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Control Strategies for Modular Multilevel Converters (MMC)

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Abstract

Modular Multilevel Converters (MMC) have emerged as a key technology for medium- to high-voltage power conversion applications such as HVDC transmission, large-scale renewable integration, and flexible AC transmission systems. Despite their superior performance and modularity, MMCs present complex control challenges due to their multi-level structure, numerous submodules, and circulating currents. This paper comprehensively reviews advanced control strategies developed for MMCs, including fundamental current and voltage balancing controls, sophisticated switching algorithms, and multifunctional approaches addressing harmonic suppression, power factor correction, and fault tolerance. Emphasis is placed on modern methods such as model predictive control, adaptive and robust controls that accommodate system nonlinearities and parameter uncertainties. Implementation aspects, including digital control hardware and the impact of control delays, are also discussed. The paper highlights recent advancements that improve system stability, efficiency, and reliability, thus facilitating MMC deployment in evolving power grids with high renewable penetration and stringent grid code requirements.

Keywords: Modular Multilevel Converter; Control Strategies; Voltage Balancing; Circulating Current; Model Predictive Control; Harmonic Suppression; Fault-Tolerant Control

1 INTRODUCTION

The rapid evolution of power electronics and the increasing demand for high-voltage, high-power applications have driven significant advancements in converter technologies. Among various converter topologies, the Modular Multilevel Converter (MMC) has emerged as a revolutionary solution, particularly suited for medium- to high-voltage direct current (MVDC and HVDC) transmission systems, large-scale renewable energy integration, and flexible AC transmission systems (FACTS). Despite its promising features, the inherent complexity of MMC architecture poses significant challenges in its control and operation. The converter consists of numerous submodules, each containing capacitive energy storage elements and semiconductor switches, which require precise coordination to achieve desired voltage waveforms and power flow. Control strategies must address multiple objectives simultaneously, including balancing the capacitor voltages across all submodules, regulating output current and voltage, minimizing switching losses, and enhancing system stability under dynamic load and grid conditions.

Furthermore, the growing penetration of renewable energy sources and the push towards smart grids have introduced stringent requirements on power quality, fault tolerance, and dynamic response capabilities. Effective control of MMCs is critical to ensure the seamless integration of these technologies into the power grid, enabling enhanced grid flexibility and reliability. Consequently, the development of advanced control methodologies that can accommodate the nonlinearities and multi-variable nature of MMCs has become a focal point in both academic research and industrial applications.

2 OVERVIEW OF MODULAR MULTILEVEL CONVERTERS

2.1 MMC Structure and Operating Principles

The Modular Multilevel Converter is composed of multiple identical submodules (SMs) connected in series within

each converter arm. Each submodule typically consists of a half-bridge or full-bridge topology equipped with semiconductor switches and energy storage capacitors. By controlling the switching states of these submodules, the MMC synthesizes a stepped output voltage waveform that closely approximates a sinusoidal signal with significantly reduced harmonic distortion. The converter's modular architecture allows for scalable voltage levels, as the total output voltage is the sum of the voltages across all inserted submodules. Operating under a half-bridge configuration, the MMC controls the insertion or bypass of each submodule capacitor voltage, effectively shaping the output waveform. The balancing of capacitor voltages and the management of circulating currents within the converter arms are critical to stable operation. The arm currents consist of the load current superimposed with a circulating current component, which must be carefully regulated to prevent overvoltage or undervoltage conditions on the submodule capacitors and to minimize power losses.

2.2 Electrical Characteristics and Advantages

The MMC exhibits several unique electrical characteristics that distinguish it from conventional multilevel converters. Its modular design inherently reduces voltage stress on semiconductor devices, allowing the use of lower-rated components which enhances reliability and reduces cost. The stepped waveform generation results in low total harmonic distortion (THD), thereby minimizing the need for extensive filtering and improving power quality. Additionally, MMCs offer remarkable scalability, making them suitable for a wide range of voltage and power levels, from medium voltage industrial drives to ultra-high voltage DC transmission. The converter's topology naturally facilitates fault tolerance by isolating faulty submodules and reconfiguring operation with minimal interruption[1]. Its ability to control circulating currents and capacitor voltage levels enables improved dynamic performance and energy efficiency. Moreover, the distributed energy storage across numerous capacitors provides inherent energy buffering, which enhances transient response and stability under fluctuating load or grid conditions.

2.3 Main Challenges and Control Requirements

Despite its advantages, MMC technology faces several control challenges due to its complex multi-level structure and dynamic operating environment. One primary challenge lies in maintaining voltage balance across hundreds or even thousands of submodule capacitors, which is essential for ensuring uniform stress distribution and preventing premature component failure. The management of circulating currents is another critical issue, requiring precise control to avoid excessive losses and potential instability. Furthermore, the switching pattern must be optimized to minimize switching losses and electromagnetic interference while achieving high-quality output waveforms. Control systems must also ensure robust performance under transient conditions such as sudden load changes, grid disturbances, or faults. The multi-variable and nonlinear nature of the MMC requires advanced control algorithms capable of real-time optimization and adaptive compensation. Additional requirements include rapid and accurate maximum power point tracking when MMCs interface with renewable energy sources, fault detection and mitigation capabilities, and the integration of modular control schemes that scale with converter size. Successfully addressing these challenges is vital for maximizing the efficiency, reliability, and longevity of MMC-based power conversion systems[2].

3 FUNDAMENTAL CONTROL STRATEGIES FOR MMC

3.1 Current Control Methods

Effective current control is paramount in ensuring the reliable operation and performance of Modular Multilevel Converters. The MMC's arm currents consist of the load current component and circulating currents that do not contribute to power transfer but affect converter losses and capacitor voltage stability. Traditional current control schemes often employ Proportional-Integral (PI) regulators within synchronous reference frames to regulate the output current, ensuring accurate tracking of reference waveforms and minimizing harmonic distortion. Advanced methods extend this approach by decoupling the load current from circulating current components, allowing independent regulation. Circulating current control is crucial to suppress unwanted oscillations and mitigate power losses within the converter arms. Strategies such as repetitive control, model predictive control, and sliding mode control have been proposed to enhance robustness and dynamic response under varying load and grid conditions.

Model predictive control, in particular, provides an optimal switching sequence by forecasting future system states, enabling superior disturbance rejection and fast transient response. Furthermore, current control schemes must be designed to accommodate the nonlinearities and multi-variable nature of MMCs, requiring adaptive or robust controllers to maintain stability and performance in the face of parameter variations and external perturbations.

3.2 Voltage Balancing Control

Voltage balancing across submodule capacitors represents one of the most critical challenges in MMC operation, directly impacting converter reliability and lifespan. Imbalances arise due to non-uniform switching states, differences in capacitor aging, and fluctuating load or grid conditions, which can cause overvoltage or undervoltage stresses on individual submodules. Effective voltage balancing strategies ensure that all capacitor voltages remain within safe operating limits by dynamically adjusting the switching patterns to insert or bypass specific submodules as required. Various approaches have been developed, including decentralized and centralized control architectures. Decentralized methods allow individual submodules to regulate their capacitor voltages locally, promoting scalability and fault tolerance but sometimes at the cost of slower overall system response. Centralized voltage balancing leverages global system information to coordinate submodule switching more precisely, improving voltage uniformity and reducing stress. Additionally, voltage balancing algorithms often incorporate predictive models and optimization techniques to anticipate voltage deviations and proactively adjust control actions. Pulse Width Modulation (PWM)-based methods combined with real-time monitoring of capacitor voltages have become standard practice to achieve effective balancing without compromising the converter's output quality or efficiency[3].

3.3 Submodule Switching State Control

The control of switching states in each submodule is fundamental to the MMC's ability to synthesize high-quality voltage waveforms and ensure efficient power conversion. Switching state control determines which submodules are inserted into the circuit at any instant, directly influencing output voltage levels, harmonic content, and converter losses. Sophisticated switching algorithms seek to minimize switching transitions to reduce losses and electromagnetic interference while maintaining the desired output voltage profile. Techniques such as nearest level modulation, selective harmonic elimination, and optimized pulse patterns are widely employed to achieve these goals. The large number of submodules in MMCs introduces complexity in determining optimal switching combinations, often requiring heuristic or optimization-based approaches to balance performance and computational feasibility. Real-time implementation of switching control must consider device limitations, switching frequency constraints, and thermal management to prevent premature component degradation. Furthermore, the integration of switching control with current and voltage balancing loops is essential to ensure coherent operation and system stability. Advances in digital control platforms have enabled the deployment of sophisticated algorithms capable of handling the intricate coordination required, ultimately enhancing the MMC's dynamic response, efficiency, and operational reliability.

4 ADVANCED CONTROL ALGORITHMS

4.1 Vector Control Techniques

Vector control techniques have become fundamental in the precise regulation of Modular Multilevel Converters due to their ability to decouple the control of active and reactive power components. By transforming three-phase currents and voltages into a rotating reference frame, vector control simplifies the complex multivariable control problem into independently manageable components. This transformation facilitates the application of classical control strategies, such as PI controllers, to regulate the direct and quadrature current components with high accuracy and fast dynamic response. The decoupled control approach enhances the converter's performance under steady-state and transient conditions, enabling rapid adjustment to grid disturbances and load changes. Moreover, vector control frameworks often incorporate feedforward compensation and disturbance observers to improve robustness and reduce steady-state errors[4]. The flexibility of vector control also supports the implementation of advanced modulation schemes, such as space vector pulse width modulation (SVPWM), which further improves output waveform quality and reduces switching losses. However, precise parameter identification and synchronization with

the grid are prerequisites for effective vector control, making it essential to integrate robust phase-locked loops and adaptive mechanisms within the control architecture.

4.2 Model Predictive Control (MPC)

Model Predictive Control represents a paradigm shift in MMC control strategies by leveraging a predictive model of the converter's behavior to optimize control actions over a finite horizon. Unlike conventional feedback controllers that react to errors, MPC anticipates future system dynamics by solving an optimization problem at each sampling instant. This forward-looking approach enables the direct incorporation of system constraints, such as voltage and current limits, switching frequency bounds, and thermal restrictions, into the control decision process. MPC's capability to handle multivariable interactions and nonlinearities inherent in MMCs makes it particularly suited for managing circulating currents and capacitor voltage balancing simultaneously. The predictive framework inherently provides fast transient response and improved disturbance rejection, essential for maintaining system stability under rapid load or grid fluctuations. Moreover, MPC can seamlessly integrate multiple control objectives, such as minimizing switching losses while ensuring high-quality output waveforms. Despite its advantages, the implementation of MPC requires significant computational resources and accurate system models. Advances in real-time digital signal processing and optimization algorithms have progressively mitigated these challenges, enabling practical deployment of MPC in high-performance MMC applications.

4.3 Adaptive and Robust Control Methods

Adaptive and robust control methods address the challenges posed by parameter uncertainties, nonlinearities, and external disturbances in MMC operation. Adaptive control dynamically adjusts controller parameters in real-time to accommodate changes in system characteristics, such as component aging, temperature variations, or fluctuating grid conditions. This continuous adaptation enhances the converter's resilience and maintains optimal performance without the need for manual retuning. Techniques such as model reference adaptive control (MRAC) and adaptive fuzzy logic controllers have been successfully applied to MMCs, providing flexible and self-tuning solutions. Robust control, on the other hand, focuses on guaranteeing system stability and performance within predefined bounds despite worst-case uncertainties and disturbances. Methods like H-infinity control and sliding mode control offer mathematically rigorous frameworks to design controllers that are inherently insensitive to parameter variations and external perturbations. Sliding mode control is particularly effective in dealing with the nonlinear dynamics of MMCs and suppressing circulating currents through its inherent robustness and finite-time convergence properties. The combination of adaptive and robust strategies often yields hybrid control schemes that capitalize on the strengths of both approaches, resulting in controllers that are both flexible and resilient. Such advanced control methodologies are indispensable for ensuring the reliable, efficient, and long-term operation of MMCs in increasingly complex and demanding power system environments[5].

5 MULTIFUNCTIONAL CONTROL STRATEGIES

5.1 Harmonic Suppression Control

Harmonic distortion is a significant concern in power electronics systems, particularly in Modular Multilevel Converters, where the switching actions and nonlinear load conditions inherently introduce harmonics into the output voltage and current waveforms. Effective harmonic suppression control is essential to improve power quality, reduce electromagnetic interference, and ensure compliance with grid codes and standards. Various strategies have been developed to mitigate harmonics, ranging from passive filtering to active control methods integrated within the converter's control framework. Advanced harmonic suppression techniques leverage real-time harmonic detection algorithms combined with targeted injection of compensating signals to cancel specific harmonic components. Selective Harmonic Elimination (SHE) and repetitive control methods are widely adopted for their ability to selectively target and reduce dominant harmonics with minimal impact on fundamental frequency operation. Moreover, adaptive filtering and predictive control approaches enhance the harmonic mitigation by dynamically adjusting control parameters in response to changing load conditions and grid disturbances. Implementing harmonic suppression within the MMC control architecture not only improves output waveform quality but also reduces

thermal and mechanical stresses on system components, thereby extending the converter's operational lifespan and reliability.

5.2 Power Factor Correction and Reactive Power Control

Maintaining an optimal power factor and precise reactive power control is critical for the efficient operation of electrical grids and to minimize transmission losses. Modular Multilevel Converters, due to their modularity and high controllability, are well-suited to perform advanced power factor correction and reactive power compensation functions. These converters can dynamically adjust the phase angle and magnitude of the output current to achieve near-unity power factor operation, effectively reducing the reactive power demand from the grid. Reactive power control also plays a pivotal role in voltage regulation and grid stability, especially under fluctuating load and renewable energy penetration conditions. By integrating sophisticated control algorithms, such as vector control and model predictive control, MMCs can modulate reactive power injection or absorption in real time, responding promptly to grid voltage variations or faults. Additionally, coordinating active and reactive power control allows the MMC to support grid ancillary services, such as voltage support and harmonic compensation. The precise regulation of power factor and reactive power not only enhances energy efficiency but also mitigates penalties imposed by grid operators for poor power quality, making MMCs valuable assets in modern smart grid infrastructures[6].

5.3 Fault Detection and Fault-Tolerant Control

Fault detection and fault-tolerant control are indispensable for ensuring the safety, reliability, and continuous operation of Modular Multilevel Converters, especially in critical power system applications. The complex topology and high number of submodules in MMCs introduce multiple potential fault modes, including semiconductor device failures, capacitor faults, and sensor malfunctions. Early and accurate fault detection mechanisms rely on real-time monitoring of electrical signals, such as arm currents, voltages, and temperature, combined with advanced diagnostic algorithms like model-based observers, artificial intelligence, and machine learning techniques. Once a fault is detected, fault-tolerant control strategies enable the converter to maintain operation by isolating or bypassing faulty submodules while reconfiguring control schemes to compensate for the reduced capacity. Redundancy and modularity of the MMC architecture facilitate graceful degradation and seamless transition to safe operating modes without interrupting power delivery. Techniques such as dynamic reconfiguration, adaptive control adjustments, and robust protection schemes are employed to mitigate the impact of faults, minimize downtime, and prevent cascading failures. The integration of fault detection and fault-tolerant control enhances the overall system resilience, ensures compliance with stringent safety standards, and supports uninterrupted power supply in demanding industrial and utility environments.

6 IMPLEMENTATION AND OPTIMIZATION OF CONTROL SYSTEMS

6.1 Digital Control Platforms and Hardware Implementation

The practical implementation of control algorithms for Modular Multilevel Converters relies heavily on advanced digital control platforms that provide the necessary computational power, flexibility, and real-time performance. Contemporary digital signal processors (DSPs), field-programmable gate arrays (FPGAs), and microcontroller units (MCUs) serve as the backbone hardware for executing complex control tasks, including modulation, feedback regulation, and fault management. The selection of an appropriate digital platform depends on factors such as processing speed, parallelism capability, ease of programming, and cost. FPGAs offer unparalleled parallel processing capacity, enabling high-speed, deterministic control loop execution essential for multilevel modulation and model predictive control, while DSPs provide a balanced approach combining high computational throughput with relatively straightforward software development. The integration of analog-to-digital converters (ADCs) with high resolution and fast sampling rates is critical to accurately capture voltage and current signals, thereby ensuring precise feedback for control loops. Additionally, digital platforms must support robust communication interfaces to coordinate with other system components and supervisory control units[7]. Effective hardware implementation involves meticulous attention to signal conditioning, noise reduction, and synchronization mechanisms to minimize latency and ensure reliable operation under varying electromagnetic environments common in power electronic

systems.

6.2 Effects of Control Delay and Sampling Time

Control delay and sampling time are pivotal factors that significantly influence the dynamic performance and stability of control systems in Modular Multilevel Converters. The inherent time lag between signal acquisition, processing, and actuation introduces phase shifts that can degrade system responsiveness and potentially destabilize the control loop. Longer sampling intervals reduce the control bandwidth and delay the system's reaction to rapid disturbances or transient events, thus increasing overshoot and settling time. Conversely, excessively short sampling times impose higher computational demands and may exacerbate noise sensitivity, leading to erroneous control actions. Therefore, an optimal balance must be struck to achieve fast and stable control without overwhelming hardware resources or compromising signal integrity. Analytical and simulation-based methods, such as discrete-time control theory and frequency-domain analysis, are employed to quantify the effects of delays and design compensatory mechanisms. Techniques like predictive compensation, feedforward control, and delay-aware observer design help mitigate adverse impacts by anticipating future system states or adjusting control actions proactively. Understanding and managing control delay and sampling time are indispensable for realizing high-performance MMC control systems that maintain stability and robustness under diverse operating conditions.

6.3 Parameter Optimization of Control Strategies

Optimizing control parameters is a fundamental step in enhancing the efficiency, stability, and robustness of Modular Multilevel Converter control systems. Parameter tuning involves adjusting controller gains, observer coefficients, and modulation indices to achieve desired dynamic responses, minimize steady-state errors, and suppress undesirable oscillations or harmonics. Traditional manual tuning methods, such as trial-and-error and Ziegler-Nichols heuristics, often prove inadequate due to the nonlinear, multivariable nature of MMCs and their operating environment. Modern optimization approaches employ systematic algorithms including genetic algorithms, particle swarm optimization, and gradient-based techniques to explore parameter spaces efficiently and identify optimal settings. These methods can incorporate multiple objectives, such as minimizing total harmonic distortion, reducing switching losses, and maximizing transient response speed, while respecting physical and safety constraints. Furthermore, adaptive optimization schemes that adjust parameters in real-time based on operating conditions and system feedback have gained prominence, enabling control systems to maintain optimal performance despite component aging, load variations, or environmental changes. Comprehensive parameter optimization not only improves converter performance but also extends device longevity and reduces maintenance costs, making it a critical aspect of MMC control system design and deployment[8].

7 CONCLUSION

Modular Multilevel Converters represent a transformative advancement in power electronics for high-voltage and high-power applications. This paper has systematically analyzed the key control challenges inherent to MMCs and surveyed a range of strategies aimed at achieving stable, efficient, and reliable operation. Fundamental controls for current regulation and voltage balancing ensure basic operational stability and waveform quality, while advanced algorithms such as model predictive control and adaptive robust methods address nonlinearities and dynamic uncertainties. Multifunctional control schemes further enable MMCs to fulfill grid-supportive roles, including harmonic mitigation, reactive power compensation, and fault tolerance, which are vital for integration into modern smart grids. The practical implementation considerations, including hardware selection and the management of control delays, are crucial for translating theoretical methods into operational systems. Ongoing research in control optimization, fault detection, and real-time adaptive mechanisms will continue to enhance MMC capabilities, supporting the transition towards more flexible, efficient, and resilient power systems worldwide.

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