Research on the Suppression of Switching Losses in Multilevel Converters

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Abstract. Multilevel converters (MLCs) have been widely applied in fields such as high-voltage direct current (HVDC) transmission, electric vehicles, and wind power generation due to their advantages in improving power quality, reducing harmonics, and high-power applications. However, due to the influence of switching losses on system efficiency and thermal management, how to effectively suppress switching losses has always been a hot research topic. This paper reviews the research progress of switching loss suppression in multilevel converters in recent years, focusing on the following aspects: firstly, reducing switching losses by optimizing switching frequency and control strategy, such as low-frequency modulation technology and repetitive control; secondly, the proposal of new converter topology structures, such as modular multilevel converter (MMC) and hybrid multilevel converter (Hybrid MLC); thirdly, the combination of switching loss suppression methods and current circulation control techniques. Finally, this paper summarizes the challenges in current research and outlines the future research trends in switching loss optimization of multilevel converters.

Keywords: Multi-Level Converter, High-Voltage Direct Current Transmission, Optimized Switching Frequency, Topology Structure, Current-Loop Control Technology

1 Introduction

With the rapid development of power electronics technology, multilevel converter (MLC) has been widely used because of its ability to effectively reduce harmonics and improve power transmission quality. Compared with traditional two-level converters, multilevel converters can achieve smoother voltage waveform by providing more voltage steps, thus significantly reducing harmonics and improving the power factor of the system, which makes multilevel converters have obvious advantages in high-power and high-voltage applications, especially for efficient conversion of DC and AC current [1, 2]. However, although multilevel converters have many advantages, their high-frequency switching loss is always one of the key factors restricting their performance. Switching loss not only directly affects the energy efficiency of the converter but also

J. Iqbal (ed.), *Proceedings of the 2025 2nd International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2025)*, Advances in Engineering Research 272,
https://doi.org/10.2991/978-94-6463-821-9_14

affects the thermal management and reliability of the equipment. Therefore, how to effectively suppress the switching loss and improve the efficiency of the converter has become the focus of current research.

Switching loss suppression methods of multilevel converters mainly include: first, reducing switching frequency by optimizing switching frequency and control strategy, such as low-frequency modulation technology [3]. The second is to adopt a new converter topology, such as a modular multilevel converter (MMC), whose modular design makes the switching frequency of each module low, which can effectively reduce the switching loss [4]. The third is to reduce the additional loss caused by the asymmetry between modules through the circulation current control technology [5]. In addition, with the progress of control strategies in recent years, advanced control methods such as model predictive control (MPC) and repetitive control have also been proposed to optimize the switching loss of multilevel converters [6].

In this paper, the research progress of switching loss suppression in multilevel converters in recent years is reviewed, with emphasis on several main technical methods and their application effects. The purpose of this paper is to provide a theoretical basis and technical reference for the performance optimization of multilevel converters in the future by combining and analyzing the switching loss suppression technology.

2 Research Progress

In recent years, many methods and strategies have been proposed to suppress the switching loss of multilevel converters. These methods can be roughly classified into the following categories: low-frequency modulation strategy, topology optimization design, switching control technology, cyclic current suppression, and comprehensive optimization control. In these studies, various methods complement each other and provide solutions for the reduction of switching losses.

2.1 Low-frequency modulation and optimal control strategy

Low-frequency modulation technology reduces switching losses by using a lower switching frequency in the converter. By reducing the switching frequency, not only the number of switching times of each switching element can be reduced, but also the generation of high-frequency harmonics can be reduced. In traditional high-frequency modulation, each switch brings a change in voltage and current, which produces a large loss at high frequencies. The formula for switching loss is as follows:

$$P_{sw} = \frac{1}{2} V_{DC} I_{DC} (f_{sw} t_{sw})$$

Among them, P_{sw} is the switching loss, V_{DC} is the DC voltage, I_{DC} is the DC current, f_{sw} is the switching frequency, t_{sw} is the switching time. In low-frequency modulation, the switching frequency f_{sw} is reduced, thus reducing the number of switches and switching losses per cycle.

The low-frequency modulation method proposed by Tu et al. effectively reduces the switching frequency in modular multilevel converters (MMCS), thereby reducing switching losses and improving the system efficiency of the converters [3]. This method reduces the impact of switching frequency on the system by extending each switching cycle.

In addition, with the progress of control strategies, model predictive control (MPC) has gradually become a new optimization direction. By taking into account future system dynamics, MPC effectively predicts future states during the control process, thereby optimizing control actions and reducing unnecessary switching operations. The multi-objective MPC strategy proposed by Townsend et al. was applied to the cascade H-bridge STATCOM system, which effectively suppressed the switching loss and maintained a good system dynamic response [6].

2.2 New converter topology and modular design

The design of the new converter topology provides an innovative idea for the suppression of switching loss. In recent years, modular multilevel converters (MMC) have been widely used in large-scale power systems and become an effective means to reduce switching losses. Ng et al. proposed a design scheme based on MMC to optimize high-power wind turbines. Its modular design not only reduces the switching frequency but also effectively reduces the impact of harmonics on the system and improves the efficiency of the system [4].

In addition, the Hybrid modular multilevel converter (Hybrid MLC) has also aroused the interest of researchers.

By combining a half-bridge and full-bridge structure, the hybrid converter can isolate DC faults and improve system reliability while ensuring the quality of output voltage waveform. In the design, the half-bridge unit is responsible for providing a lower level of voltage, while the full-bridge unit provides a higher level of voltage. The key to the hybrid design is to coordinate the work of different level units and avoid overwork of some modules by rationally distributing the load of each unit, thus reducing switching losses.

The three-level hybrid modular multilevel converter proposed by Li et al., with its special topology and new level unit, can effectively isolate DC faults, improve system reliability, and reduce switching losses due to modular design while improving the stability of power transmission [7].

2.3 Cyclic current control and harmonic suppression

An important source of switching loss is the circulating current due to the asymmetry of the current waveform. The circulating current is generated when the current between the converter modules is asymmetrical. Since the switching frequency and current characteristics of each module are not completely consistent, there may be an imbalance in the current waveform, resulting in unnecessary current cycling, which not only adds additional switching losses but also may affect the stability of the system. To solve this problem, Xu et al. proposed an AC cycle current suppression technology, which minimizes the cycle current in the system through accurate current control and regulation [5]. This technology can effectively reduce the fluctuation of the current waveform, thus inhibiting the switching loss.

At the same time, in recent years, repetitive control technology has also been introduced into the research of multilevel converters. This method reduces current harmonics by periodically adjusting the control signal of the converter and further reduces the additional switching loss caused by harmonics. He et al. proposed a strategy based on repetitive control, which successfully suppressed the AC cycle current, optimized the switching loss, and improved the stability and dynamic response of the system [8].

2.4 Comprehensive optimization strategy

With the development of switching loss suppression technology, the comprehensive optimization strategy has gradually become a trend. Researchers began to combine a variety of methods, such as low-frequency modulation, control optimization, modular design, and other techniques, to propose a new optimization scheme. Through the cooperative work of multiple strategies, the best performance can be achieved in different application scenarios. For example, a comprehensive control strategy based on MPC can combine low-frequency modulation, switching frequency optimization, and current cycle suppression to improve the performance and efficiency of multilevel converters.

The advantage of the comprehensive optimization strategy is that it can flexibly adjust the control strategy according to the actual operating environment and dynamically optimize the switching loss. With the development of intelligent control technology (such as deep learning, etc.), there may be more comprehensive optimization control methods based on artificial intelligence in the future, providing a more efficient and flexible solution for the switching loss suppression of multi-level converters.

3 Analysis and Discussion

3.1 Main achievement

From the above studies, it can be seen that the switching loss suppression technology of multilevel converters has made remarkable progress. Table 1 shows the comparison between the research results of switching loss suppression technology of multilevel converter and the applicable scenarios. The results show high practicability and innovation in different application scenarios. These achievements are mainly reflected in the following aspects:

3.1.1 Harmonic suppression and low-frequency switching technology.

By optimizing modulation strategies, such as the stepped waveform generation method proposed by Kimura et al. [1, 2] and the midpoint clamping and flyover capacitance topology analyzed by Fazel et al. [2, 9], the influence of higher harmonics is significantly reduced, and the switching frequency is also reduced to achieve lower switching losses. These studies have laid the foundation for the application of multilevel converters in HVDC transmission and wind power generation.

3.1.2 Innovative method of cycle current suppression.

The cyclic current suppression method proposed by Tu Qingrui et al., based on the improved phase-shifted carrier PWM technology and the proportional resonance control scheme proposed by Xu She et al., not only effectively suppresses the harmonic of the cyclic current, but also greatly reduce the power loss of the converter [3, 5]. The application of this kind of technology is especially suitable for modular multilevel converter (MMC), which improves its efficiency in the HVDC transmission system.

3.1.3 Dynamic control and intelligent optimization strategy.

Townsend et al. and Liqun He et al. respectively proposed methods based on model predictive control (MPC) and repetitive control strategies [6, 8]. These intelligent control strategies not only perform well in current tracking and capacitor voltage balance but also significantly reduce switching losses by dynamically optimizing the switching state, providing reliable support for efficient operation.

3.1.4 Application of new topology structure.

The Hybrid modular multilevel converter (Hybrid MMC) developed by Rui Li et al. and the improved half-bridge and full-bridge models developed by Adam et al. [7, 10] demonstrate the potential of low loss and high reliability through innovative topological design. These studies demonstrate that topology optimization can strike a good balance between high performance and low loss, especially in high-voltage applications.

3.1.5 The potential of wide bandgap semiconductor devices.

Although specific experiments on wide bandgap semiconductors such as SiC and GaN are not specifically discussed in depth in this paper, several studies imply the possibility of further optimization by increasing the switching speed and reducing the on-off loss. This indicates the direction for the efficient operation of multilevel converters in the future.

3.2 Comparative analysis of techniques

By summarizing the multilevel switching loss suppression technology, this paper further summarizes the advantages and disadvantages of different technical methods and their application scenarios, as shown in the following table:

Table 1. Comparison of research results and application scenarios of switching loss suppression technology for multilevel converters

Technical method	Key principle	Advantage	boundedness	Typical application scenario
Soft switching technology [1, 2]	Zero Voltage Switch (ZVS), Zero Current Switch (ZCS))	Significantly reduce switching losses and improve system efficiency	The control strategy is complex, and the applicability is narrow	High voltage direct current (HVDC), variable frequency drive
Optimal modulation strategy [3, 6]	Dynamic carrier phase adjustment, Phase-shifted carrier Pulse Width Modulation (CSPWM)	Reduce the frequency of high-frequency switching, low harmonic content	High hardware requirements and complex real-time calculation	Modular multilevel Converter (MMC)
Cycle current suppression [5, 8]	Proportional Resonance Controller (PRC), Repetitive Control	Suppress harmonic current and reduce current stress	The application scenario is relatively simple	Wind power grid-connected, modular multilevel inverter
New topology design [7, 10]	Hybrid topology (Hybrid MMC), a combination of half-bridge and full-bridge	The device has low cost, high efficiency, and strong DC fault-blocking ability	The engineering is difficult, and the test is complicated	HVDC transmission, wind power system
Dynamic frequency control [4, 6]	Adjust switching frequency based on load to avoid unnecessary high-frequency switching.	Adaptive adjustment improves dynamic efficiency.	The control strategy depends on the load characteristics, which are difficult to implement under complex working conditions.	Renewable energy connected to the grid, frequency conversion drive
Wide bandgap	SiC/GaN devices with	High switching	The device cost is high,	Scenarios with high

semiconductor applications [9]	high switching speed and low on-loss	frequency, low loss, and better performance than silicon devices	and the reliability needs to be improved	power density

3.3 Future development direction of technology

Although some progress has been made in the research of switching loss suppression in multilevel converters, there are still many challenges and research Spaces in practical applications. Future research will focus on the following directions:

3.3.1 Further optimization of switching loss.

Most of the current switching loss suppression technologies focus on reducing the switching frequency and optimizing the control strategy, but how to further reduce the switching loss is still an urgent problem to be solved in high-power and large-scale systems. Future research can focus on more efficient control strategies, such as adaptive control based on machine learning, so that the control strategy can be adjusted in real time according to load changes so as to optimize the switching loss more accurately [3].

3.3.2 The application of new semiconductor devices.

With the development of power semiconductor technology, wide-bandgap semiconductor materials (such as gallium nitride GaN and silicon carbide SiC) are gradually applied in the field of power electronics [4, 9]. These new materials have higher switching frequencies and lower on-off losses, which can significantly reduce switching losses in converters. Future research should further explore how these novel semiconductor devices can be combined with the design of multilevel converters to improve the overall efficiency of the system.

3.3.3 Combination of modularity and fault-tolerant technology.

In the application scenarios of high reliability and high stability, the fault-tolerant design of a multilevel converter is particularly important. In the future, the combination of modular design and fault-tolerant technology will become an important research direction [5, 10]. By designing a modular multilevel converter with high fault tolerance, not only the reliability of the system can be improved, but also the switching loss can be effectively reduced when the fault occurs, and the normal operation of the system can be maintained.

3.3.4 Integrated intelligent control and fault detection.

With the development of artificial intelligence and big data technology, future multilevel converters may integrate more intelligent control algorithms and fault detection mechanisms [8]. By monitoring the converter's operating status in real-time and predicting and optimizing control strategies through intelligent algorithms, the performance of multilevel converters can be significantly improved, especially in terms of reducing switching losses and improving fault tolerance.

Future research will focus more on the cooperative optimization of converter control and hardware, the combination of intelligent control and new power electronic components, and the efficient operation of multilevel converters in complex application scenarios.

4 Conclusion

In this paper, the research progress of switching loss suppression in multilevel converters in recent years is reviewed, with emphasis on low frequency modulation, modularization design, switching control technology and cyclic current control. These methods can reduce the switching loss and improve the system efficiency effectively by reducing the switching frequency, reducing the switching times and optimizing the control strategy. The low-frequency modulation technique reduces the loss by reducing the switching frequency. The modular design reduces the number of switches per module and further optimizes performance. The circulating current control technology effectively reduces the extra loss caused by asymmetric switching.

In this paper, the advantages and limitations of these methods in different application scenarios are discussed. For example, low-frequency modulation techniques reduce switching losses but require more complex control strategies. Modular design can effectively reduce losses, but it is still a challenge to implement in large-scale systems. Cycle current control has a significant effect in reducing power loss, especially for MMC.

Future research should focus on the optimization of intelligent control strategies, such as adaptive control based on machine learning, to achieve more accurate switching loss optimization. At the same time, the application of wide band gap semiconductor materials (such as SiC, GaN) should be explored to increase the switching frequency and reduce the on-off loss. In addition, the combination of modular design and fault-tolerant technology, as well as the integration of intelligent control and fault detection, will be key to improving system reliability and performance.

To sum up, future research should pay more attention to the collaborative optimization of control and hardware, the application of new semiconductor devices, and the combination of intelligent control technology to further improve the efficiency and stability of multilevel converters.

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