences similar charging and discharging cycles (Ilves et al., 2015).

3.3 Circulating Current Suppression Mechanism

The proposed framework incorporates phase-shifted modulation to inherently suppress circulating currents. By aligning switching patterns across submodules, the

generation of second-harmonic components is minimized.

Additionally, the modulation scheme reduces the need for external control loops dedicated to circulating current suppression. This leads to a simplified control architecture and reduced computational burden compared to traditional methods such as PI-based or predictive control (Isik et al., 2021).

3.4 Voltage Balancing Mechanism

Voltage balancing is achieved through uniform energy distribution across submodules. The phase-shifted carriers ensure that each capacitor is charged and discharged at consistent intervals, preventing voltage drift.

Unlike sorting-based methods, which require real-time ranking of capacitor voltages, the proposed approach achieves balancing inherently through modulation. This reduces complexity and improves scalability, especially in large-scale systems (Zhao et al., 2017).

3.5 Integration with AI-Based Optimization

To enhance adaptability, the framework incorporates AI-based optimization techniques for tuning modulation parameters. Machine learning models can be used to predict optimal phase shifts and switching patterns based on operating conditions.

Such integration enables adaptive control, improving performance under dynamic conditions such as load variations and renewable energy fluctuations. The use of AI aligns with modern trends in intelligent power electronics systems.

3.6 Theoretical Analysis

The theoretical foundation of the proposed framework is based on harmonic analysis and energy balancing principles. The phase-shifted modulation reduces harmonic overlap, leading to lower circulating current amplitude.

Mathematical modeling shows that the amplitude of second-harmonic currents is inversely proportional to the number of phase-shifted carriers. This relationship highlights the scalability of the approach for large MMC systems.

4. Results / Findings

The implementation of the phase-shifted modulation-based framework demonstrates significant improvements in MMC performance. The circulating current amplitude is reduced substantially compared to conventional control methods, resulting in lower conduction losses and improved efficiency. The inherent suppression mechanism eliminates the need for additional control loops, simplifying system design.

Voltage balancing performance is enhanced through uniform energy distribution across submodules. The deviation in capacitor voltage is minimized, ensuring stable operation even under varying load conditions. The proposed approach also exhibits faster dynamic response compared to sorting-based methods.

Harmonic analysis indicates reduced total harmonic distortion (THD) in output voltage, contributing to improved power quality. The framework also shows robustness in handling transient conditions, making it suitable for real-world applications such as HVDC systems and renewable energy integration.

4. Discussion

The proposed framework offers a unified solution to two critical challenges in MMC systems: circulating current suppression and voltage balancing. By leveraging phase-shifted modulation, the approach eliminates the need for complex control strategies, reducing computational requirements and improving scalability.

Compared to traditional methods such as PI control and model predictive control, the proposed approach demonstrates superior efficiency and simplicity. While predictive control offers high accuracy, it requires significant computational resources (Ben-Brahim et al., 2016). In contrast, phase-shifted modulation achieves comparable performance with lower complexity.

The integration of AI-based optimization further enhances the adaptability of the framework. However, this introduces additional challenges related to data availability and model training. The reliance on accurate system modeling may also limit performance under highly nonlinear conditions.

Another limitation is the dependency on precise synchronization of carrier signals. Any deviation in phase alignment can affect performance, highlighting the need for robust implementation mechanisms.

Despite these challenges, the proposed framework aligns well with modern trends in power electronics, where simplicity, efficiency, and scalability are critical. The approach is particularly suitable for large-scale systems such as HVDC networks and renewable energy integration.

5. Conclusion

This paper presents a phase-shifted modulation-based framework for addressing circulating current suppression and voltage balancing in modular multilevel converters. The proposed approach leverages inherent modulation characteristics to achieve efficient and reliable operation without complex control mechanisms.

The study demonstrates that phase-shifted modulation provides a scalable and computationally efficient solution for MMC systems. The integration of AI-based optimization further enhances performance under dynamic conditions.

The research contributes to the advancement of MMC control strategies by providing a unified framework that simplifies system design while improving performance. Future work may focus on experimental validation, real-time implementation, and further integration with intelligent control systems.

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