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PERFORMANCE EVALUATION OF MODULAR MULTILEVEL CONVERTER ARCHITECTURES FOR HIGH-VOLTAGE DIRECT CURRENT APPLICATIONS

Nadeem Ahmed Tunio[*1], Mohsin Ali Tunio[2], Fatima Tul Zuhra[3], Peer Muhammad Brohi[4]

[*1,2,4]*Department of Electrical Engineering, Mehran University of Engineering and Technology SZAB Campus Khairpur Mirs' 66020 Pakistan*
[3]*Information Technology Department, Shaheed Benazir Bhutto University Sanghar Campus, Sanghar, Sindh, Pakistan*

[*1]nadeemtunio@muetkhp.edu.pk

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Corresponding Author: *
Nadeem Ahmed Tunio

Abstract
The increasing demand for efficient long-distance High Voltage Direct Current (HVDC) integrated with renewable energy resources is universally has been intensified around the globe. The modular Multilevel Converters (MMC) is its component due to its modular structure design, high efficiency, higher dynamic performance and low harmonic distortion. This paper offers a design and performance assessment of MMC architectures for HVDC applications, highlighting its real-time authentication through Hardware-in-the-Loop (HIL) environments. The study delivers a thorough investigation of MMC modulation strategies, and multilevel output synthesis. Using real-time simulation platforms, the simulation results validate the converters' improved excellent power quality across a wide operating range. Overall, the results confirm that simulation and HIL supported development expressively fortifies the dependability, performance, and practical deployment of MMCs in modern HVDC transmission lines.

INTRODUCTION

The electrical power transmission has experienced a thoughtful technical change, developing from conservative, mechanically controlled setups headed for power electronic based advanced architectures that enable high capacity, long distance, and environmentally concerned transfer of electrical energy [1]. This shift is rapidly growing due to complex power system due to the integration of renewable energy resources in the existing grid towards sustainable growth which undermines the technical and operational limitations of conventional High Voltage AC transmission lines (HVAC) [2].

The HVAC has been employed as the backbone for the transmission of bulk power , on the other side high need of reactive power , associated power losses and intrinsic stability limitations have increased concerns for its suitability [3]. However the HVDC has evolved as an excellent choice for power transmission over long distance, high-power, having ability to easily adjust and control active and reactive power, reduce power losses, and improve power system stability as a key enabler of renewable energy corridors [4].

Modular Multilevel Converter (MMC), extensively known as the most advanced Voltage Source Converter (VSC) topology for HVDC applications. MMC's are composed of cascaded submodules, which enables its scalability, minimizes switching frequency, high-quality multilevel voltage construction and considerably reduce Total Harmonic Distortion (THD) compared to Line Commutated Converters (LCCs) and conventional 2 level or 3 level VSCs [5].

MMC provides numerous advantages that have redefined the design and control of HVDC systems, its structure enhances fault tolerance, ensuring continued operation while its superior dynamic response enhances grid stability under transient disturbances [6]. The converter's ability to function efficiently across a varying levels of voltage and power enables it suitability for multi-terminal HVDC, hybrid AC/DC networks, and integration of large scale renewable generation [7]. The demand for accurate, high-fidelity modeling of MMC considering the circulating current reduction, the balancing of capacitor voltage and modulation approach optimization has improved the importance of advanced simulation tools and Hardware-in-the-Loop (HIL) platforms. HIL enable real-time examination of converter effectiveness under realistic HVDC conditions, minimizing development risks and hastening deployment [8].

The advancement of high-power transmission networks reveals a clear shift from exiting HVAC lines to more capable HVDC transmission lines for transmitting large blocks of electrical power to enhance operational stability integrated with renewable energy resources [9]. The previous studies focus on comparative analysis analyses between HVAC and HVDC transmission systems. While HVAC lines exist due to voltage transformation and traditional infrastructure, their technical limitations pronounced when comes power transmission over longer distances [10].

Effects of load types inductive and capacitive, power losses due corona and skin-effect, voltage variation and the demand for the reactive power and its compensation considerably reduce the efficiency and performance of HVAC efficiency, particularly in remote renewable energy plants, and intercontinental interconnections. Therefore HVDC technology has evolved as an excellent alternative, ensuring reduced transmission losses, increased voltage regulation, provision of connecting asynchronous grid interconnection, features that are essential for the modern power systems [11]. Inside this change the development of power electronic converter has played a crucial role as the previously HVDC installations were largely based on Current Source Converters (CSCs) and then Voltage Source Converters (VSCs). The CSC based converter systems, which rely on line commutated thyristor and large DC-side inductors, undergo from partial dynamic control capability, increased reactive power consumption, controlled modulation flexibility, and susceptibility to commutation failures [12].

The advent of VSC based HVDC systems marked an important advancement by enabling independent control of active and reactive power. Despite these advantages, VSC systems show complex multi-time-scale interactions involving AC network dynamics, DC-link capacitor behavior, switching harmonics, and mechanical system coupling. The reported challenges mentioned revealed from the literature include subsynchronous oscillations, high-frequency resonances, and increased switching losses, necessitating high switching frequencies and bulky filters to meet harmonic standards , which limit the scalability and efficiency of conventional VSC architectures in ultra-high-voltage and high-power applications [13].

The studies have suggested improvements to NLM through optimized switching sequences, improved capacitor voltage balancing algorithms, and hybrid or binary-weighted submodule arrangements to further reduce losses and improve dynamic performance. The circulating current suppression, arm voltage control, and capacitor energy balancing have also been widely examined to ensure stable MMC operation under steady-state and transient conditions. Submodule topology selection is another critical research area influencing MMC performance, efficiency, and fault tolerance, half-bridge submodules are widely adopted due to their simplicity and low conduction losses; however, they lack inherent DC fault-blocking capability [14].

The literature review therefore show that while CSC and VSC are the basics for the power transmission trough HVDC lines, however the concern for efficiency, reliability, and scalability demands of modern power systems, force the researchers to consider MMC supported by continuous advances in submodule design, modulation strategies, control methodologies, and HIL-based validation platforms, which has emerged as the dominant and most promising converter architecture for next-generation HVDC applications.

This work focuses on the design of MMS through simulation and performance evaluation for power transmission through HVDC lines. Using detailed model development with real-time HIL validation, the work presents how modern simulation environments enhance the accuracy, robustness, and practical applicability of MMC control and operation. Through this investigation, the study demonstrates the central role of MMC in shaping the next generation of efficient, reliable, and resilient HVDC power transmission systems.

Research Methodology

This methodology presents the MATLAB/Simulink modeling of the Modular Multilevel Converter (MMC), including its structural configuration with phase arm inductances and half-bridge submodules, along with the mathematical modeling of arm voltages and circulating currents. MMC configurations of 3, 6, 9, 35, and 51 voltage levels are evaluated under identical operating conditions, and offline simulation results are comparatively analyzed in terms of total harmonic distortion, modulation index, and phase arm currents, circulating current, and voltage–current waveforms. Furthermore, a Hardware-in-the-Loop (HIL) setup is employed to validate the simulation results under real-time conditions. The design workflow of this study is illustrated in Figure 1 and simulation circuit shown in Figure 2. Nearest Level Modulation (NLM) is adopted for switching control due to its effectiveness in high-level MMC operation and harmonic reduction and the process is shown in Figure 3.

MMC was set up using average value model and half bridge sub-modules, is shown in Figure 4 sketching the structure of MMC used in this study. Each arm of the MMC has reactor, L_{arm} , which controls the flow of currents under any abnormal situation.

Figure 4 shows the flow chart of the modular multilevel converter and its working, used to convert the high voltage direct current to high voltage alternating current efficiently which consists of two arms i.e. upper arm and lower arm. Each arm has sub-modules connected in series and arms are connected using inductor to limit current in case of voltage difference in arms. Capacitor is inserted in each sub-module to maintain a particular voltage level, across each switch diode is connected to control the current flow.

Mathematical Modeling
Modeling in MATLAB/Simulink
Real time testing
HIL Implementation
Output /Performance Evaluation

Figure 1: HIL based design process

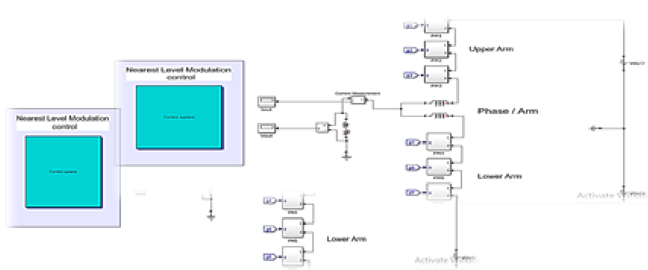


Figure 2: MMC simulation circuit

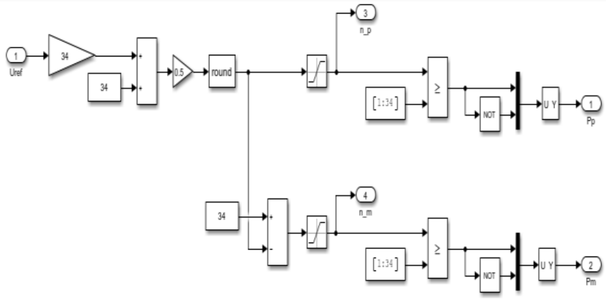


Figure 3: NLM Mode

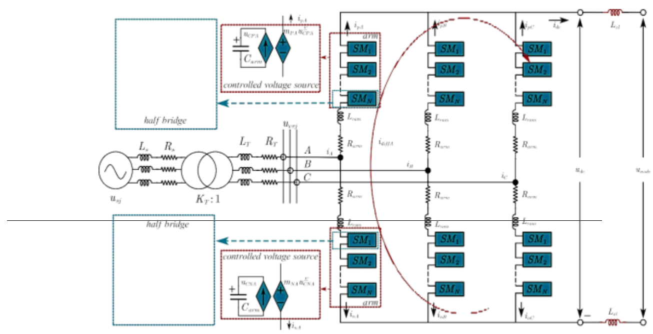


Figure 4: Schematic diagram of three phase multilevel converter.

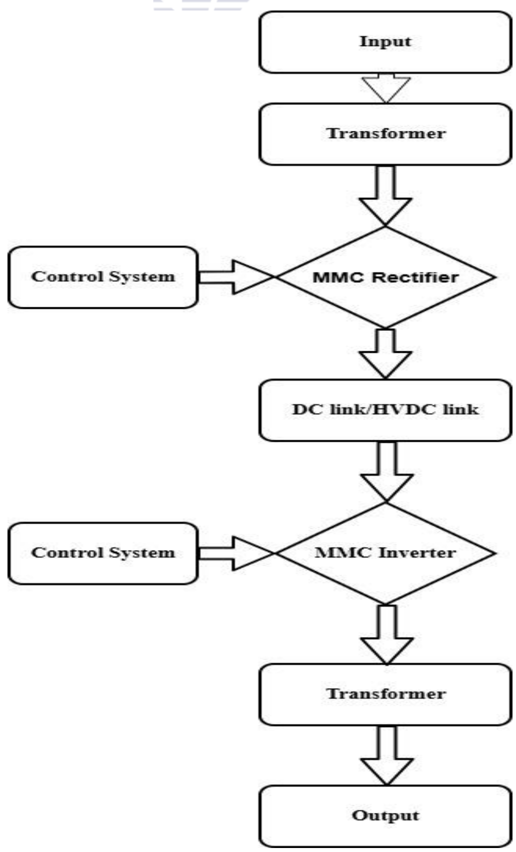


Figure 5: Flow chart of modular multilevel converter

Results and Discussion

This section presents a performance evaluation of MMC architectures using **HIL-supported simulations** for HVDC applications. The graphical results illustrate inverter voltage and current outputs, single-phase voltage, arm and circulating currents, and modulation index behavior, while **THD and modulation index values are summarized in tables** for comparative assessment across different MMC levels.

A. Results for 3-level multilevel converter

In the initial stage of this study, a **3-level modular multilevel converter (MMC)** is developed and analyzed using **offline simulation and Hardware-in-the-Loop (HIL), oriented modeling** to establish a baseline for real-time HVDC validation. In the beginning we have simulated the modular multilevel converter of 3-levels. The sub-modules were connected in the both arms of modular multilevel converter. The output waveforms of voltage and current are described below and the total harmonic distortion is also shown. Figure 6(a) shows the output voltage

Waveforms of a three level modular multilevel converter connected to an RL-load spaced 120^0 apart. These waveform output shows how the converter generates less smooth AC voltage than sinusoidal waveform from stepped levels. Where red waveform indicates phase-A, blue waveform reveals phase-B and black waveform shows phase-C.

The Figure 6(b) indicates the three-phase output waveforms of inverter current of a three level modular multilevel converter spaced 120^0 apart connected to an RL-load and along with low distortion by effective modulation.

The Figure 6(c) shows the harmonic distortion analysis where it is shown that the signal contains multiple harmonics with harmonic distortion of 7.75% which indicates the waveform has moderate distortion.

The Figure 6(d) shows the behavior of arm current in a single-phase modular multilevel converter where initially current decreases due to system startup or transients effects and after stabilization, it transients into a periodic sinusoidal waveform which reveals that converter has reached the steady state level.

The Figure 6(e) indicates that modulation index behavior of a 3 level inverter, it shows that how the inverter adjusts its modulation index dynamically to regulate output voltage. The waveform variations reflect the inverter's response to changing load or control conditions, helping ensure stable and efficient power conversion.

The Figure 6(f) shows the circulating current behavior in the arms of a 3-level modular multilevel converter during simulation, the waveform illustrates the involvement of current to help the assess system stability and control to reduce the losses to ensure efficient converter operation.

These results confirm that the 3-level MMC provides a valid baseline for HIL-based evaluation and motivates the transition to higher-level MMC architectures for improved harmonic performance in HVDC applications.

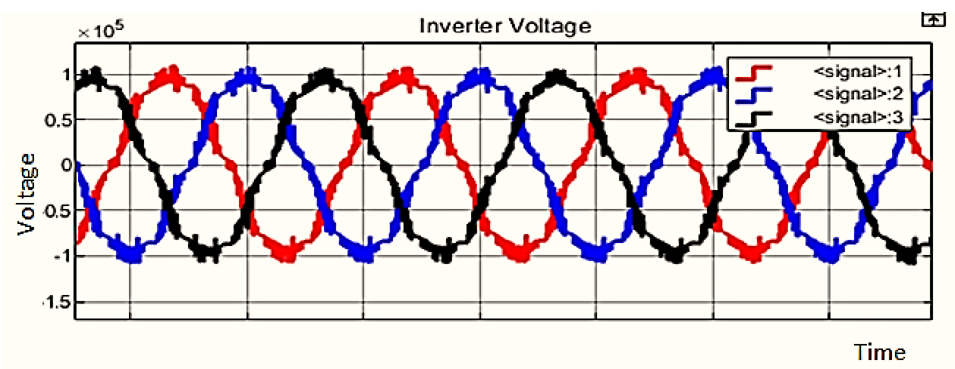
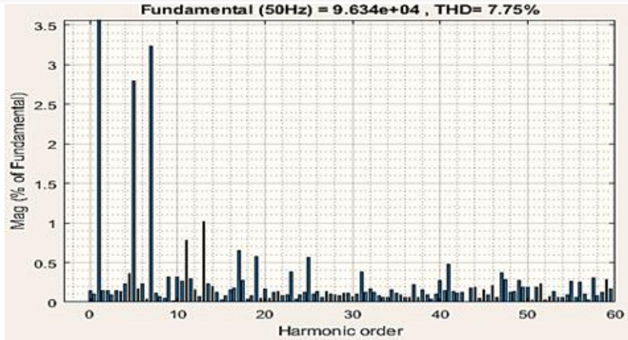


Figure 6(a): Output Voltage Waveform with RL load



6(b): Current Waveform output with R-L load

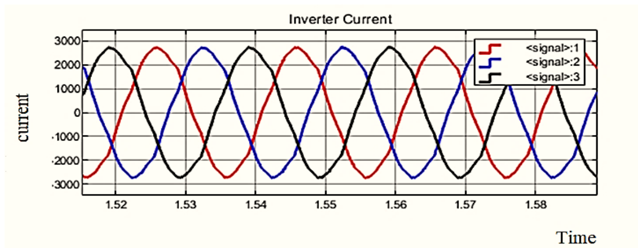


Figure 6(c): Total harmonic distortion output

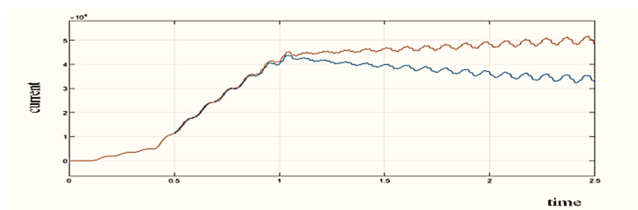


Figure 6(d): Arm current of single phase

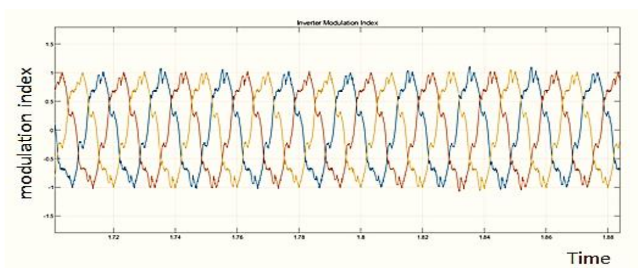


Figure 6 (e): Modulation Index of inverter

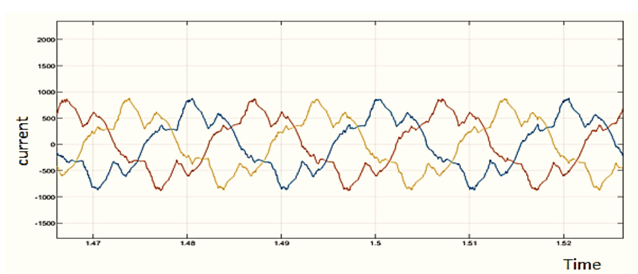


Figure 6 (f): Arms circulating Current

Figure 6 (a-f): Results for 3-level modular multilevel converter

B. Results for 6-level modular multilevel converter

A 6-level modular multilevel converter (MMC) is developed and analyzed using **offline simulation and Hardware-in-the-Loop (HIL) oriented modeling** for real-time HVDC validation. The modular multilevel converter of 6-levels has been modulated. The sub-modules were connected in the both arms of modular multilevel converter. Figure 10 shows the output voltage waveforms of a six level modular multilevel converter connected to an RL-load, spaced 120^0 apart. These waveform output shows how the converter generates smooth AC voltage, sinusoidal waveform from stepped levels.

The Figure 7(a) indicates the three-phase output waveforms of inverter current of a six level modular multilevel converter spaced 120^0 apart connected to an RL-load with low distortion through effective modulation. It is seen than the as the number of levels are increased , the output waveform of current is observed smooth as compared to three-level as shown in Figure 7(b).

The Figure 7(c) shows the harmonic analysis of 6 level converter, with the percentage harmonic distortion of 7.21% which indicates that by increasing the levels from three-level to six level harmonic distortion has decreased up to 0.64%.

The Figure 7(d) indicates single phase arm current output of a 6 level MMC, showing that the converter is operating in a steady state condition, delivering smooth and periodic current, furthermore it is clear that the control technique is effectively regulating the arm current ensuring stable performance and minimal distortion at the output

The Figure 7(e) shows the circulating current behavior in the arms of a 6-level MMC , where it is seen the output is smoother as compared to 3-level converter by considering the reference sinusoidal waveform which illustrates the involvement of current to help the assess system stability and control to reduce the losses to ensure efficient converter operation.

Figure 7(f) shows that modulation index behavior, where the number of levels increased from 3-level to 6-level, the output is smoother as compared to 3-level converter, it is revealed that how the inverter adjusts its modulation index dynamically to regulate output voltage. The waveform variations reflect the inverter's response to changing load or control conditions, helping ensure stable and efficient power conversion.

It is concluded that 6-level MMC demonstrates noticeable improvement in output voltage waveform quality and harmonic reduction compared to the 3-level configuration, validating the effectiveness of increasing converter levels for enhanced HVDC applications.

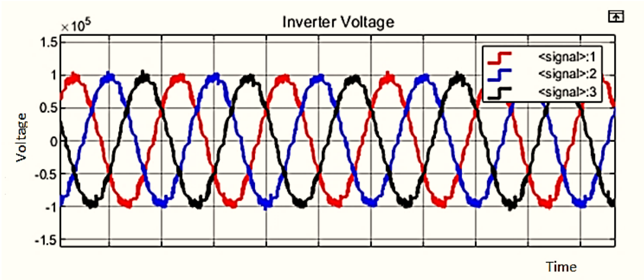


Figure 7 (a): Inverter voltage output

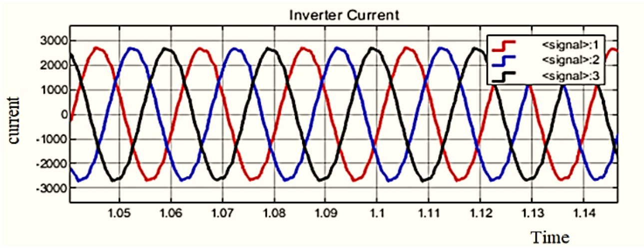


Figure 7 (b): Inverter current output

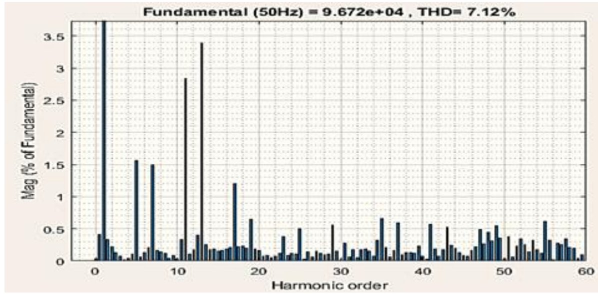


Figure 7 (c): Output total harmonic

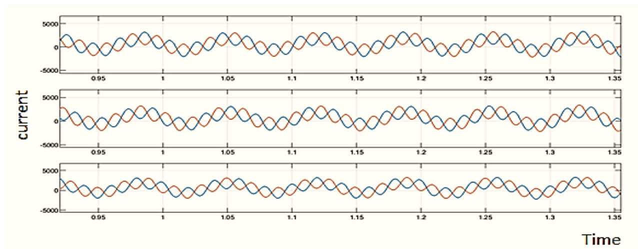


Figure 7 (d): Single phase arm phase current

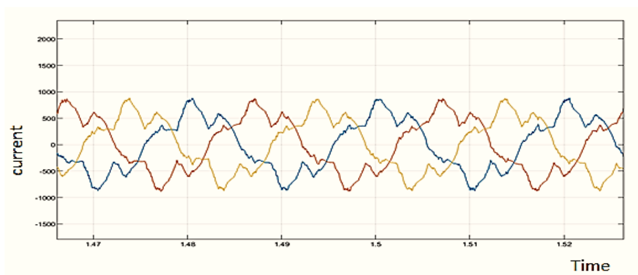


Figure 7 (e): Output circulating current

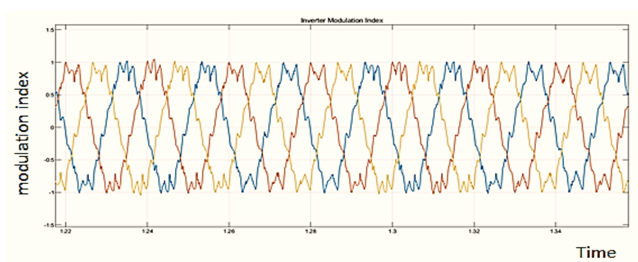


Figure 7 (f) Modulation index

Figure 7 (a-f): Results for 6-level modular multilevel converter

C. Results for 9-level modular multilevel converter

In 9 level MMC, the sub modules were connected in the both arms of MMC. Figure 8(a) shows the output voltage waveforms of a 9 level MMC connected to an 3 phase RL-load, spaced 120^0 apart, these waveform output shows how the converter generates smooth AC voltage than three-level and six level converter's output.

The Figure 8(b) indicates the three-phase waveforms of inverter current of 9 MMC to a three phase R-L load spaced 120^0 apart low distortion through effective modulation. It is clear that as the number of levels increased, the output waveform of current will be smoother as compared to 3 & 6 level converters.

The Figure 8(c) shows single phase arm current output of a nine-level modular multilevel converter. The sinusoidal waveforms shows that the converter is operating in a steady state condition, delivering smooth and periodic current than 3-level and 6-level converters , further the control technique is effectively regulating the arm current ensuring stable performance with minimum distortion in the output.

The Figure 8(d) shows the harmonic distortion analysis of 9 level MMC, where the percentage of harmonics is 2.91% which indicates that waveform has less distortion, as level increased from 3 to 9, the harmonic distortion has decreased up to 4.8%.

The Figure 8(e) indicates the circulating current behavior in the arms of a 9 level MMC , waveforms are smoother as compared to 3-level and 6-level converter , considering the reference sinusoidal waveform which illustrates the involvement of current to help the assess system stability and control to reduce the losses to ensure efficient converter operation.

The Figure 8(f) shows that modulation index behavior of an inverter, by increasing the number of levels from 3-level to 9-level and the output is smoother as compared to 3-level and 6-level converters and it shows that how the inverter adjusts its modulation index dynamically to regulate output voltage. The waveform variations reflect the inverter’s response to changing load or control conditions, helping ensure stable and efficient power conversion.

The results for the 9-level MMC indicate the further reduction in harmonic distortion and smoother voltage waveforms, highlighting the benefits of higher modularity in improving power quality for HVDC applications.

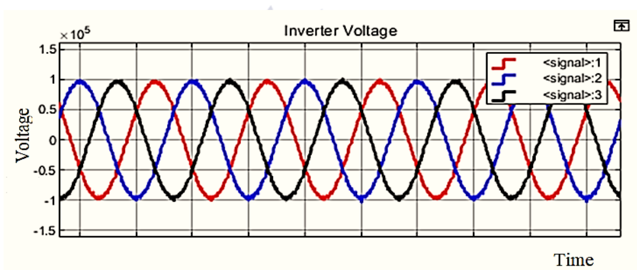


Figure 8 (a): Inverter voltage output

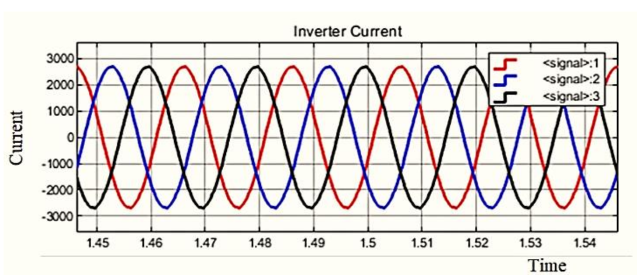


Figure 8 (b): Inverter output current

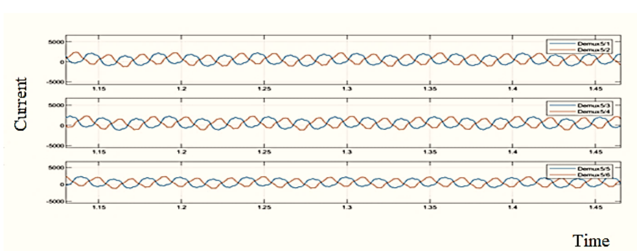


Figure 8 (c): Single phase arm current

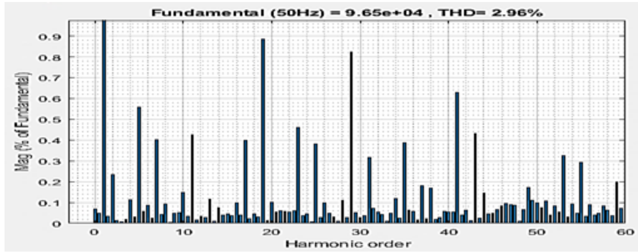


Figure 8 (d): Total harmonic distortion

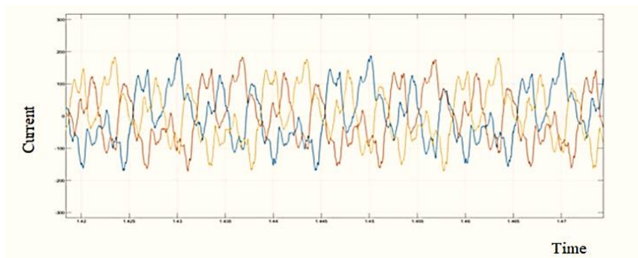


Figure 8 (e): Output of circulating current

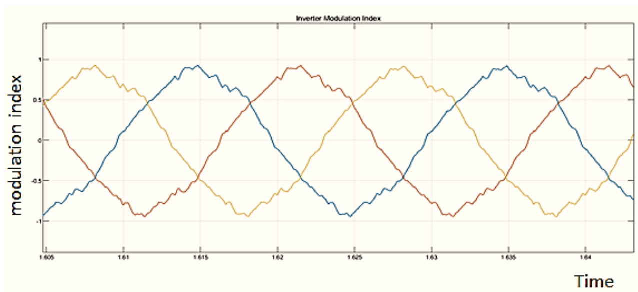


Figure 8 (f): Output of modulation index

Figure 8 (a-f): Results for 9-level modular multilevel converter

Conclusion

This research demonstrates that the Modular Multilevel Converter (MMC) is a highly efficient and scalable solution for modern high-power and HVDC applications. By focusing the constraints of conventional VSC and CSC topologies, as high switching losses, limited scalability, and issue of harmonic distortion, the MMC demonstrates superior substitute for high-voltage systems. The established three-phase MMC model, implemented with half-bridge sub-modules and controlled through Nearest Level Modulation (NLM), attains near-sinusoidal stepped output with low switching frequency, reduced losses, and stable capacitor voltage balancing. Simulation results reveal that NLM is appropriate for converters with increased numbers of sub-modules due to its simplicity, low computational cost and minimized THD without additional filtering. MATLAB/Simulink results revealed the THD below 8% without using filters, meeting IEEE standards. The real-time HIL implementation using OPAL-RT further confirms the practical applicability of the proposed control design under dynamic operating conditions. This this study determines that MMC with its modular structure, excellent harmonic performance, fault tolerance, and flexible scalability , plays an important role in high voltage power applications, making it compatible as a key enabler of future smart and sustainable power transmission systems.

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Data Availability: All the data is available within the manuscript.

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