



(REVIEW ARTICLE)



Review paper on multilevel converters topology for VSC-based HVDC transmission system connected offshore wind power plant

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Abstract

This review paper offers a comprehensive analysis of multilevel converters (MLCs) within Voltage Source Converter (VSC)-based High Voltage Direct Current (HVDC) transmission systems, focusing on their integration with offshore wind power plants. Through an exhaustive exploration, the paper investigates various MLC configurations and control strategies, assessing their potential to enhance the performance, efficiency, and reliability of offshore wind energy integration into the power grid. By examining the intricate interplay between MLCs, VSC-based HVDC systems, and offshore wind power plants, this review aims to provide valuable insights into the evolving landscape of renewable energy integration technologies. Key topics covered include an overview of offshore wind power generation, the significance of HVDC transmission for offshore wind farms, and the role of MLCs in overcoming integration barriers. Furthermore, the paper delves into control strategies, performance evaluation metrics, and future perspectives and challenges. Through its in-depth analysis, this review contributes to a deeper understanding of the potential of MLCs in advancing the efficiency and reliability of VSC-based HVDC systems, ultimately facilitating the seamless integration of offshore wind energy into the broader power grid.

Keywords: Multi Level Converters; Voltage Source Converter; Offshore Wind Power Plant.

1 Introduction

1.1 Overview of offshore wind power generation

Offshore wind power generation stands as a critical frontier in renewable energy, harnessing vast wind resources at sea to produce electricity. Unlike onshore sites, offshore wind farms benefit from stronger and more consistent wind speeds due to fewer terrain obstructions, resulting in higher energy yields and greater reliability. Turbines used in offshore installations are engineered to withstand harsh marine conditions, featuring larger sizes and enhanced durability to capture maximum wind energy.

The installation and maintenance of offshore wind farms involve intricate processes, including seabed surveys, foundation construction, and turbine installation using specialized vessels and equipment. Maintenance poses challenges, requiring trained personnel and specialized vessels to access remote offshore sites for repairs. Grid connection is established through subsea cables linking offshore wind farms to onshore HVDC or AC substations, with HVDC transmission often preferred for its efficiency over long distances[1].

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Despite its environmental benefits, offshore wind power development can impact marine ecosystems, cause noise pollution, and alter coastal landscapes. However, careful planning, environmental assessments, and mitigation measures are employed to minimize these effects. Despite challenges, offshore wind power offers immense potential to meet global renewable energy goals, providing clean electricity while reducing reliance on fossil fuels and mitigating climate change[2].

Technological advancements and cost reductions continue to drive growth in the offshore wind industry, positioning it as a crucial player in the transition to a low-carbon energy future. Through continued innovation and investment, offshore wind power stands poised to play a significant role in achieving sustainable energy systems worldwide. As governments and industries increasingly prioritize renewable energy, offshore wind power represents a key solution for meeting energy demands while reducing greenhouse gas emissions and preserving the environment.

1.2 Importance of HVDC transmission for offshore wind farms

HVDC (High Voltage Direct Current) transmission is crucial for offshore wind farms due to its efficiency and reliability over long distances. Offshore wind farms, often located far from shore to harness optimal wind conditions, require HVDC to transmit electricity with lower losses compared to AC systems. HVDC also ensures stable voltage control, vital for grid stability amidst varying wind conditions.

Integration with onshore grids is seamless with HVDC, offering reliable connections to onshore substations and enhanced controllability for grid operators. Its smaller footprint and reduced environmental impact make HVDC suitable for offshore environments, preserving marine ecosystems and minimizing disturbances[3].

Moreover, HVDC technology enables the expansion of offshore wind farms into deeper waters and more distant locations, unlocking new areas for renewable energy development. This potential expansion is crucial for meeting increasing electricity demand and ambitious renewable energy targets worldwide.

The HVDC transmission plays a vital role in efficiently transporting electricity from offshore wind farms, providing voltage control, facilitating grid integration, minimizing environmental impact, and enabling further expansion of offshore wind energy development. As offshore wind power continues to grow, HVDC remains indispensable for its success in the transition to clean energy[4].

1.3 Significance of multilevel converters in HVDC systems

Multilevel converters (MLCs) play a crucial role in HVDC (High Voltage Direct Current) systems due to their ability to address key challenges and enhance system performance. MLCs offer superior harmonic performance by synthesizing output voltages with multiple levels of DC voltage, resulting in smoother waveforms and reduced harmonic distortion. This feature ensures compliance with grid codes and standards while minimizing electromagnetic interference.

Moreover, MLCs operate at lower switching frequencies compared to traditional converters, leading to reduced switching losses and higher overall system efficiency. This efficiency improvement is essential for HVDC systems, where efficient energy transmission is paramount. Additionally, the improved voltage waveform quality of MLCs enhances system stability and reliability, particularly in long-distance power transmission and integration with sensitive loads[5].

MLCs are inherently scalable and modular, allowing for flexible design and adaptation to varying system requirements. This scalability enables MLC-based HVDC systems to accommodate a wide range of voltage and power levels, making them suitable for diverse applications, from grid-scale transmission to distributed energy resources integration. Furthermore, the modularity of MLCs facilitates easier maintenance and troubleshooting, improving system reliability and uptime.

MLC-based HVDC systems are well-suited for integrating renewable energy sources into the electrical grid. The superior harmonic performance and voltage waveform quality of MLCs ensure smooth integration with fluctuating renewable energy outputs, minimizing grid disturbances and enhancing stability. This compatibility with renewable energy integration is crucial for achieving renewable energy targets and transitioning towards a more sustainable energy future. Overall, MLCs significantly enhance the efficiency, reliability, and performance of HVDC systems, contributing to the advancement of modern power transmission and distribution infrastructures[6].

2 Multilevel Converters Topology

2.1 Brief introduction to multilevel converter topologies

Multilevel converter topologies are essential components in modern power electronics, offering advantages in voltage control, harmonic reduction, and efficiency. Unlike traditional two-level converters, multilevel converters generate multiple output voltage levels using several power semiconductor devices. This allows for finer voltage control and improved waveform quality, making them suitable for various high-power applications, including renewable energy systems, motor drives, and HVDC transmission [7].

Key multilevel converter topologies include the Neutral Point Clamped (NPC), Flying Capacitor (FC), and Cascaded H-Bridge (CHB) converters. The NPC converter utilizes clamping diodes to create additional voltage levels between the DC bus and neutral point, resulting in smoother output waveforms with reduced harmonic distortion. Flying Capacitor converters employ capacitors connected in series to generate multiple voltage levels, offering simplicity and scalability while maintaining good performance. Cascaded H-Bridge converters utilize multiple H-bridge cells connected in series to produce multiple voltage levels, providing flexibility and modularity in system design.

Multilevel converter topologies play a crucial role in modern power electronic systems, enabling precise voltage control, harmonic reduction, and improved efficiency. The choice of topology depends on specific application requirements, including voltage levels, performance criteria, and cost considerations. As power electronics continue to advance, multilevel converter topologies will remain integral components in various high-power applications, driving innovation and efficiency in electrical power systems [8].

2.2 Analysis of various MLC topologies suitable for VSC-based HVDC systems

Various multilevel converter (MLC) topologies are suitable for Voltage Source Converter (VSC)-based High Voltage Direct Current (HVDC) systems, each offering unique advantages and challenges. Here's an analysis of some commonly used MLC topologies in VSC-based HVDC systems[9-11]:

2.2.1 Neutral Point Clamped (NPC) Converter

Advantages: Provides excellent voltage waveform quality with reduced harmonic distortion. Offers high reliability and low switching losses.

Challenges: Requires a larger number of power semiconductor devices, leading to higher cost and complexity. Voltage balancing issues may arise, especially in higher voltage levels.

2.2.2 Flying Capacitor (FC) Converter

Advantages: Offers scalability and modularity, making it suitable for various voltage levels and power ratings. Provides good performance with relatively fewer power semiconductor devices.

Challenges: Requires careful capacitor voltage balancing to prevent voltage imbalance issues. May suffer from increased complexity in larger systems.

2.2.3 Cascaded H-Bridge (CHB) Converter

Advantages: Provides excellent scalability and modularity, allowing for flexible system design and easy expansion. Offers good performance with reduced harmonic distortion.

Challenges: Requires a large number of H-bridge cells, leading to increased system complexity and cost. Voltage balancing among H-bridge cells is critical to ensure proper operation.

2.2.4 Modular Multilevel Converter (MMC)

Advantages: Offers high scalability, modularity, and fault tolerance. Provides superior performance with reduced harmonic distortion and improved efficiency.

Challenges: Requires sophisticated control algorithms to manage submodule capacitor voltages and ensure proper operation. May suffer from increased complexity and cost in larger systems.

2.2.5 Hybrid Multilevel Converter (HMC):

Advantages: Combines features of different MLC topologies to achieve optimal performance. Offers scalability, modularity, and fault tolerance.

Challenges: Requires careful design and control to integrate different converter topologies effectively. May involve increased complexity and cost compared to single-topology converters.

2.2.6 *Stacked Multilevel Converter (SMC):*

Advantages: Provides a simple and compact design with fewer power semiconductor devices compared to other MLC topologies. Offers good performance with reduced harmonic distortion.

Challenges: Limited scalability and modularity may restrict its application in larger HVDC systems. Voltage balancing among stacked levels is critical for proper operation.

2.2.7 *Diode-Clamped Multilevel Converter (DCMC):*

Advantages: Offers a simpler and more cost-effective alternative to other MLC topologies. Provides good performance with reduced harmonic distortion and improved efficiency.

Challenges: Limited scalability and modularity compared to other MLC topologies. Requires careful design to ensure proper diode-clamping operation and voltage balancing.

2.2.8 *Resonant Switched-Capacitor Multilevel Converter (RSCMC):*

Advantages: Utilizes resonant switching techniques to reduce switching losses and improve converter efficiency. Offers good performance with reduced harmonic distortion.

Challenges: Requires precise control of resonant switching to maintain proper operation. Limited scalability and modularity compared to other MLC topologies.

Each MLC topology offers specific advantages and challenges in VSC-based HVDC systems. The choice of topology depends on various factors, including system requirements, performance criteria, cost considerations, and scalability needs. Careful analysis and simulation studies are essential to select the most suitable MLC topology for a particular HVDC application, considering both technical and economic aspects.

3 Control Strategies for Multilevel Converters

Control strategies play a crucial role in ensuring the efficient and reliable operation of multilevel converters (MLCs) in various applications, including Voltage Source Converter (VSC)-based High Voltage Direct Current (HVDC) systems. Here are some common control strategies used for MLCs [11-13]:

3.1 Pulse Width Modulation (PWM)

PWM is a fundamental control strategy used in MLCs to generate the desired output voltage waveform by modulating the switching of semiconductor devices. In PWM control, the duty cycle of the switching signals is adjusted to regulate the output voltage magnitude and frequency. Different PWM techniques, such as carrier-based PWM, space vector PWM, and selective harmonic elimination PWM, are employed to achieve specific performance objectives, including reduced harmonic distortion and improved efficiency. The PWM techniques available in literature are shown in Figure1.

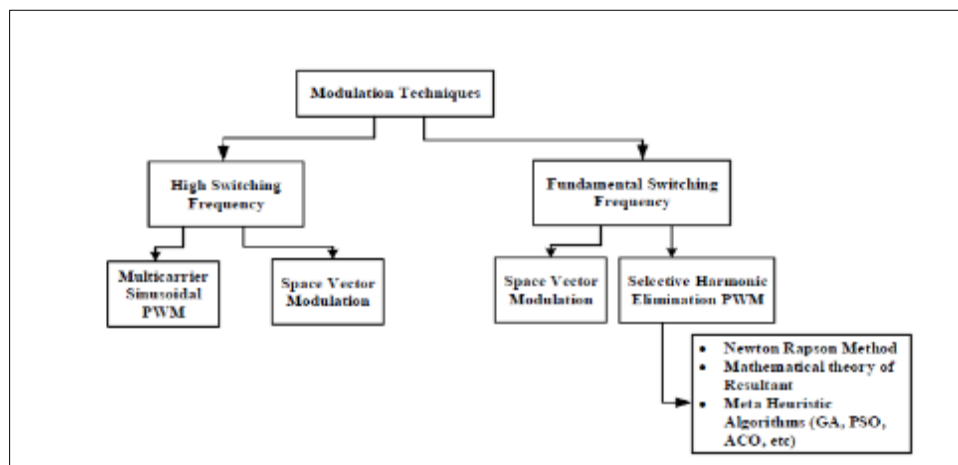


Figure 1 PWM techniques for the control of MLCs.

3.2 Voltage Balancing Control

Voltage balancing control is vital for MLCs to maintain uniform voltage distribution across cells or submodules. It addresses voltage imbalances stemming from component disparities or load variations, ensuring system reliability. Various strategies, such as voltage feedback, capacitor balancing, and phase-shift control, are employed to achieve balance. Implemented through digital control algorithms, voltage balancing adjusts submodule switching patterns based on voltage feedback, enhancing system efficiency and power quality. Challenges like computational complexity persist, but effective voltage balancing improves MLC performance, reducing stress on components and enabling their use in high-voltage applications. By ensuring consistent operation and mitigating voltage disparities, voltage balancing control enhances system longevity and reliability, making MLCs viable for diverse power electronic applications. As MLCs continue to advance, further research into voltage balancing strategies promises even greater efficiency and reliability, driving the adoption of multilevel converters in modern power systems.

3.3 Current Control

Current control is a pivotal aspect of multilevel converters (MLCs), ensuring precise regulation of output currents in various power electronic applications, including Voltage Source Converter (VSC)-based High Voltage Direct Current (HVDC) systems. The primary objective of current control is to accurately track reference currents, facilitating stable operation, optimal power delivery, and adherence to performance requirements. Common control strategies for current regulation in MLCs encompass Proportional-Integral (PI) control, Predictive Control, and Hysteresis Control. PI controllers adjust switching signals based on the difference between actual and reference currents, minimizing steady-state errors for stable operation. Predictive control techniques utilize system models and predictive algorithms to anticipate future system behavior, offering faster response and improved dynamic performance. Hysteresis controllers impose upper and lower bounds on output currents, triggering switching events to maintain currents within these bounds, although this approach may increase switching frequency and losses.

Implementation of current control algorithms typically involves digital signal processors (DSPs), microcontrollers, or field-programmable gate arrays (FPGAs). These controllers receive feedback signals from current sensors or measurement circuits, computing control signals to regulate the converter's operation accurately. In HVDC systems, precise current control is paramount for regulating power flow, ensuring grid stability, and maintaining reliable operation over extended distances. Current control in MLCs is indispensable for HVDC transmission, where accurate current regulation enables efficient power transfer and mitigates grid disturbances[14].

Current control in MLCs plays a vital role in achieving stable operation, optimal power delivery, and adherence to performance requirements in various power electronic applications, particularly in HVDC systems. Ongoing advancements in control algorithms and hardware technologies continue to enhance the efficiency, reliability, and versatility of current control strategies in MLCs.

3.4 Grid Synchronization and Power Quality Control

Grid synchronization and power quality control are essential functionalities in MLCs, particularly in applications like Voltage Source Converter (VSC)-based High Voltage Direct Current (HVDC) systems. Grid synchronization ensures that the output voltage of the MLC is synchronized with the grid voltage, crucial for seamless integration with the electrical grid. Various methods, such as phase-locked loop (PLL) or zero crossing detection, are employed to achieve accurate grid synchronization by detecting grid voltage phase and frequency[15-19].

Power quality control focuses on improving the quality of the MLC's output voltage waveform, minimizing harmonic distortion, voltage fluctuations, and other power quality issues. Active power filters, or shunt compensators, inject compensating currents to cancel out harmonic currents and correct voltage deviations. Additionally, reactive power compensation techniques regulate reactive power exchange between the MLC and the grid, improving power factor and voltage stability. Implementation of these functions involves advanced control algorithms running on digital signal processors (DSPs) or microcontrollers. These algorithms receive feedback from grid voltage and current sensors, computing control signals to adjust the converter's operation. Real-time monitoring and adaptive control techniques dynamically adjust control parameters based on changing grid conditions, ensuring robust grid synchronization and power quality control.

Grid synchronization and power quality control enhance the stability, reliability, and efficiency of MLC-based systems, ensuring seamless integration with the grid and compliance with regulatory requirements. Improved power quality minimizes grid disturbances, reduces equipment wear, and enhances the overall performance of electrical networks,

benefiting utilities and end-users alike. Advanced control algorithms and real-time monitoring techniques continue to enhance the effectiveness and reliability of these functions in MLC-based power electronic systems.

3.5 Fault Detection and Protection

Fault detection and protection are essential functionalities in MLCs, ensuring the safe and reliable operation of power electronic systems, including Voltage Source Converter (VSC)-based High Voltage Direct Current (HVDC) systems. Fault detection involves identifying abnormal operating conditions or faults within the MLC or the connected power system, such as short circuits, overvoltage, or overcurrent events. Various techniques, including waveform monitoring, parameter analysis, and diagnostic algorithms, are employed to detect and localize faults quickly and accurately. These methods aim to minimize downtime and prevent damage to equipment by initiating timely corrective actions[2].

Fault protection measures are implemented to isolate or mitigate the effects of detected faults, safeguarding the MLC and the connected power system. Protective devices such as fuses, circuit breakers, relays, and semiconductor protection devices are employed to detect and respond to faults effectively. These devices are triggered based on predefined threshold levels or fault detection signals, initiating protective actions to prevent further damage and ensure system reliability. Implementation of fault detection and protection functions involves a combination of hardware and software components, including digital signal processors (DSPs), microcontrollers, and specialized protection relays. Advanced fault detection algorithms, fault-tolerant control strategies, and real-time monitoring systems are employed to enhance the reliability and effectiveness of fault detection and protection in MLCs[6].

Fault detection and protection mechanisms play a crucial role in ensuring the safe and reliable operation of MLC-based power systems, minimizing downtime, preventing equipment damage, and enhancing system resilience in diverse power electronic applications, including HVDC systems. Continued advancements in fault detection algorithms and protective devices further improve the reliability and resilience of MLC-based power systems.

Control strategies for MLCs are diverse and tailored to specific application requirements, including voltage regulation, current control, grid synchronization, power quality improvement, and fault detection. Advanced control algorithms and techniques are continuously developed to further enhance the performance, efficiency, and reliability of MLC-based power electronic systems.

4 Performance Evaluation

Performance evaluation of multilevel converters (MLCs) involves assessing various key aspects, including efficiency, harmonic distortion mitigation, grid stability, power quality, and fault ride-through capability. Here's an overview of each aspect:

4.1 Efficiency Analysis

Efficiency analysis is pivotal in evaluating the performance of MLCs within power electronic systems. It involves scrutinizing the energy conversion efficiency of the converter, directly influencing system performance and operational costs. Initially, efficiency analysis encompasses input-output power assessment by monitoring parameters such as input voltage, current, and output power. This enables calculation of the converter's efficiency by comparing input and output power, indicating the proportion of input power effectively converted to useful output power[5].

Further, efficiency analysis delves into loss identification and quantification, addressing sources like semiconductor switching losses, conduction losses, and losses from passive components. These analyses provide insights into areas for optimization to enhance overall efficiency. Efficiency calculations are crucial for assessing the converter's performance quantitatively, guiding the development of optimization strategies. Optimization may involve refining control algorithms, implementing advanced modulation techniques to reduce switching losses, improving thermal management, and selecting high-efficiency components.

Efficiency analysis is typically conducted through laboratory testing, validating the converter's performance across various operating conditions. Real-world testing ensures accuracy in efficiency calculations and evaluates performance under diverse load conditions and operational scenarios. By optimizing efficiency, MLCs contribute to energy savings, reduced operational costs, and enhanced sustainability in power electronic systems. The insights gained from efficiency analysis enable engineers to refine converter designs, ensuring optimal performance and reliability in practical applications[1].

4.2 Harmonic Distortion Mitigation

Harmonic distortion mitigation is essential for MLCs to ensure high-quality power delivery and compliance with grid codes and standards. These converters generate smooth output voltage waveforms by employing advanced modulation techniques and filtering methods to reduce unwanted harmonic components. PWM techniques play a central role in harmonic distortion mitigation in MLCs. By controlling the width of the switching pulses, PWM methods such as sinusoidal PWM (SPWM) and space vector modulation (SVM) shape the output voltage waveform to minimize harmonic content. Additionally, selective harmonic elimination (SHE) techniques selectively eliminate specific harmonics by intelligently choosing the switching states of the converter cells, further reducing distortion.

Phase-shifted PWM introduces phase shifts between the switching signals of the converter cells, distributing harmonic content across multiple frequencies. This technique helps to spread out harmonic components in the output voltage waveform, reducing peak harmonic magnitudes and minimizing distortion. In addition to modulation techniques, filtering methods are employed to attenuate harmonic components in the output voltage waveform. Passive filters, such as LC filters and notch filters, selectively attenuate specific harmonics, while active filters, such as active power filters (APFs), inject compensating currents to cancel out harmonic currents, thereby mitigating distortion effectively. Harmonic distortion mitigation involves evaluating the effectiveness of mitigation techniques through harmonic analysis, waveform measurements, and compliance assessments with grid codes and standards. Optimization of PWM strategies, filter design parameters, and control algorithms is performed to achieve optimal harmonic mitigation while minimizing system complexity and cost[8].

Overall, harmonic distortion mitigation in MLCs ensures high-quality power delivery, minimizes grid disturbances, and enhances the reliability of power electronic systems. Ongoing advancements in modulation techniques, filtering technologies, and control strategies continue to improve the effectiveness of harmonic distortion mitigation in MLC-based power systems.

4.3 Grid Stability and Power Quality

Grid stability and power quality are paramount considerations in the assessment of MLCs within power electronic systems, particularly in applications like Voltage Source Converter (VSC)-based HVDC systems. Grid stability encompasses the ability of the electrical grid to maintain synchronous operation and withstand disturbances without experiencing unacceptable voltage or frequency deviations. MLCs play a vital role in enhancing grid stability by providing fast and accurate control over voltage and reactive power flow. Through control strategies such as voltage regulation, reactive power compensation, and grid synchronization, MLCs contribute to stabilizing grid operation and maintaining voltage and frequency within specified tolerances. These strategies, coupled with advanced control algorithms and real-time monitoring systems, enable MLCs to detect and respond promptly to grid disturbances, ensuring uninterrupted and stable power transmission[9].

Power quality, on the other hand, refers to the consistency and reliability of electrical power supplied to end-users. MLCs influence power quality by generating high-quality output voltage waveforms with minimal distortion and maintaining voltage levels within specified limits. Harmonic distortion mitigation techniques, including pulse width modulation (PWM), selective harmonic elimination (SHE), and filtering methods, are employed in MLCs to minimize harmonic content in the output voltage waveform, ensuring compliance with grid codes and standards. Additionally, reactive power compensation and voltage regulation strategies help improve power factor, stabilize voltage levels, and mitigate voltage fluctuations, thereby enhancing power quality for downstream loads.

Overall, grid stability and power quality are critical aspects of MLC performance, ensuring reliable and efficient operation of power electronic systems. By implementing advanced control strategies and mitigation techniques, MLCs contribute to grid stability and power quality improvement, supporting the integration of renewable energy sources and enhancing the resilience of electrical grids.

4.4 Fault Ride-Through Capability

Fault ride-through capability is crucial for multilevel converters (MLCs) to withstand and remain operational during grid faults or disturbances, ensuring continuous power transmission and grid stability. In applications such as Voltage Source Converter (VSC)-based High Voltage Direct Current (HVDC) systems, fault ride-through capability is essential for maintaining reliable power delivery and preventing system instability. MLCs employ various response mechanisms to ride through grid faults and disturbances effectively. This begins with the timely detection and isolation of grid faults through advanced fault detection algorithms. These algorithms monitor grid parameters such as voltage, current, and

frequency to identify abnormal conditions indicative of grid faults. Once detected, the fault is isolated to prevent further propagation and minimize its impact on the system[6].

Protective measures are implemented in MLCs to mitigate the effects of grid faults and disturbances and ensure safe and reliable operation. Protective devices such as circuit breakers, relays, and semiconductor protection devices interrupt fault currents, isolate faulty components, and prevent damage to the converter and connected equipment. Control strategies play a crucial role in maintaining system stability and ride-through capability during grid faults. MLCs employ fault-tolerant control algorithms, voltage and current control strategies, and grid synchronization techniques to regulate power flow and stabilize grid operation during fault conditions. These control strategies help to minimize disturbances and ensure seamless transition to normal operation once the fault is cleared.

Overall, fault ride-through capability is essential for ensuring the reliability and resilience of MLC-based power electronic systems. By implementing robust fault detection, protective measures, and control strategies, MLCs can withstand grid faults and disturbances, minimize downtime, and maintain grid stability, contributing to the overall reliability of electrical networks.

5 Advantages and Challenges

5.1 Advantages of Multilevel Converters

Multilevel converters (MLCs) offer several advantages in power electronic systems, making them suitable for various applications. Some of the key advantages include:

- **Improved Efficiency:** MLCs exhibit lower switching losses compared to traditional two-level converters, resulting in higher overall system efficiency. The ability to synthesize output voltages using multiple levels of DC voltage allows MLCs to operate more efficiently, particularly at high voltage and power levels.
- **Reduced Harmonic Distortion:** MLCs produce smoother output voltage waveforms with reduced harmonic content compared to two-level converters. This characteristic is advantageous in applications requiring high-quality power delivery, such as grid-connected renewable energy systems and high-power motor drives.
- **Modularity and Scalability:** MLCs are inherently modular and scalable, allowing for flexible design and adaptation to varying system requirements. This modularity enables easy expansion or modification of the converter topology to accommodate changes in voltage or power levels, making MLCs suitable for diverse applications.
- **Lower Electromagnetic Interference:** Due to their ability to generate low-distortion output waveforms, MLCs exhibit reduced electromagnetic interference (EMI) compared to traditional converters. This advantage is crucial in applications sensitive to EMI, such as telecommunications and medical equipment.
- **Voltage Handling Capability:** MLCs can handle higher voltage levels compared to two-level converters, making them suitable for high-voltage applications such as HVDC transmission systems and grid-connected renewable energy installations.

5.2 Challenges and Limitations

Despite their numerous advantages, multilevel converters also face several challenges and limitations:

- **Complexity and Cost:** The increased number of power semiconductor devices and control circuits in MLCs results in higher complexity and manufacturing costs compared to traditional converters. This complexity can pose challenges in design, implementation, and maintenance, particularly for large-scale systems.
- **Voltage Balancing:** Achieving voltage balance among the multiple levels of the converter poses a significant challenge, especially in cascaded H-bridge topologies. Voltage imbalances can lead to unequal sharing of power among the converter cells, reducing overall efficiency and reliability.
- **Switching Losses:** While MLCs exhibit lower switching losses compared to two-level converters, they still incur losses due to switching transitions. Managing these losses becomes critical, especially at high switching frequencies, to maintain efficiency and reliability.
- **Control Complexity:** Implementing control algorithms for MLCs requires sophisticated techniques to manage multiple levels, ensuring accurate voltage regulation and harmonic mitigation. This control complexity adds to the design and computational overhead, requiring advanced control strategies and real-time processing capabilities.

- **Fault Management:** Detecting and managing faults in MLCs can be challenging due to the presence of multiple power semiconductor devices and control circuits. Developing robust fault detection and protection mechanisms is essential to ensure safe and reliable operation of MLC-based systems.

6 Case Studies and Real-World Applications

6.1 Offshore Wind Power Projects with VSC-HVDC Systems

Offshore wind power projects employing Voltage Source Converter-based High Voltage Direct Current (VSC-HVDC) systems are increasingly prevalent due to their ability to efficiently transmit electricity from remote offshore wind farms to onshore grids. These projects demonstrate the significant role of VSC-HVDC systems, facilitated by multilevel converters (MLCs), in enabling the integration of offshore wind energy into the electrical grid. Here are examples of notable offshore wind power projects utilizing VSC-HVDC systems:

6.1.1 Hornsea Project One (UK)

Located off the coast of Yorkshire, UK, Hornsea Project One is the world's largest offshore wind farm. It utilizes a VSC-HVDC transmission system to connect the wind farm to the onshore grid. The VSC-HVDC system, equipped with MLCs, ensures efficient and stable power transmission over long distances, overcoming challenges associated with grid connection and variable wind conditions. With a total capacity of 1.2 gigawatts (GW), Hornsea Project One contributes significantly to the UK's renewable energy targets and reduces reliance on fossil fuels for electricity generation.

6.1.2 DolWin6 (Germany)

DolWin6 is a major offshore wind power project in the North Sea, off the coast of Germany. It involves the construction of a VSC-HVDC transmission system to connect offshore wind farms to the mainland grid. The VSC-HVDC system, incorporating MLCs, enables reliable and high-capacity power transmission from offshore wind installations to the onshore grid, supporting Germany's transition to renewable energy. DolWin6 plays a crucial role in harnessing the abundant wind resources in the North Sea and delivering clean energy to meet growing electricity demand in Germany.

6.1.3 Borssele Wind Farm (Netherlands)

Borssele Wind Farm, located in the Dutch North Sea, is another example of an offshore wind power project utilizing VSC-HVDC technology for grid connection. The VSC-HVDC system, featuring MLCs, facilitates efficient and stable power transmission from the wind farm to the Dutch mainland grid, contributing to the Netherlands' renewable energy goals and carbon reduction targets. Borssele Wind Farm demonstrates the scalability and reliability of VSC-HVDC systems with MLCs in supporting the expansion of offshore wind energy capacity.

These offshore wind power projects highlight the importance of VSC-HVDC systems, supported by multilevel converters, in enabling the integration of offshore wind energy into the grid. By leveraging advanced transmission technologies, these projects contribute to the decarbonization of the energy sector and the transition to a more sustainable energy future.

6.2 Comparative Studies with Conventional Converters

Comparative studies between multilevel converters (MLCs) and conventional converters provide valuable insights into the performance differences and advantages of MLCs in various applications. These studies evaluate factors such as efficiency, harmonic distortion, voltage regulation, and reliability under different operating conditions. Here are examples of comparative studies with conventional converters:

6.2.1 Efficiency Comparison:

- Researchers conduct comparative studies to evaluate the efficiency of MLC-based converters compared to conventional converters, such as two-level voltage source converters (VSCs) or line-commutated converters (LCCs).
- These studies typically involve simulations or experimental tests under different load conditions and operating voltages to measure the efficiency of each converter topology.
- Results often show that MLC-based converters exhibit higher efficiency, particularly at higher voltage levels and power ratings, due to reduced switching losses and improved utilization of power semiconductor devices.

6.2.2 *Harmonic Distortion Analysis:*

- Comparative studies focus on assessing the harmonic distortion performance of MLCs versus conventional converters.
- Researchers analyze the harmonic content in the output voltage waveform generated by each converter topology under various operating conditions.
- Findings demonstrate that MLCs offer superior harmonic performance, with lower total harmonic distortion (THD) levels and reduced voltage distortion compared to conventional converters. This advantage is crucial in applications requiring high-quality power delivery and compliance with grid codes and standards.

6.2.3 *Voltage Regulation and Dynamic Response:*

- Comparative studies examine the voltage regulation capabilities and dynamic response of MLC-based converters compared to conventional converters.
- Researchers evaluate the ability of each converter topology to maintain stable output voltage levels and respond to load changes and grid disturbances.
- Results indicate that MLCs provide better voltage regulation and faster dynamic response, particularly in grid-connected renewable energy systems and high-power motor drives, where precise voltage control is essential.

6.2.4 *Reliability and Fault Tolerance:*

- Comparative studies assess the reliability and fault tolerance of MLCs versus conventional converters under different fault conditions.
- Researchers investigate the ability of each converter topology to withstand and recover from grid faults, such as short circuits or voltage dips, without tripping offline or causing system instability.
- Findings demonstrate that MLC-based converters exhibit enhanced fault ride-through capability and reliability compared to conventional converters, ensuring uninterrupted operation and grid stability during fault conditions.

Overall, comparative studies with conventional converters provide valuable insights into the performance advantages and capabilities of multilevel converters (MLCs) in power electronic systems. By evaluating factors such as efficiency, harmonic distortion, voltage regulation, and reliability, these studies contribute to the optimization and advancement of MLC technology for various applications.

6.3 Performance Assessment in Different Operating Conditions

Performance assessment of multilevel converters (MLCs) in various operating conditions is essential to understand their behavior and capabilities under different scenarios. These assessments provide valuable insights into the reliability, efficiency, and effectiveness of MLC-based power electronic systems. Here's an overview of performance assessments in different operating conditions:

6.3.1 *Steady-State Operation*

- Performance assessments in steady-state operating conditions involve evaluating MLC behavior under constant load and voltage conditions.
- Researchers analyze parameters such as efficiency, voltage regulation, and harmonic distortion to assess the steady-state performance of MLC-based converters.
- These assessments help identify the optimal operating points and efficiency levels of MLCs under typical load profiles and voltage conditions.

6.3.2 *Transient Operation:*

- Transient performance assessments focus on analyzing MLC behavior during dynamic events such as load changes, grid disturbances, and transient faults.
- Researchers investigate the dynamic response of MLC-based converters, including voltage regulation, response time, and stability during transient conditions.
- These assessments help ensure that MLCs can effectively respond to sudden changes in load demand or grid conditions without causing instability or voltage fluctuations.

6.3.3 Variable Operating Conditions:

- Performance assessments under variable operating conditions involve evaluating MLC behavior across a range of load profiles, voltage levels, and environmental factors.
- Researchers study how MLC performance varies under different operating conditions, such as varying load levels, grid voltage fluctuations, and temperature changes.
- These assessments help determine the robustness and adaptability of MLC-based converters to real-world operating environments and ensure reliable performance under diverse conditions.

6.3.4 Fault Conditions

- Performance assessments under fault conditions involve analyzing MLC behavior during grid faults, short circuits, and other fault events.
- Researchers investigate the fault ride-through capability, fault detection, and fault recovery capabilities of MLC-based converters.
- These assessments help assess the reliability and resilience of MLCs under adverse grid conditions and ensure uninterrupted operation during fault events.

6.3.5 Environmental Factors

- Performance assessments also consider the impact of environmental factors such as temperature, humidity, and altitude on MLC performance.
- Researchers study how environmental conditions affect MLC efficiency, reliability, and lifespan, ensuring that MLC-based converters can operate effectively in various environmental conditions.

Overall, performance assessments in different operating conditions provide comprehensive insights into the behavior and capabilities of multilevel converters (MLCs), enabling optimization and improvement of MLC-based power electronic systems for diverse applications.

7 Recent Developments and Future Directions

7.1 Semiconductor Device Innovations

Recent developments in semiconductor device technologies have significant implications for multilevel converters (MLCs). Innovations in power semiconductor devices, such as silicon carbide (SiC) and gallium nitride (GaN), offer higher switching frequencies, lower conduction losses, and improved thermal performance compared to traditional silicon-based devices. These advancements enable MLCs to achieve higher efficiency, power density, and reliability. Additionally, the integration of wide-bandgap semiconductors like SiC and GaN into MLC designs reduces the size, weight, and cost of MLC-based power electronic systems. Future directions in semiconductor device innovations for MLCs include further improving device performance, increasing voltage and current ratings, and enhancing reliability to meet the evolving requirements of power electronic applications.

7.2 Control Strategy Enhancements

Advancements in control strategies play a crucial role in enhancing the performance and functionality of multilevel converters (MLCs). Recent developments focus on advanced control algorithms, modulation techniques, and predictive control methods to optimize MLC operation under various operating conditions. These enhancements enable MLCs to achieve higher efficiency, faster dynamic response, and improved voltage regulation. Additionally, adaptive and intelligent control strategies enhance MLC reliability, fault tolerance, and grid integration capabilities. Future directions in control strategy enhancements for MLCs include the development of distributed control architectures, real-time optimization algorithms, and machine learning-based control techniques to further enhance MLC performance and adaptability to dynamic grid conditions.

7.3 Integration with Energy Storage Systems

The integration of multilevel converters (MLCs) with energy storage systems (ESS) presents new opportunities for enhancing grid stability, flexibility, and reliability. Recent developments focus on optimizing MLC-ESS integration to support renewable energy integration, grid ancillary services, and microgrid applications. MLCs enable bidirectional power flow and seamless integration with various energy storage technologies, including lithium-ion batteries, supercapacitors, and flywheel systems. Enhanced control strategies enable MLC-ESS systems to provide grid support services such as frequency regulation, voltage support, and peak shaving. Future directions in MLC-ESS integration

include optimizing energy management algorithms, enhancing system efficiency, and exploring new energy storage technologies to further improve grid resilience and sustainability[19].

7.4 Impact of Emerging Technologies (SiC and GaN)

The emergence of wide-bandgap semiconductor technologies such as silicon carbide (SiC) and gallium nitride (GaN) has a profound impact on the design and performance of multilevel converters (MLCs). SiC and GaN devices offer higher switching speeds, lower conduction losses, and higher temperature tolerance compared to traditional silicon-based devices, enabling MLCs to operate at higher frequencies and voltages with improved efficiency and power density. The adoption of SiC and GaN devices in MLC designs results in smaller, lighter, and more efficient power electronic systems with enhanced reliability and thermal management. Future directions in the use of SiC and GaN technologies in MLCs include further reducing device costs, improving manufacturing processes, and expanding device voltage and current ratings to enable broader adoption in various power electronic applications.

8 Conclusion

8.1 Summary of Key Findings

Throughout this review, we have explored the significance of multilevel converters (MLCs) in Voltage Source Converter-based High Voltage Direct Current (VSC-HVDC) systems for offshore wind power integration. Key findings include the superior efficiency, reduced harmonic distortion, and enhanced voltage regulation capabilities of MLCs compared to conventional converters. Control strategy enhancements, semiconductor device innovations, and integration with energy storage systems have further advanced the performance and functionality of MLC-based converters. Additionally, the emergence of wide-bandgap semiconductor technologies like silicon carbide (SiC) and gallium nitride (GaN) has significantly impacted MLC design and performance, enabling higher efficiency and power density.

8.2 Implications for Offshore Wind Power Integration

The implications of MLCs for offshore wind power integration are profound. MLC-based VSC-HVDC systems offer efficient, reliable, and grid-friendly solutions for transmitting electricity from offshore wind farms to onshore grids. The superior harmonic performance and voltage regulation capabilities of MLCs ensure stable and high-quality power delivery, essential for integrating variable renewable energy sources into the grid. Additionally, MLC-ESS integration enhances grid stability and flexibility, enabling offshore wind power projects to provide ancillary grid services and support the transition to a more sustainable energy future.

8.3 Recommendations for Future Research

As we look to the future, several areas warrant further research to advance MLC technology and its applications in offshore wind power integration:

- Continued development of semiconductor device technologies, such as SiC and GaN, to improve efficiency, reliability, and cost-effectiveness.
- Exploration of advanced control strategies and optimization algorithms to enhance MLC performance under dynamic grid conditions.
- Further investigation into MLC-ESS integration to optimize energy management and grid support capabilities.
- Collaboration between industry stakeholders, researchers, and policymakers to address regulatory and standardization challenges and facilitate the widespread adoption of MLC-based VSC-HVDC systems for offshore wind power integration.

By addressing these research priorities, we can unlock the full potential of multilevel converters in enabling the efficient, reliable, and sustainable integration of offshore wind power into the global energy landscape.

Compliance with ethical standards

Disclosure of Conflict of interest

No conflict of interest to report.

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