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A Comparative Review of Circulating Current Control Strategies in Modular Multilevel Converters for High- and Medium-Voltage Applications

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ABSTRACT: The Modular Multilevel Converter (MMC) has become a cornerstone in high-voltage and high-power applications such as HVDC transmission, renewable energy integration, and industrial drives due to its modular architecture, scalability, and superior harmonic performance. However, critical challenges persist—particularly in circulating current suppression, capacitor voltage balancing, and efficient control—especially in large-scale deployments. This work provides a consolidated review and comparison of recent advancements in circulating current control strategies in MMCs aimed at improving power handling capability, efficiency, and reliability.

Among the strategies discussed, a Circulating Current Optimization Control (CCOC) technique introduces a calculated second harmonic current injection that minimizes arm current peaks and capacitor voltage ripple without increasing submodule capacitance. Complementarily, a Reduced Order Generalized Integrator (ROGI)-based controller implemented on FPGA platforms offers effective harmonic elimination with low computational and hardware costs, achieving a substantial reduction in total harmonic distortion (THD). A flowchart-guided control scheme further refines current regulation by incorporating inductor voltage into the circulating current model, which is particularly effective in medium voltage MMCs with a limited number of submodules per arm. Utilizing a generalized Phase Disposition PWM (PD-PWM), this method strategically applies inductor voltages through switching redundancy, leading to noticeable improvements in system efficiency and current harmonic suppression.

Simulation and experimental validations confirm the effectiveness of these techniques, demonstrating reduced RMS arm currents, improved voltage balance, and lower power losses. The findings underscore the critical importance of optimized and intelligent control strategies in enabling the next generation of efficient, reliable, and scalable MMC systems for advanced power electronics applications.

KEY WORDS: Modular Multilevel Converter (MMC) Circulating Current Optimization Control (CCOC), total harmonic distortion , Reduced Order Generalized Integrator (ROGI).

I.INTRODUCTION

The Modular Multilevel Converter (MMC) has emerged as a leading power conversion technology due to its distinct advantages in high-voltage and high-power applications. [1], [2] Its modular structure, which consists of cascaded submodules (SMs) connected in series, enables high scalability, superior efficiency, and low harmonic distortion. MMCs are increasingly adopted in critical applications such as High Voltage Direct Current (HVDC) transmission systems, renewable energy integration, industrial motor drives, and electric vehicles. The modular nature of the converter makes it highly flexible, allowing it to easily scale up to meet the voltage and power requirements of various systems while maintaining near-ideal sinusoidal output waveforms. However, despite these advantages, the MMC topology faces several challenges, particularly in achieving voltage balancing, minimizing circulating currents, and ensuring system reliability in large-scale systems with many submodules.[3]

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Recent advancements in MMC technology have focused on improving various aspects of its design and operation. In terms of semiconductor devices, the transition to wide-bandgap materials like Silicon Carbide (SiC) and Gallium Nitride (GaN) has revolutionized MMC performance by enabling faster switching frequencies, reducing conduction losses, and improving thermal performance. This shift not only improves efficiency but also enhances the converter's ability to operate at higher frequencies, which is essential for high-speed industrial applications and the integration of renewable energy sources. Along with advancements in semiconductors, significant research has been dedicated to enhancing control strategies to mitigate issues like capacitor voltage imbalance and circulating currents, which can reduce system efficiency, reliability, and lifespan.[4]

The voltage balancing problem remains a critical challenge in MMCs. Uneven voltage distribution across the submodule capacitors can lead to reduced output voltage quality, increased circulating currents, and faster degradation of components. Various control and voltage balancing techniques have been proposed in recent literature, ranging from modulation schemes and predictive control algorithms to the introduction of sensorless control methods aimed at minimizing the need for a large number of voltage sensors, which are costly and complex to manage in large-scale systems.[5], [6] Despite these advancements, achieving optimal voltage balancing with minimal sensors remains a challenging and active area of research, particularly in high-voltage applications such as HVDC systems that can involve hundreds or even thousands of submodules per phase.[7]

Furthermore, protection mechanisms and fault-tolerant design have received increased attention as researchers explore ways to enhance the reliability of MMCs in the face of faults, component failures, or environmental stress. Strategies such as active fault detection, reconfiguration techniques, and redundancy are being explored to ensure that the MMC can maintain stable operation even when individual submodules or components fail. These improvements are crucial for the widespread adoption of MMCs in mission-critical applications like renewable energy systems, where reliability and uptime are paramount.

On the other hand, current control methods in MMCs ensure precise regulation of output currents for optimal system performance. Techniques like inner current loop control using Proportional-Integral (PI) controllers enable fast and efficient current tracking, while Model Predictive Control (MPC) enhances dynamic performance by predicting future states and optimizing control actions. Average current control is often applied in HVDC systems to reduce switching losses and ensure smooth operation under fluctuating loads. In practical applications, combined voltage and current control strategies, such as cross-loop and dual-loop control systems, are commonly used to tightly regulate both voltage and current, ensuring stable operation in response to large load changes. While these methods significantly improve the performance of MMCs, challenges such as computational complexity and the need for sensor less control techniques to reduce system costs and improve reliability remain active areas of research.

II. Optimized Circulating Current Control for Enhanced Efficiency and Power Handling in Modular Multilevel Converters [7]

The Modular Multilevel Converter (MMC) is a widely preferred topology for high-power applications due to its modularity, scalability, and superior harmonic performance. One of the critical challenges in MMC operation is the presence of circulating currents (CC), especially the second-harmonic component, which impacts the design and rating of semiconductors, inductors, and capacitors within the converter. Traditional approaches to suppress or eliminate this circulating current can help reduce power losses but often compromise other aspects such as power handling capability or voltage ripple. In this context, the paper introduces a Circulating Current Optimization Control (CCOC) scheme, which not only reduces the peak arm current but also ensures the capacitor voltage ripple (CVR) remains within predefined limits, thereby enhancing both the efficiency and power density of MMCs without increasing the submodule capacitance.[7]

The core idea of the CCOC is to optimally control the amplitude and phase angle of the second harmonic circulating current (SHCC). By injecting an SHCC with a specifically calculated amplitude and phase, the peak value of the arm current can be minimized. The paper provides a detailed mathematical analysis showing that the optimal phase angle for SHCC injection should be $\pi/2 + 2\phi$, where ϕ is the power factor angle. Additionally, the amplitude of the SHCC is derived as a function of modulation index (m), output current (Im), and power factor, ensuring the SM capacitor voltage ripple does not exceed that which occurs at zero power factor using conventional suppression methods. This dual-objective strategy—minimizing both arm current peak and CVR—forms the basis of the proposed CCOC design.[8]

To implement the control strategy, the SHCC reference is generated in the dq-frame using an internal phase-locked loop (IPLL) that tracks the converter output current phase. This approach eliminates the need to explicitly measure or estimate

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the power factor angle, simplifying implementation. The dq components of the circulating current are regulated using PI controllers to ensure the actual SHCC follows its optimized reference. The simulation and experimental results validate the effectiveness of the CCOC scheme, showing significant reductions in arm current peaks and improved power handling capability without increasing the submodule capacitor size.

III. FPGA-Based Circulating Current Control in Modular Multilevel Converters Using Reduced Order Generalized Integrator [9]

The novel control strategy for Modular Multilevel Converters (MMCs) focused on eliminating second-order harmonic circulating currents (2HCC), which are known to cause power losses, increased voltage ripple, and reduced efficiency. The proposed controller is based on a Reduced Order Generalized Integrator (ROGI) and is implemented in the stationary αβ reference frame. Unlike conventional methods that rely on estimating or measuring the DC component of circulating currents, the ROGI-based controller eliminates this requirement, resulting in a simpler design with lower computational complexity. This control approach is suitable for both three-phase and single-phase systems and offers enhanced implementation feasibility on low-cost digital platforms like FPGAs.

To validate the control strategy, the authors implemented the ROGI-based controller using VHDL on a Digilent Atlys FPGA board equipped with a Xilinx Spartan-6 chip. The system was simulated and co-simulated using MATLAB/Simulink and ModelSim, verifying performance in both steady-state and transient conditions. Simulation results demonstrated effective suppression of the second-order harmonic current from 73.42 A to just 0.12 A, with a total harmonic distortion reduction from 114.83% to 5.77%. The proposed control system also maintained submodule capacitor voltage balance and showed robust behavior under load step changes, proving its effectiveness in real-world scenarios.[9]

In addition to superior harmonic elimination, the ROGI controller requires fewer FPGA resources compared to traditional SOGI-based designs. It uses only one resonant controller in the αβ frame instead of two or three, leading to a 17% and 7% reduction in FPGA resource usage compared to SOGI in the abc and αβ frames, respectively. The authors further confirm the controller's practical viability by generating PWM gating signals and conducting a successful FPGA-based hardware demonstration. The proposed method's simplicity, low hardware cost, and high efficiency make it a promising solution for MMC applications in renewable energy and high-voltage DC transmission systems.[10]

To implement the proposed strategy, the paper uses a generalized Phase Disposition PWM (PD-PWM) technique that produces 2N+1 levels in the output voltage. This modulation method supports redundant switching combinations, especially at odd voltage levels, which are used to regulate the circulating current. By selecting between different redundant combinations—depending on whether the actual circulating current is below or above the reference—the system can apply a small positive or negative voltage across the inductors to drive the current toward its target. This intelligent redundancy utilization ensures effective circulating current control without affecting the capacitor voltage balancing. For even voltage levels, which do not produce any inductor voltage, the circulating current remains unchanged, preserving the integrity of the control strategy.
The proposed control scheme was validated through both simulation and hardware implementation using a scaled-down prototype. The results demonstrated a noticeable reduction in the root-mean-square (rms) value of the arm current compared to conventional controllers, particularly in configurations with a low number of SMs per arm.[10] This reduction also translated to lower conduction losses and improved system efficiency while maintaining comparable capacitor voltage stability. Harmonic analysis confirmed that the proposed method significantly decreased the second and fourth harmonic components in the circulating current, contributing to the overall performance improvement. The simplicity of the PWM scheme and the avoidance of additional sensors further highlight the practical benefits of this control strategy for medium voltage MMC systems[11].

IV. Flowchart-Guided Circulating Current Control for Medium Voltage Modular Multilevel Converters [12]

To enhanced circulating current control method for Modular Multilevel Converters (MMCs) specifically designed for medium voltage applications. Unlike traditional approaches that neglect the influence of arm inductor voltages in circulating current modeling, this work incorporates those voltages into the control design. This is particularly important

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in medium voltage systems, where the number of submodules (SMs) per arm is relatively low, making the per-unit voltage across the inductors significant. By including the inductor voltage in the differential mode model of the MMC, the authors derive a more accurate circulating current reference. This reference comprises a DC component for capacitor voltage stabilization, a fundamental component for energy balancing, and a modified second harmonic component that is computed based on arm insertion indices and the modulation index. This approach reduces unnecessary current injection and, consequently, the total circulating current magnitude.[12]
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V. CONCLUSION

The three circulating current control strategies proposed each address distinct challenges associated with Modular Multilevel Converters (MMCs), applying innovative techniques based on application context and design priorities. One method introduces a circulating current optimization control technique that strategically injects a second harmonic current with an optimized amplitude and phase. Rather than eliminating the second harmonic component, this approach uses it constructively to reduce the peak value of the arm current while keeping the submodule capacitor voltage ripple within safe design limits. This balance allows the converter to operate with reduced semiconductor stress and enhanced power handling capacity without requiring an increase in submodule capacitance, making the method highly efficient for systems operating across varying power factors and modulation indices.
Another approach adopts a control method based on the reduced order generalized integrator (ROGI) implemented in the stationary αβ reference frame. This strategy focuses on completely eliminating second harmonic circulating currents without relying on measurement or estimation of DC components. It simplifies controller design by reducing the number of resonant controllers and computational load, making it highly suitable for low-cost FPGA implementation. The ROGI-based controller is particularly effective in embedded digital platforms due to its minimal hardware resource consumption, demonstrating strong harmonic suppression with low total harmonic distortion and improved system efficiency.
A different strategy addresses circulating current control in medium voltage MMCs, where the number of submodules per arm is limited, making the impact of arm inductor voltage non-negligible. This method incorporates inductor voltage directly into the circulating current model, improving the accuracy of the reference current calculation. It utilizes redundant switching states available in 2N+1 level PD-PWM schemes to apply small, targeted voltage changes that drive the circulating current toward its desired value. This technique effectively reduces conduction losses, suppresses harmonics, and maintains capacitor voltage stability, all without requiring additional sensors. It is particularly well-suited for medium-voltage applications where accurate modeling of internal dynamics is crucial for efficient operation.

AUTHOR'S BIOGRAPHY

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