Research on Harmonic Suppression of Multi-Level Converters

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Abstract. Modular multi-level converter (MMC) has become an important technology for high-voltage flexible DC power transmission due to its modularity, scalability, and high-quality voltage quality, and has shown its wide application prospects in a large number of fields. Although research has focused on its harmonic suppression, modulation, and control technologies, they still face various challenges and need to be improved to improve system performance and stability. To this end, based on the summary of existing research, this paper reviews the mathematical model of MMC and its commonly used modulation methods and discusses its application in harmonic suppression from three aspects: step wave modulation, space vector modulation, and carrier modulation. , further, discuss the effect of the control strategy on harmonic suppression. Finally, this paper deeply explores the generation mechanism of MMC harmonics, summarizes the advantages and disadvantages of various suppression methods, and evaluates their effectiveness, scope of application, and cost by comparing the effects of different suppression methods under different conditions. Looking ahead, challenges will be faced in the future, such as exploring advanced harmonic suppression methods such as multiplexing technologies, passive filters, and active filters.

Keywords: Modular Multi-Level Converter, Modulation Method, Harmonic Suppression, Control Strategy, Efficiency Loss

1 Introduction

With the growth of global energy demand, multi-level converters (MLCs) have gradually become a research hotspot in the field of power electronics due to their low harmonic distortion, high efficiency, and good power quality. Modular Multilevel Converter (MMC) has shown great application potential, especially in high-voltage direct current transmission (HVDC), renewable energy access, and electric vehicles, thanks to its modular design and high voltage output.

However, despite MMC's many advantages, harmonic problems are still a bottleneck that limits its application. With the increase in power levels, harmonic distortion is becoming increasingly significant, especially in high-voltage DC transmission and high-

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power motor drive systems. Harmonics not only increases equipment loss but may also affect the stability and power quality of the system. Therefore, how to effectively suppress harmonics and optimize modulation and control strategies has become the focus of current research. At present, the research on harmonic suppression mainly focuses on two aspects: modulation strategy and control strategy. For example, the new VSC technology proposed by Ding can minimize the generated harmonics and, in most cases, eliminate the need for AC filters [1]. Wuren uses power and current dual-ring control to achieve flexible power regulation and harmonic suppression [2]. However, with the increase in the scale of the system, the stability and adaptability of traditional methods face challenges, and new methods, such as model predictive control (MPC), have gradually gained attention.

This review aims to summarize and evaluate the current modulation and control strategies of MMC harmonic suppression, focusing on the advantages and challenges of different modulation methods in harmonic suppression. This introduces the mathematical modeling, main modulation methods, and control strategies of MMC. Finally, the current research status of MMC in the field of harmonic suppression is summarized.

2 MMC Mathematical Model

Figure 1 is the topology of the MMC three-phase system, which is an N+1 level output system composed of 6 bridge arms. The upper and lower bridge arms of each phase are each composed of N submodules. The most commonly used submodule for MMC is a half-bridge submodule, which has simple control methods and is easy to package. These submodules include half-bridge, full-bridge structure, and hybrid structure. This system adopts a half-bridge submodule structure consisting of 2 IGBTs and 1 DC capacitor. Each submodule can implement AC/DC or DC/AC power conversion. In the normal state, the sum of the voltages of the (j)th upper arm submodule isU_{pj},the output voltage of the (j)th phase is u_{oj},and the upper bridge arm current of phase (J) is $i_{pj}$and the lower bridge arm current isi$_{nj}$. The system also includes the total voltageu$_{nj}$ of the lower bridge arm sub module in phase (J), the output voltage u_{oj} consistent with the upper bridge arm, the bridge arm inductance L_{arm}, the bridge arm resistance R_{arm}, the DC side input voltageU_{dc} of the whole bridge arm, and the bridge arm circulating current i_{cir}.

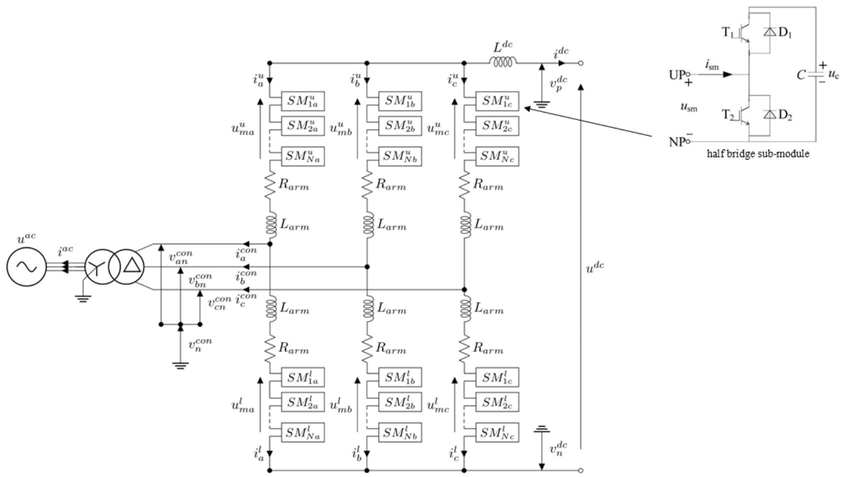

Fig. 1. The structure of the MMC topology(Picture credit: Original)

According to Kirchoff's voltage law, the voltage equilibrium equation of the upper and lower bridge arms of MMC can be obtained

$$u_{pj} = u_{oj} + L_{\text{arm}} \frac{di_{pj}}{dt} + R_{\text{arm}} i_{pj} \quad (1)$$

$$u_{nj} = u_{oj} + L_{\text{arm}} \frac{di_{nj}}{dt} + R_{\text{arm}} i_{nj} \quad (2)$$

$$u_{pj} + u_{nj} = U_{\text{dc}} \quad (3)$$

$$i_{\text{cir}} = \frac{i_{pj} - i_{nj}}{2} \quad (4)$$

(1) and (2) are the voltage balance equations of the upper and lower bridge arms, (3) are the overall constraint relationship of the voltage balance, and (4) are the definition of the circulation. These equations describe the dynamic relationship between bridge arm voltage, current, and inductance and are the basis for analyzing harmonic characteristics and designing control strategies.

Table 1. HBSM working status [3]

	The i_{sm} direction is positive			**The i_{sm} direction is negative**		
T1	1	0	0	1	0	0
T2	0	1	0	0	1	0
U_{sm}	U_c	0	U_c	U_c	0	0
status	input	cutting	lock	input	cutting	lock

The working status of the half-bridge submodule can be seen in Table 1; there are 6 working statuses, namely:

1. P0 status: HBSM is disconnected, and the output voltage of the submodule is 0V.
2. N0 state: HBSM is disconnected, and the output voltage of the submodule is 0V.
3. P1 state: The positive electrode HBSM passes the positive current, and the negative electrode HBSM passes the negative current with minimum resistance and energy loss.
4. N1 state: In contrast to the P1 state, the positive electrode HBSM passes the negative current, and the negative electrode HBSM passes the positive current.
5. P2 state: The negative electrode HBSM passes the positive current, and the positive electrode HBSM passes the negative current. At this time, the negative electrode HBSM should be locked.
6. N2 state: In contrast to the P2 state, the negative electrode HBSM passes the negative current, and the positive electrode HBSM passes the positive current. At this time, the positive HBSM should be locked.

Among them, "N" and "P" in N0, N1, N2, and P0, P1, and P2 represent negative and positive, respectively, and the numbers represent different working modes. P0 is a positive zero state; P1 is a positive conduction state; P2 is a positive locked state; N0 is a negative zero state; N1 is a negative conduction state; N2 is a negative locked state.

By controlling the number of times of input, cutting, and locking operations of the submodule, different output voltages can be achieved. These states describe the different operating conditions of the HBSM in the circuit the corresponding current directions, and how to control the output voltage through different operating states.

3 Common Modulation Methods

Harmonic rejection of multi-level converters, especially MMC, mainly relies on efficient modulation strategies. The modulation strategy directly affects the generation and distribution of harmonics by optimizing the switching sequence and waveform generation. Common modulation methods include space vector modulation (SVM), step wave modulation (SHE), and pulse width modulation (PWM). The classification of MMC modulation technology is shown in Figure 2. Table 2 lists the characteristics of each modulation strategy of MMC.

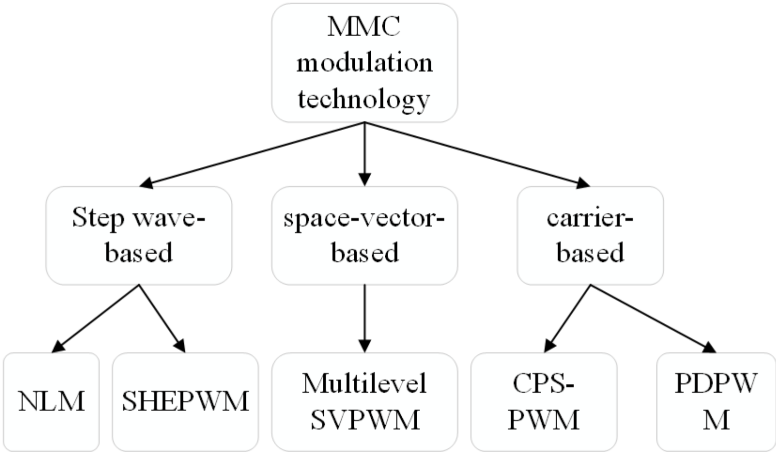

Fig. 2. Classification of MMC Modulation Techniques (Picture credit: Original).

Table 2. MMC modulation strategy characteristics [1]

Modulation method	Number of output levels	Equivalent switching frequency	Note
PWM	N + 1	-	Generally not used
SHE_PWM	N + 1	-	Generally not used
NLM	N + 1	-	Applicable when the value of N is large
PD_PWM	N + 1	f_0	High-output harmonic content
CPS_PWM	N + 1	Nf_0	High-output harmonic content
PPS_PWM	N + 1	Nf_0	High-output harmonic content

3.1 Based on step wave modulation technology

SHE is a modulation technology that optimizes waveform quality by eliminating specific low harmonics. By accurately calculating the switching angle, SHE can effectively reduce the total harmonic distortion rate of the AC voltage. When applied in multi-level converters, the computational complexity of SHE increases dramatically, especially in high-voltage and high-power systems, the scale of the switching angle meter becomes huge, and the demand for computing resources increases accordingly. In response to the above shortcomings, Xu improved the calculation methods of Np_j and Nn_j on the basis of asynchronous modulation of ladder waves, greatly reducing the calculation amount [3].

3.2 Based on space vector modulation technology

The SVM can select the optimal voltage vector within a given time interval, thereby minimizing the generation of low harmonics. However, SVM has a high computational complexity, especially in high-level MMC systems, and the consumption of computing resources has become its main disadvantage. Bai uses three-level SVM to control each subunit and evenly stagger the sampling times of adjacent subunits to achieve MMC multi-level output and reduce the harmonic content of output voltage and current [4].

3.3 Carrier-based modulation technology

PWM technology is one of the most common modulation methods in multi-level converters. When using the PWM strategy, the investment time and switching frequency of each MMC submodule vary greatly, resulting in seriously unbalanced capacitor voltage on the DC side of each submodule and inconsistent switching tube loss and heating conditions, resulting in the system not being able to operate normally. Bai has improved its implementation process based on the study of the carrier stacking PWM strategy principle and its application problems in MMC. Multiple carriers are rotated in a certain period to control the MMC submodules so that the overall control algorithm of the system is simplified. [5]

From the perspective of maintaining the dynamic balance of power of the upper and lower bridge arms of each phase, Kong designs a voltage fluctuation suppression strategy based on the injection of high-frequency common mode voltage and high-frequency circulation [6]. The first-level main controller uses DSP to realize bridge arm current sampling, modulation wave generation, and communication with the auxiliary controller; the second-level auxiliary controller uses FPGA to realize modulation strategy, fault protection, and communication with the submodule controller; the third-level submodule controller controls the submodule capacitance-voltage sampling, PWM expansion, and fault diagnosis through FPGA and AD chips. This strategy can achieve excellent output harmonic characteristics at low switching frequency while ensuring the normal and reliable operation of the system, and the harmonic performance improves with the increase of the MMC cascade.

4 Control Strategies

Total Harmonic Distortion (THD) is an important indicator for measuring the harmonic content in the output waveform. The lower the THD, the better the quality of the output waveform. By analyzing the harmonic spectrum of the output waveform, one can understand the content of harmonics at different frequencies, thus evaluating the harmonic suppression effect. Moreover, by observing the output waveform, it is possible to intuitively judge the harmonic suppression effect. The closer the output waveform is to a sine wave, the better the harmonic suppression effect.

In Kong's research, through calculation and analysis, the optimal switching angle was determined, minimizing the THD of the primary voltage of the transformer [7]. This indicates that choosing an appropriate switching angle is crucial for harmonic suppression. The selection of the optimized switching angle needs to consider multiple factors, including the parameters of the transformer harmonic loss model, the requirements of the system, and the number of sub-modules. Moreover, through simulation, the harmonic suppression effects of the THD - optimized modulation strategy, the traditional quasi-two-level modulation strategy, and the stepped-wave modulation strategy were compared. The simulation results show that the THD-optimized modulation strategy can significantly reduce the THD of the voltage and current on the primary side of the transformer, decrease the harmonic content, and reduce the harmonic loss. By analyzing the relationship curve between the total harmonic loss and the current THD, the effect of the THD-optimized modulation strategy on harmonic suppression can be seen more intuitively. At the same time, there are also some limitations. Although the THD-optimized modulation strategy can effectively reduce the harmonic content, it cannot completely eliminate harmonics. The selection of the optimized switching angle needs to be adjusted according to specific system parameters, which requires certain calculation and analysis work.

The THD-optimized modulation strategy is mainly optimized for the harmonic loss of the transformer, and its suppression effect on other harmonic sources (such as switching device losses) is limited.

In Luo's research, the advantages were analyzed in three aspects: harmonic filtering, improving control accuracy, and reducing switching losses [8]. By using an Improved Band - Pass Filter (IBF) to filter the harmonic components of the arm current and voltage reference values, switching harmonics and circulating current harmonics can be effectively suppressed, and the error in the number of sub-modules during Nearest Level Modulation (NLM) control can be reduced. The optimized sampling values are more accurate, which can reduce the error in the NLM modulation process, improve the control accuracy, and thus reduce the harmonic content in the output waveform. By suppressing harmonics, redundant switching actions can be reduced, thereby reducing switching losses and improving the system efficiency.

In Wu's research, further exploration can be carried out from two aspects: the power-current dual-loop control method and the three-level inverter [9]. The power-current dual-loop control method is divided into a current control loop and a power control loop.

Current Control Loop: This control loop can compare the current reference value with the actual feedback current signal and make rapid adjustments according to the difference, thus compensating for non-linear disturbances and reducing current harmonics.

Power Control Loop: By controlling the active and reactive power injected into the grid, the current is indirectly controlled, thereby reducing current harmonics.

The three-level inverter is divided into a multi-level topology and harmonic-eliminating PWM control.

Multi-level Topology: Compared with the two-level inverter, the three-level inverter has a more abundant output voltage level, can approximate the sine wave more smoothly, and thus reduce voltage and current harmonics.

Harmonic-eliminating PWM Control: This control method compares multiple triangular waves with a sine wave, which can effectively eliminate harmonics of specific orders and further improve power quality.

5 Prospect

By analyzing the relationship curve between the total harmonic loss and the current THD, more advanced harmonic suppression technologies can be further studied, such as multiplexing technology, passive filters, and active filters. Explore the combination of the THD-optimized modulation strategy with other harmonic suppression technologies to further improve the harmonic suppression effect. The THD - optimized modulation strategy is an effective method to suppress the harmonic loss of the transformer in the isolated modular multilevel DC-DC converter (MMDC). By choosing an appropriate optimized switching angle, the harmonic content can be significantly reduced, and the efficiency of the converter can be improved. However, this strategy also has certain limitations and needs to be combined with other harmonic suppression technologies to achieve an ideal harmonic suppression effect. At the same time, it can be seen that more advanced filter designs are needed. More advanced filter design methods can be studied, such as adaptive filters, digital filters, etc., to further improve the harmonic suppression effect. Through multi-objective optimization control, multiple objectives such as harmonic suppression, switching losses, and system efficiency can be comprehensively optimized to design a better control strategy. At the same time, it can also be applied to other multi-level converters. The improved NLM sampling optimization strategy can be applied to other multi-level converters, such as the Modular Multilevel Converter (MMC), to improve their harmonic suppression capabilities. In summary, the improved NLM sampling optimization strategy can effectively suppress the harmonics in the M3C, improve the quality of the output waveform, and have important theoretical and application value [10].

6 Conclusion

By analyzing the relationship curve between the total harmonic loss and the current THD, the effect of the THD-optimized modulation strategy on harmonic suppression can be seen more intuitively. At the same time, there are also some limitations. Although the THD-optimized modulation strategy can effectively reduce the harmonic content, it cannot completely eliminate harmonics. The selection of the optimized switching angle needs to be adjusted according to specific system parameters, which requires certain calculation and analysis work.

This review deeply explores the mechanism of harmonic generation in multi-level converters and finds effective suppression methods. It extensively collects relevant academic literature, industry reports, existing experimental data, etc., combs the harmonic characteristics of multi-level converters with different topologies, and the advantages and disadvantages of various suppression methods used in the past. Through the above-mentioned methods, the data obtained from experiments or simulations are sorted out, the effects of different suppression methods under different conditions are compared, and their effectiveness, scope of application, cost, etc. are analyzed.

Based on the comprehensive research content, efficient and practical harmonic suppression strategies for multi - level converters are summarized, the limitations of the current research are pointed out, and the future research directions that can be expanded are proposed, forming a complete research summary result.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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