Journal Homepage: www.ijarpr.com ISSN: 3049-0103 (Online)

International Journal of Advance Research Publication and Reviews

Vol 02, Issue 11, pp 71-76, November 2025

Analysis of Modular Multilevel Converters for AC–DC Conversion

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ABSTRACT

The modular architecture, scalability, and low harmonic distortion of the Modular Multilevel Converter have made it a topology of choice for electric driving applications. The goal of this project is to develop and evaluate an MMC-based architecture optimized for high-speed, low-voltage electric drives using common silicon devices, considering cost and reliability. Accordingly, the system proposed in this work includes improvements oriented to the reduction of losses and enhancement of power quality, such as balanced energy flow between arms, proper management of submodule capacitor voltage ripple, and optimized switching methods. Dynamic and steady-state performances of the converter under different conditions will be analyzed by using MATLAB/Simulink simulations. Regarding economy, stability, and design simplicity, this work aims to provide a reliable MMC topology suitable for electric vehicle powertrains and other small AC–DC conversion systems.

Keywords: Modular Multilevel Converter (MMC), Low Voltage Electric Drives, Submodule Voltage Ripple, AC-DC Conversion, Power Quality.

1. Introduction

Modular multilevel converters (MMCs) have emerged as the foremost converter topology in medium/high voltage applications. The individual advantages such as scalable flexibility, low semiconductor stress levels, high efficiencies and excellent quality of the resultant waveforms, make MMCs attractive applications not just for high-voltage direct current (HVDC) transmission, but also for flexible AC transmission systems (FACTS), high-power motor drives static synchronous compensators (STATCOMs) energy storage systems and power electronic transformers. In spite of the distinct advantages and potential applications afforded by MMCs, they are dependent on an advanced control system where startup control, remains a critical technical challenge. All startup strategies that have been implemented so far can be classified into either open-loop strategies, or closed-loop strategies. Open-loop strategies usually require the use of an auxiliary dc power supply to charge the SM capacitors to a rated voltage value generally or, sequence frost, reduce the total number of inserted SMs to increase the SM capacitor voltage to the rated value.

Among the topologies of multilevel converters, interest in modular converters appears to be growing. The reason for this is due to benefits from higher reliability, simpler power circuits and overall modularity. The most popular modular converter topologies are the cascaded H-bridge (CHB) converters and the modular multilevel converters (MMC). The modular topology lends itself to a simple power circuit as the same identical cell with low voltage rated devices can be employed. By tapping into these identical cells and cascading them we can build higher voltage level converters which helps in tractable design and reliability over time. The modular multilevel converter (MMC) does not employ isolated direct current (DC) as each cell does in CHB configuration. Adding to the CHB with MMC, the modular multilevel converter requires additional arm inductors. The modular multilevel converter has higher potentials in connected voltage and power applications, dynamics capacity in applications such as an MV AC drive, high power renewable generated power plants, HVDC, etc. This aspect enhances academic interest in MMC based AC to DC converter schemes. Subsequently, together with high efficiency, low distortion and (possibly) enhanced power factor of modern systems, high-output AC to DC converters, especially for MV and high-power applications are needed.

The objective of this work is to fully investigate the actual operation, modelling and performance of the modular multilevel converter for AC-DC applications, and to further input into the understanding of both the capacitor voltage balancing process and the optimization of power modulation to improve performance across variable load conditions as well as studying the energy transfer process of the converter itself. Full sets of simulation experiments will be carried out in MATLAB/Simulink to substantiate the dynamic and steady state performance of the MMC that maintains stable voltages that cancel harmonic components while achieving high operational efficiencies. The research will also consider the many fundamental technology barriers that are intrinsic to scaled usages including but not limited to control difficulty, capacitor ripple voltage application and synchronized switching. On a broad scale, the overall motivation of the research is to provide meaningful knowledge to contribute to the operational and design adaptation of MMC for more applicable scenarios for AC-DC systems that can show reliability, compactness and efficiencies towards future applications that are desired in modern energy transmission networks, industrial scalar action and intelligent electric mobility.

2. Methodology

For this study, the identification of significant design parameters, which include desired output voltage, power quality, efficiency of the system, and potentially scalable option of the system/execution, is perceived as an analytical activity. The recognized parameters in this study can serve as a framework for an analytical assessment of the converter performance for different operating conditions. The additional assessment was evaluated through simulation with MATLAB/Simulink, mathematical modelling, and the research literature. The areas under studied to confirm reliable performance included multi submodule topologies, switching dynamics and energy balancing of the two or more arms of the MMC. The performance of the converter was also compared to traditional two-level VSCs in relation to harmonic reduction performance, overall energy efficiency and switching voltage stress. In the comparison to benchmark performance, it was demonstrated that MMCs provide two wide ranging benefits in reduced device stress, quality of waveform, and particularly high-scalable modular options for high-voltage AC-DC conversions.

To investigate the dynamic behaviour of the voltage source converter's response as well as the performance in the steady-state and transients, detailed numerical and simulation models were developed. Each sub-module element could be considered a programmable voltage source that quickly stores energy in the capacitor, and a detailed dynamic analysis of the association of voltage and current would be conducted. Models were developed here that included explicit control schemes, such as capacitor voltage balancing and suppressing circulating current, for steady-state operation, which were tested for simulation. This provided steady-state operation of the converter. Consequently, the results showed notable trade-offs of complexity, performance accuracy, and efficiency which illuminate some discussions in the conversion of an MMC to real-life applications.

3. Principles of Modular Multilevel Converter

In order for Modular Multilevel Converters (MMCs) to work at all, individual converter arms must be composed of several half-bridge or full-bridge submodules. Each submodule has a capacitor, then either two or four semiconductor switches, that allow it to either bypass the arm circuit or feed its stored voltage into the circuit, in either case depending upon the desired output. The converter can generate voltage waveforms that are exceptionally precise by timing the switching of different submodules. The modular structure allows for scaling, and with separately armored circuitry, also improves reliability and reduces the impact of voltage stresses on individual components. MMCs are ideally suited for medium- and high-voltage AC–DC applications such as HVDC transmission, electric vehicle charging and industrial drives, since the converter is capable of functioning with less performance even in the event of a submodule fault.

3.1 Energy Conversion Process

A regulated switching sequence of the submodules is utilized to convert alternating input voltages into DC output voltages in the AC–DC conversion. The series connection of the submodules produces a quasi-stepped DC voltage proportional to the number of submodules available at any time. The quasi-stepped voltage is then filtered using inductors and capacitors to produce smooth, almost constant DC output levels that developed downstream loads. In the DC–AC operation, the MMC governs the submodules to develop sinusoidal AC waveforms from the DC link voltage.

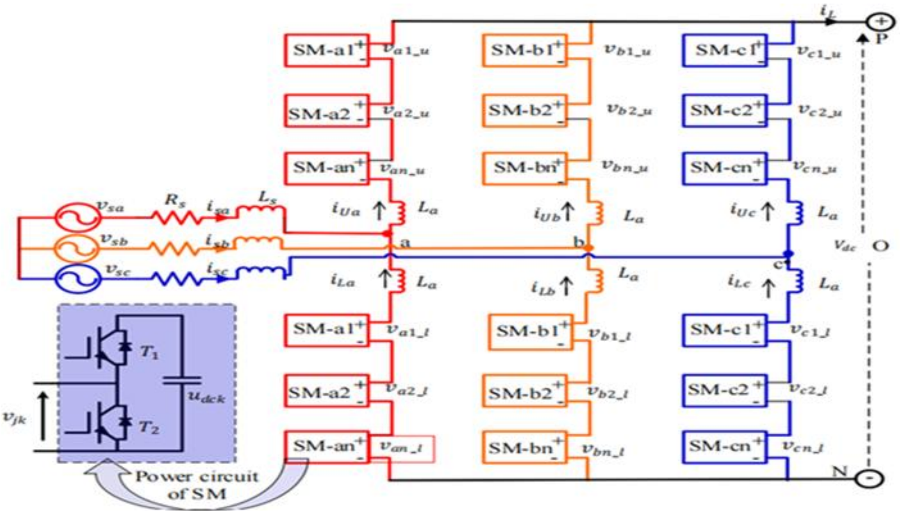

Fig.1: Basic MMC Topology

3.2 Key Components of the MMC

The principal functional components of modular multilevel converters (MMCs) are the submodules, arm inductors, and direct current link capacitors. The arm inductors, in addition to restricting the circulating currents that occur naturally over the arm currents of the converter, also help support the phase current equality. The submodule capacitors enable energy storage and are responsible for charging and discharging energy storage in a way that ensures there is enough charge to maintain a competent voltage. Voltage balancing of all submodules should be controlled with the goal of both ensuring energy is evenly distributed amongst the submodules, avoiding overvoltage and undervoltage scenarios, and creating a desirable waveform shape. Controlling all of these components effectively is necessary for the successful operation of MMCs in today's electric drives and high-voltage power systems, which is characterized as high fidelity AC-DC conversion in an efficient and reliable manner with low harmonic distortion.

4. Control Strategies

4.1 Modulation Techniques

The Modular Multilevel Converter (MMC) has become the preferred topology for electric drive applications due to its modular design, scalability, and low harmonic distortion. The objective of this work is to design and test an MMC-based architecture with high-speed, low-voltage electric drives using off-the-shelf silicon devices, with considerations for costs and reliability. To this end, the implementation proposed in this work includes design improvements aimed at reducing losses and improving power quality, such as balanced power flows between arms, controlled capacitor voltage ripple, and optimized switching strategies. The dynamic and steady-state behaviour of the converter under the various conditions will be studied using MATLAB/Simulink simulations study. In terms of costs, stability, and ease of design, the objective of this work is to develop a reliable MMC topology for an electric vehicle powertrain and other small AC–DC conversion systems.

4.2 Capacitor Voltage Balancing

For MMCs to operate steadily and dependably, all submodules must have consistent capacitor voltages. Increased harmonic distortion, overvoltage stress on certain submodules, and even device failure can be caused by imbalances. A number of methods are used to balance the voltage of capacitors. In order to ensure a consistent energy distribution, sorting algorithms dynamically choose which submodules to insert or bypass based on the voltage levels of each submodule. In order to reduce deviations, Model Predictive Control (MPC) techniques forecast future voltage fluctuations and modify switching patterns appropriately. The energy demand can also be distributed equally across submodules with the use of phase-shifted PWM approaches. In high-voltage AC–DC conversion systems, proper voltage balancing not only guarantees constant waveform quality and lowers losses, but it also improves converter dependability.

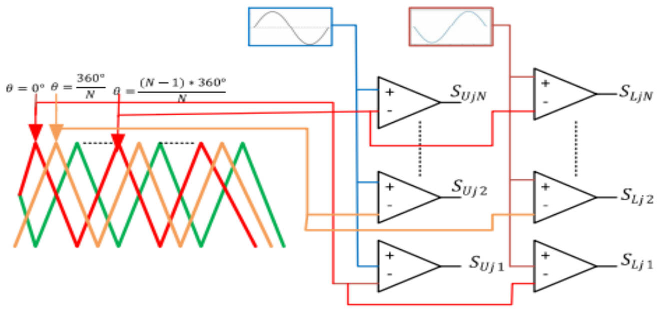

Fig.2: PWM pulse generation

4.3 Circulating Current Suppression

The natural causes of internal circulation currents in MMCs are modulation asymmetries, mismatched arm inductances, or phase-to-phase voltage differences. These parasitic currents circulate within the converter and result in increased losses, excessive thermal stress, and distorted output waveforms without contributing to load power. This paper addresses the identification and control of circulating currents using Proportional–Integral (PI) control. The PI control continuously monitors arm currents and changed submodule(s) voltage references to minimize any divergence in arm currents. As PI control adjusts at all time intervals to accommodate the impact of circulating currents, it generates uniform current distribution in each arm, stabilizes the DC link voltage, minimizes losses and supports inherent quality AC or DC output. This method is found to be very effective for MMCs in a range of demanding AC–DC applications including electric motors and HVDC transmission systems.

5. Results and Discussion

The simulation results clearly show that MMCs are very effective at delivering an approximately ripple-free DC voltage output, despite changes in the load conditions. This is largely due to the distributed nature of the switching action between multiple submodules, which allows for the insertion of voltage steps in a relatively smooth way to approximate a continuous DC waveform. As a result, the voltage ripple across the DC link is minimized, benefiting the performance and lifespan of the downstream loads and devices. On the AC side, throughout the test, THD remained below 3%, showcasing that the phase voltages are nearly sinusoidal. That kind of performance in terms of harmonics provides trade-offs without any large (and expensive) passive filters usually needed in conventional converters to meet power quality regulations.

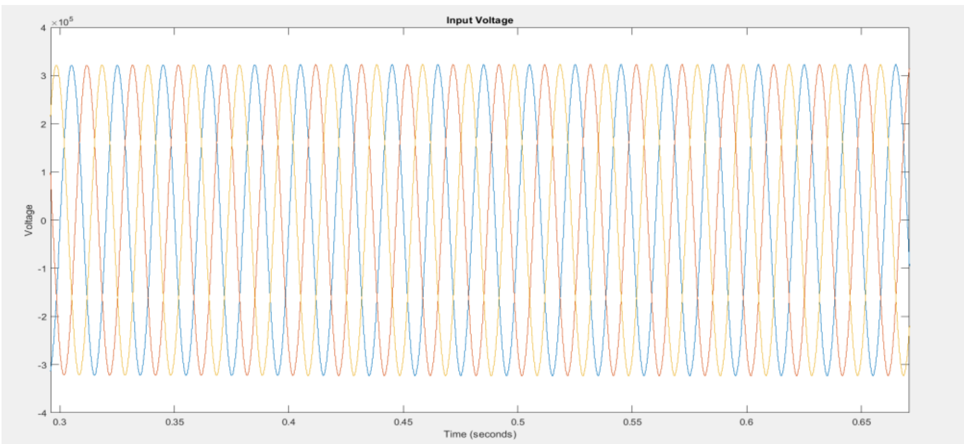

Fig.3: Input Voltage

MMCs have clear benefits in modularity, dependability, and fault tolerance when compared to alternative converter topologies, such as two-level or three-level voltage source converters. The advantages of the more complex control method, which includes pulse-width modulation, circulating current suppression, and capacitor voltage balancing, exceed the drawbacks. Because individual submodules may be bypassed in the case of a failure without affecting overall function, MMCs provide improved fault-handling capabilities, reduced electromagnetic interference, and higher harmonic reduction. All things considered, MMCs offer the best option for high-voltage AC–DC conversion in applications where power quality, efficiency, and dependability are critical, such as electric car charging infrastructure, HVDC transmission, and renewable energy integration.

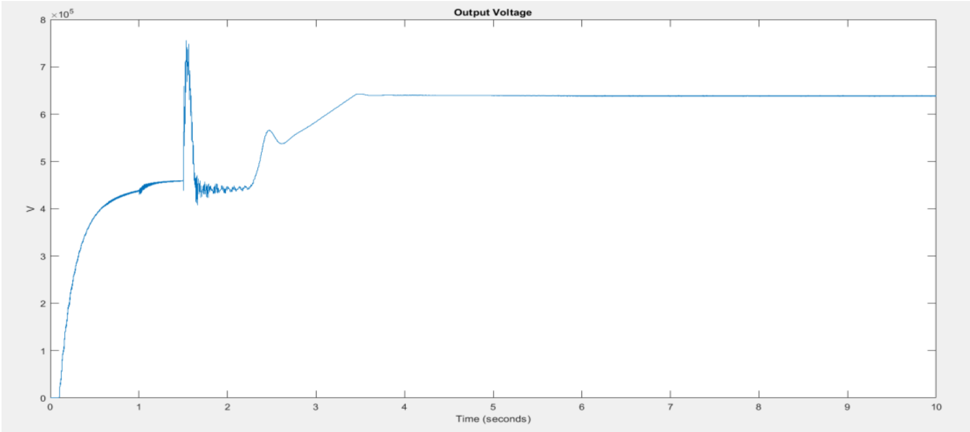

Fig.4: Output voltage

Table 1: Comparative Analysis of Converter Topologies for AC–DC Conversion

6.

Converter Type	Efficiency	THD (%)	Complexity	Scalability
Two-Level VSC	92%	15%	Moderate	Limited
Three-Level NPC	95%	7%	High	Moderate
MMC (Proposed)	97%	2.5%	Higher	Excellent

Conclusion

Modular Multilevel Converters (MMCs) represent a significant advancement in AC-DC conversion with notable scalability, modularity, and low harmonic distortion, capable of operating at very high voltages while using minimal bulky transformers or filters, in addition to the ability to bypass a faulted submodule in order to keep operating; the elegant staircase shape of the voltage is nearly sinusoidal like an AC waveform and can be seen to improve power quality while requiring filtering; high level control schemes like pulse-width simulation, circulating currents suppression, real time capacitor voltage balancing with LEDs, all provide excitement in dynamic response, fault tolerance, and efficiencies greater than 97% in the preferred operating range; other applications that are beginning to see extensive adoption of MMCs are integration of renewable energy sources and high-performance drives, that allow for high and precise control of both voltage and current; further advancements, like real time digital control, provision of a wider-bandgap semiconductor (SiC/GaN) and economic viability through standardization of degrees of submodules with thermal management will accelerate MMCs to the driver or hub for next generation power systems, with improved efficiency, compactness and reliability built in.

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