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Loss distribution analysis and accurate calculation method for bulk-power MMC

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Abstract

Accurate evaluation of power losses in a modular multilevel converter (MMC) is very important for circuit component selection, cooling system design, and reliability analysis of power transmission systems. However, the existing converter valve loss calculation methods using the nearest level modulation (NLM) method and the traditional sorting-based capacitor voltage balancing strategy are inaccurate since the submodule (SM) switching logics in the MMC arms are uncertain. To solve this problem, the switching principle of the SMs in the sorting-based voltage balancing strategy is analyzed. An accurate MMC power loss calculation method based on the analysis of loss distribution of various SM topologies, including half-bridge submodule (HBSM), full-bridge submodule (FBSM) and clamp double submodule (CDSM), is proposed in this paper. The method can accurately calculate the losses caused by the extra switching losses compared with existing methods. Simulation results based on a practical ± 350 kV/1000 MW MMC-HVDC system with variety of MMC topologies with different voltage balancing strategies demonstrate the effective-ness of the proposed method.

Keywords Modular multilevel converter, Extra switching losses calculation, Nearest level modulation

1 Introduction

The modular multilevel converter-based high voltage direct current (MMC-HVDC) system has advantages of modular design, independent control of active and reactive power, and low output voltage harmonics etc., and it has been widely applied in the fields of renewable energy grid connection, and DC power grids [1-3].

Accurate calculation of valve losses is a critical basis for circuit component selection, cooling system design and reliability evaluation of the system [4, 5]. However, the numbers of submodules (SMs) and semiconductor devices in high-voltage large-capacity MMC-HVDCs have also increased dramatically, especially when the full-bridge submodule (FBSM) or clamp double submodule (CDSM) topology with DC short-circuit fault clearing capability are adopted. The very large numbers of semiconductor devices and the complicated transient characteristics of converter valves have brought challenges to the accurate calculation of MMC losses.

Loss calculation of an MMC is closely related to its modulation methods and capacitor voltage balancing strategies. The loss calculation based on carrier phaseshifted pulse width modulation (CPS-PWM) method has been well studied [6]. The loss distribution characteristics and calculation of IGBTs and diodes under CPS-PWM are deduced in [7, 8]. The junction temperature fluctuation characteristics of each switching device are analyzed by deriving the average and effective values of the switching device current [9]. However, the influence of junction temperatures on the loss calculation of switching devices is not considered. Linear interpolation is adopted to iteratively calculate the junction temperatures of semiconductor devices in [10], where the conduction losses



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and switching losses of IGBTs and diodes are calculated though electromagnetic transient simulation based on temperature feedback. A loss calculation method of halfbridge submodule (HBSM) is proposed based on the detailed analysis of semiconductor device working principle and the converter valve thermal model. This provides data support for MMC reliability analysis and full cycle life assessment [11]. However, CPS-PWM is not suitable for high-voltage large-capacity MMC-HVDC systems.

The nearest level modulation (NLM) method based on a sorting algorithm to achieve capacitor voltage balance is widely applied in real high-voltage large-capacity MMC-HVDC systems, in which the switching frequency and loss characteristics are significantly different from the CPS-PWM method [12]. Although the conduction losses can be well estimated with sufficient accuracy by various methods [13, 14], research on switching losses is still limited, especially for the MMC with the NLM method. The switching actions of the SMs under the NLM method can be divided into two parts: necessary switching and extra switching. The necessary switching is the change of SM numbers caused by the AC output voltage changes of the MMC arms according to the references, while the extra switching is the alternation of SMs to achieve capacitor voltage balance. The complexity and randomness of the switching actions restrict the calculation accuracy of the extra switching losses.

One of the most popular methods for calculating switching losses is through simulation [15]. However, it has disadvantages of being time-consuming and requiring a detailed model. This limits its application. The other method relies on analytical models based on specific assumptions, such as ideal sinusoidal arm current and voltage references [16, 17]. These are simple and computationally-efficient. However, considerable estimation errors exist because of the neglect of the harmonics in the current and voltage. Therefore, a linear relationship between the switching losses and the average current is applied for the essential and additional switching loss estimation [18]. A method to calculate the upper limit value of switching losses of an MMC is also proposed in [19, 20]. This multiplies the maximum switching energy by the estimated average switching frequency. However, the errors of the methods proposed above are still large and the given linear relationship is, to a large extent, questionable.

In addition to the MMC modulation strategies, the SM switching losses of power devices are also closely related to the capacitor voltage balancing methods. A capacitor voltage balancing method based on the holding factor is proposed in [21]. This reduces the switching frequency by sacrificing a certain degree of capacitor voltage balancing effect. However, the selection principle of the holding factor is not elaborated, further increasing the randomness of SM actions, which brings difficulties to the switching loss calculation. In [22], a capacitor voltage balancing method by setting the maximum voltage deviation threshold is proposed. The switching frequency of the SMs can be further reduced by sorting the SM voltages only when the capacitor voltage deviations exceed the voltage threshold. However, the SM switching frequencies vary greatly depending on whether the capacitor voltages are sorted or not, making it difficult to quantitatively calculate the switching losses of power devices.

Based on the above research, SM average switching frequency optimization methods are proposed in [23, 24] by setting the rotation number of SM per control cycle. The proposed methods are simple, and can quantitatively calculate the switching frequency. Capacitor voltage balancing methods by adjusting the SM rotation number in real-time through predicting the convergence of SM capacitor voltages are proposed in [25, 26]. Although the proposed methods further reduce the SM switching frequency, the SM switching frequency is coupled to the SM rotation number, making the accurate calculation of switching losses of power devices more complex.

In order to better estimate the necessary and extra switching losses, the switching losses are calculated by assuming that the switching actions are evenly distributed during one period [27]. However, an even distribution of switching actions will introduce errors especially when the SM number is small, such as in medium voltage applications. A piecewise analytical valve loss evaluation method for an MMC-HVDC is proposed by averaging necessary switching losses during one control cycle [12], and an analytical essential switching loss estimation method for MMC with NLM is proposed in [28]. However, the extra switching losses of the above two methods are approximated by an upper limit, and this increases the cost of system hardware. Therefore, how to achieve accurate evaluation of MMC valve losses using the NLM method is still a problem requiring solution urgently. In this paper, an accurate power loss calculation method by integrating analytical calculation and simulation is proposed. This can realize the quantitative analysis of valve losses using the NLM method. It solves the difficult problem of accurately calculating extra switching losses. In addition, the proposed method is suitable for high-voltage large-capacity MMC converter valves, and for various topologies of SMs and operating conditions.

This rest of the paper is organized as follows. The mathematical model and loss characteristics of the discussed MMC are briefly introduced in Sect. 2. The static losses and the proposed switching calculation method including necessary and extra switching losses are presented in Sect. 3, whereas the low switching frequency capacitor voltage balancing method is proposed in Sect. 4. Simulations based on a practical \pm 350 kV/1000 MW MMC-HVDC project are carried out in Sect. 5. Finally, the conclusion of this paper is given in Sect. 6.

2 Mathematical model and loss characteristics 2.1 Mathematical model

A typical three-phase MMC topology is illustrated in Fig. 1. As can be seen, each arm is composed of *N* SMs, and one arm inductor L_{arm} with an equivalent series resistor R_{am} . The SM can adopt HBSM, FBSM, CDSM and other topologies, and can also be combined to form a hybrid MMC. U_{dc} and I_{dc} are the DC voltage and DC current. u_{pi} and u_{ni} are the upper and lower arm voltages, i_{pi} and i_{ni} are the upper and lower arm currents, and i_i is the AC current, where i=a, b, c represent phases A, B and C. Taking the upper arm of phase A as an example, the arm voltages and currents are obtained [29]:



Fig. 1 Topology of the three-phase MMC

$$\begin{cases} u_{\rm pa} = \frac{1}{2} U_{\rm dc} - u_{io} - L_{\rm arm} \frac{di_{\rm pa}}{dt} - R_{\rm arm} i_{\rm pa} \\ u_{\rm na} = \frac{1}{2} U_{\rm dc} + u_{io} - L_{\rm arm} \frac{di_{\rm na}}{dt} - R_{\rm arm} i_{\rm na} \end{cases}$$
(1)

$$\begin{cases} i_{pa} = -\frac{1}{2}i_{a} + \frac{1}{3}I_{dc} + i_{cir} \\ i_{na} = \frac{1}{2}i_{a} + \frac{1}{3}I_{dc} + i_{cir} \end{cases}$$
(2)

where i_{cir} is the arm circulating current, and u_{io} refers to the AC side voltages (*i* = a, b, c). During steady-state operation, the AC voltage and current of phase A are given as:

$$\begin{cases} u_{ao} = \frac{1}{2}m \cdot U_{dc}cos(\omega t + \theta_{a}) \\ i_{a} = I_{ac}\cos(\omega t + \varphi_{a}) \end{cases}$$
(3)

where *m* is the modulation ratio, ω is the fundamental angular frequency, and θ_a and ϕ_a are the phase angles of the voltage and current, respectively.

The power in the AC and DC sides of the converter are balanced. This implies the following relationship when ignoring the losses of the converter valves [13]:

$$I_{\rm dc} = \frac{3}{4} m I_{\rm ac} \cos\left(\varphi_{\rm a} - \theta_{\rm a}\right) \tag{4}$$

where I_{ac} is the amplitude of the AC current.

In practical MMC systems, the circulating current i_{cir} is usually well suppressed by the circulating current suppression control. Therefore, combining (1)-(3) and ignoring the circulating current i_{cir} in (2), the arm currents of the upper and lower arms can be obtained as:

$$i_{\rm pa} = \frac{m}{4} I_{\rm ac} \cos\left(\varphi_i - \theta_i\right) - \frac{1}{2} I_{\rm ac} \cos(\omega t + \varphi_i) \tag{5}$$

$$i_{\rm na} = \frac{m}{4} I_{\rm ac} \cos\left(\varphi_i - \theta_i\right) + \frac{1}{2} I_{\rm ac} \cos(\omega t + \varphi_i) \tag{6}$$

2.2 Loss characteristics of MMC

The MMC valve losses can be divided into static and switching losses [30]. The static losses are mainly related to the circuit parameters and the operating conditions of the converter. The switching losses are composed of IGBT switching losses and diode reverse recovery losses and are closely related to the modulation and voltage balancing strategies, which are also affected by the arm currents, capacitor voltages and switching frequency.



Fig. 2 Loss distribution of the HBSM

Table 1 Switching energy of SMs

Topology	State	Loss distributions (i _{pa} >0)
HBSM	off-state→on-state	$E_{\rm sw} = E_{\rm off}$
	on-state → off-state	$E_{\rm sw} = E_{\rm on} + E_{\rm rec}$
FBSM	off-state → on-state	$E_{\rm sw} = E_{\rm off}$
	on-state → off-state	$E_{\rm sw} = E_{\rm on} + E_{\rm rec}$
CDSM	off-state \rightarrow on-state A	$E_{\rm sw} = E_{\rm off}$
	off-state \rightarrow on-state B	$E_{\rm sw} = 2E_{\rm off}$
	on-state A \rightarrow on-state B	$E_{\rm sw} = E_{\rm off}$
	on-state A \rightarrow off-state	$E_{\rm sw} = E_{\rm on} + E_{\rm rec}$
	on-state $B \rightarrow off$ -state	$E_{\rm sw} = 2(E_{\rm on} + E_{\rm rec})$
	on-state B \rightarrow on-state A	$E_{\rm sw} = E_{\rm on} + E_{\rm rec}$

All the SMs have similar loss characteristics in the steady state operation condition and the same circuit parameters. In HBSM, the two cases of SM loss distribution according to the SM on/off states and the current path of the switch devices when the arm current i_{pa} >0 are shown in Fig. 2. The loss distribution is similar when the arm current i_{pa} <0. Among them, P_{SM} is a constant power load that remains unchanged during the normal operation of the SM. The loss distributions of HBSM, FBSM and CDSM are different when their states change, as shown in Table 1. The conduction losses of the diodes are ignored since they are relatively small. The on-state A and on-state B of the CDSM in Table 1 correspond to the states of one and two capacitors insertion, respectively.

3 Accurate loss calculation method of MMC

The losses of an MMC can be divided into static and switching losses. The calculation of static losses is relatively mature [3]:

$$\begin{cases}
P_{\text{Tcond}}(i_{\text{CE}}) = i_{\text{CE}}U_{\text{CE0}} + i_{CE}^2 r_{CE} \\
P_{\text{Dcond}}(i_{\text{f}}) = i_{\text{f}}U_{\text{f0}} + i_{\text{f}}^2 r_{\text{f}}
\end{cases}$$
(7)

where P_{Tcond} and P_{Dcond} are the conduction losses of the IGBTs and diodes, and i_{CE} and i_{f} are the currents flowing through the IGBTs and diodes, respectively. U_{CE0} and U_{f0} are the conduction voltages of the IGBTs and diodes, and

 $r_{\rm CE}$ and $r_{\rm f}$ are the conduction resistors of the IGBTs and diodes, respectively. The conduction voltage and conduction resistor change with the device junction temperature, and thus, $U_{\rm CE0}, U_{\rm f0}, r_{\rm CE}, r_{\rm f}$ can be obtained by linear interpolation [12].

However, it is difficult to accurately calculate the switching losses of an MMC, especially the extra switching losses of SMs caused by the voltage balancing method. In this paper, an accurate loss calculation method considering the extra switching actions of SMs is proposed.

3.1 The principle of the NLM method

The main idea of NLM is to approach the reference voltage through a step wave. For an MMC, the numbers of conduction SMs n_{ref} of the upper and lower arms can be calculated by:

$$n_{\rm ref,pa} = round\left(\frac{U_{\rm dc}(1 - mcos(\omega t + \theta_i))}{2U_{\rm C,ave}}\right)$$
(8)

$$u_{\rm ref,na} = round\left(\frac{U_{\rm dc}(1 + mcos(\omega t + \theta_i))}{2U_{\rm C,ave}}\right) \tag{9}$$

where $U_{C,ave}$ represents the average SM capacitor voltage in one arm.

As the modulation wave rises from 0, the conducting SMs of the lower arm gradually increase and the conducting SMs of the upper arm decrease accordingly, such that the output voltage rises with the modulation wave, as shown in Fig. 3.

In the NLM method, the MMC SM switching includes: 1) the SM number change caused by the AC output voltage changes of the MMC arms according to the reference and is called necessary switching action; 2) The extra alternation of the SMs to achieve the capacitor voltage balance is called extra switching action. The switching frequency and time of the MMC SMs are uncertain in the sorting-based capacitor voltage balancing strategy. Therefore, extracting the instantaneous currents at the switching times with the analytical method and



Fig. 3 The principle of the NLM method

calculating the switching frequency in each control cycle are the main difficulties in MMC valve loss evaluation.

3.2 Switching frequency calculation

In order to accurately evaluate MMC switching losses, it is necessary to calculate its switching frequency accurately. Various voltage balance strategies have different SM selection mechanisms. These make the switching frequency of the MMC vary greatly. According to [24], if only the necessary switching actions of the MMC are considered while ignoring the extra switching actions, the lower limit of the MMC switching frequency can be obtained as:

$$f_{\rm sw,min} = \frac{f_0}{N} \times \left(round \left(\frac{(1+m)U_{\rm dc}}{2U_{C,\rm ave}} \right) -round \left(\frac{(1-m)U_{\rm dc}}{2U_{C,\rm ave}} \right) \right) a$$
(10)

where *round* () is the nearest rounding function. f_0 is the fundamental frequency and f_s is the control frequency of the valve control system.

If the SM states rotate as many as possible in adjacent control cycles, the upper limit of the switching frequency can be obtained as:

$$f_{\rm sw,max} = \frac{2f_0}{N} \sum_{k=1}^{f_s/f_0} |\Delta n_{\rm ref}(t_k)|$$
(11)

where $\Delta n_{\rm ref}$ is the change number of the conduction SMs in adjacent control cycles. Taking the upper arm of phase A as an example, $\Delta n_{\rm ref,pa}$ can be expressed as:

$$\Delta n_{\text{ref,pa}}(t_k) = n_{\text{ref,pa}}(t_k) - n_{\text{ref,pa}}(t_{k-1})$$
(12)

As the active power and the effective value of arm current are approximately linear since the system mainly operates at unity power factor, the increase of capacitor voltage in a single control cycle is given as:

$$\Delta U_{Cpa}^{x} = \frac{1}{C} \int_{t}^{t+T_{s}} S_{x} \cdot i_{pa} dt$$
(13)

where $T_s = 1/f_s$ and S_x represents the switching function of the *x*-th SM, which satisfies the following relationship:

$$S_x = \begin{cases} 1, & \text{when } T_1 \text{ is on and } T_2 \text{ is off} \\ 0, & \text{when } T_1 \text{ is off and } T_2 \text{ is on} \end{cases}$$
(14)

The linear interpolation method can be adopted to obtain the relationship between MMC transmission power and switching frequency since the change of the capacitor voltage sequence caused by the charging and discharging of the arm current is positively correlated with the transmission power, as:

$$f_P = f_{\text{sw,min}} + \frac{f_{\text{sw,max}} - f_{\text{sw,min}}}{P_{\text{max}} - P_{\text{min}}} \times (P - P_{\text{min}}) \quad (15)$$

where f_P is the switching frequency corresponding to the instantaneous power *P*. P_{max} and P_{min} are the corresponding power limits when the switching frequency takes the upper limit and the lower limit, respectively. f_{ref} is the reference frequency determined by the voltage balance algorithm.

However, in real systems, the special operating conditions corresponding to the upper and lower limits of the switching frequency are difficult to achieve. Therefore, it is necessary to extract the switching frequency of the MMC under typical operating conditions from offline simulation, and modify the interpolation parameters. In order to ensure the accuracy of the MMC switching frequency extracted from offline simulation, a PSCAD simulation model is established based on the MMC converter station on the Guangxi side of the Luxi HVDC Project in China. The simulation parameters are shown in Table 2. All control parameters in the simulation are derived from a hardware-in-the-loop (HIL) test platform, which consists of the actual MMC project.

The valve control system and the real-time digital simulation platform based on RT-LAB are shown in Fig. 4. The real-time simulation system based on RT-LAB OP5600 is mainly used to simulate equipment such as converters, circuit breakers, and AC power grids, and to output the electrical quantities required by the valve control system in real-time. The MMC valve control system is completely consistent with the control system used in the actual project, and achieves DC voltage control, active and reactive power control, circulating current control, modulation and voltage balancing methods. The real-time simulation system based on RT-LAB interacts with the MMC valve control

Table 2 Parameters of the simulated MMC

Parameters	Value	
Rated Capacity/MVA	1000	
Rated DC voltage/kV	±350	
Rated voltage on grid side/kV	525	
Rated voltage on valve side/kV	375	
Ratio of converter transformer	525/375	
Number of SMs	468	
Number of redundant SMs	40	
Arm inductor L/mH	115	
SM capacitor C/mF	12	
Control frequency/kHz	10	



Fig. 4 The real-time simulation platform and the MMC valve control system in Guangxi, China

system through high-speed optical fiber to exchange data, such as SM voltages, SM status, and pulse signals of the power devices.

The switching frequency fitting curves obtained respectively by adopting the traditional sorting based capacitor voltage balancing method, the low switching frequency voltage balance method (LSF1) in [23] and the LSF2 in [24] are shown in Fig. 5. It shows the relationships between the switching frequency and the active power of the system with three voltage balance methods, which are within the range of the analytical calculation results.

The switching frequency in the sorting based capacitor voltage balancing strategy is close to the theoretical upper limit, and the switching frequency of the LSF1 method is largely between the theoretical upper and lower limits. The switching frequency of the LSF2 method is close to the theoretical lower limit in the no-load condition. It increases when the transmission power increases. The existing switching loss calculation methods by estimating the average switching frequency

1.4Traditional method LSF Switching Frequency/Hz 1.3 0.2 0.1 0.0 200 400 600 0 800 1000 Power/MW Fig. 5 The switching frequency of the MMC

have a large error and cannot truly reflect the switching loss characteristics of the MMC. Therefore, this paper considers the relationship between switching frequency and active power by offline simulation and linear interpolation technology, to provide a basis for accurate calculation of the extra switching losses.

3.3 Necessary switching losses

The switching losses caused by the necessary switching actions in the MMC arms can be obtained through the accumulation of switching energy and the necessary switching times of a single SM, namely:

$$P_{\text{sw,nec_arm}} = f_0 \times \sum_{k=1}^{f_s/f_0} \left(E_{\text{sw}}(i(t_k)) \times n_{\text{sw,nec}}(t_k) \right)$$
(16)

where P_{sw,nec_arm} is the necessary switching losses of the MMC arm, E_{sw} is the switching energy of a single SM switching action, and $i(t_k)$ is the instantaneous current corresponding to the action time t_k . The necessary switching number $n_{sw,nec}$ of the SM can be calculated as:

$$n_{\text{sw,nec}}(t_k) = |\Delta n_{\text{ref}}(t_k)| = \left| n_{\text{ref}}(t_k) - n_{\text{ref}}(t_{k-1}) \right|$$
(17)

where Δn_{ref} is the change number of the conduction SMs in adjacent control cycles. This is obtained by (8) or (9).

The switching energies of the SMs can be obtained according to Table 1 when the number of inserted SMs increases or decreases caused by the AC output voltage changes of the MMC arms according to the references. The IGBT and diode switching energies have been elaborated in [12], and the polynomial fitting calculation formulas are:

$$E_{\rm on} = a_{\rm on2}i^2 + a_{\rm on1}|i| + a_{\rm on0} \tag{18}$$

$$E_{\rm off} = a_{\rm off2} i^2 + a_{\rm off1} |i| + a_{\rm off0}$$
 (19)

Table 3	Parameters	of switching ener	gy calculation
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a _{on2} /Ω·s	a _{on1} /V⋅s	a _{on0} /mJ
8.3436e-04	0.1771	507.1966
1.1001e-03	0.0023	586.3481
a _{off2} /Ω·s	a _{off1} ∕V·s	a _{off0} /mJ
1.3411e-04	1.2458	122.6001
1.0879e-04	1.3761	148.5985
a _{rec2} /Ω·s	a _{rec1} ∕V·s	a _{rec0} /mJ
-2.5350e-04	1.0873	309.6171
-2.9379e-04	1.2473	419.0136
	a _{on2} /Ω·s 8.3436e-04 1.1001e-03 a _{off2} /Ω·s 1.3411e-04 1.0879e-04 a _{rec2} /Ω·s - 2.5350e-04 - 2.9379e-04	a_{on2}/Ω ·s a_{on1}/V ·s8.3436e-040.17711.1001e-030.0023 a_{off2}/Ω ·s a_{off1}/V ·s1.3411e-041.24581.0879e-041.3761 a_{rec2}/Ω ·s a_{rec1}/V ·s $-2.5350e$ -041.0873 $-2.9379e$ -041.2473

$$E_{\rm rec} = a_{\rm rec2}i^2 + a_{\rm rec1}|i| + a_{\rm rec0}$$
(20)

where $E_{\rm on}$ and $E_{\rm off}$ represent the respective IGBT turnon and turn-off energies, while $E_{\rm rec}$ represents the diode reverse recovery energy. $a_{\rm on}$, $a_{\rm off}$, and $a_{\rm rec}$ are the polynomial fitting coefficients of IGBT and diode switching energies, respectively. Taking the Infineon FZ1200R33HE3 type IGBT as an example, the required parameters for fitting can be obtained by consulting the data sheet, as shown in Table 3.

According to the junction temperature and voltage feedback, the IGBT turn-on energy is corrected as:

$$\begin{cases} E_{\text{on}_{T}} = K_{V} \bigg[E_{\text{on}_{1}25^{\circ}\text{C}} + (E_{\text{on}_{1}50^{\circ}\text{C}} - E_{\text{on}_{1}25^{\circ}\text{C}}) \frac{T - 125}{150 - 125} \bigg] \\ K_{V} = \frac{U_{\text{C,ave}}}{U_{\text{CE}_{ref}}} \end{cases}$$
(21)

where K_V is the voltage regulation coefficient. U_{CE_ref} and $U_{C,ave}$ are the reference voltage and SM capacitor voltage. These are provided by the device data sheet. $E_{on_125^{\circ}C}$ and $E_{on_150^{\circ}C}$ are the IGBT turn-on energy calculated from (21) and Table 3 at 125 °C and 150 °C, respectively. The IGBT turn-off energy and diode reverse recovery energy at any temperature are calculated similarly.

In order to calculate the instantaneous arm currents at the switching times, the existing study extracts the level change times and the instantaneous current values by solving the inverse trigonometric function for the step wave corresponding to the arm voltage reference values [13]. However, in actual MMC-HVDC projects, the number of arm SMs is often higher than the number of converter valve control sampling points in the power frequency cycle. Taking the Luxi HVDC Project in China as an example, the number of arm SMs is 468, the control frequency of the valve control system is 10 kHz, and the control sampling points are 200 in each power frequency cycle. Therefore, N+1 levels cannot be completely output, and is limited by the control



frequency, as shown in Fig. 5. The switching times of SMs in each fundamental frequency period can be obtained from Fig. 6 as:

$$t_k = \frac{k}{f_s}, \ k = 1, 2, \dots, \frac{f_0}{f_s}$$
 (22)

Substituting the switching times into the arm currents (5) and (6), the instantaneous current $i(t_k)$ at the switching time t_k can be obtained. The number of necessary switching SMs in adjacent periods can be obtained from (17).

In summary, the necessary switching losses of an MMC can be obtained through the switching energies of the three SM topologies in Table 1. The total necessary switching losses of the MMC are thus given as:

$$P_{\rm sw,nec_MMC} = 6P_{\rm sw,nec_arm}$$
(23)

3.4 Extra switching loss calculation

The extra switching losses are also calculated by accumulating the switching energy and the extra switching times of a single SM, as:

$$P_{\text{sw,ext_arm}} = f_0 \cdot \sum_{k=1}^{f_s/f_0} \left[E_{\text{sw,ext}}(i(t_k)) \cdot n_{\text{sw,ext}}(t_k) \right] \quad (24)$$

where $n_{\text{sw,ext}}(t_k)$ represents the extra switching times during each control cycle.



Тороlоду	Extra switching energy
HBSM	$E_{\rm sw} = E_{\rm on} + E_{\rm off} + E_{\rm rec}$
FBSM	$E_{\rm sw} = E_{\rm on} + E_{\rm off} + E_{\rm rec}$
CDSM	$E_{\rm sw} = 2E_{\rm on} + 2E_{\rm off} + 2E_{\rm rec}$

 Table 4
 The extra switching energy

The extra switching of SMs in the discrete control system have the same action times as the necessary switching. The same method for calculating the instantaneous value of the arm current can be adopted. The extra switching of SMs is described as the exchange of the same number of SMs with different switching states, as shown in Fig. 7. Therefore, the MMC switching frequency can also be expressed as:

$$f_P = \frac{f_0}{2N} \sum_{k=1}^{f_s/f_0} \left(2n_{\rm sw,ext}(t_k) + |\Delta n_{\rm ref}(t_k)| \right)$$
(25)

The alternating number of the SMs can be approximately obtained by evenly distributing the switching actions in the power frequency cycle, as:

$$n_{\rm sw,ext}(t_k) = N \cdot \frac{f_P}{f_s} - \frac{|\Delta n_{\rm ref}(t_k)|}{2}$$
(26)

From the circuit topology analysis, when the switching states of the two HBSMs are exchanged, the switching energy $E_{sw,ext}$ is given as:

$$E_{\rm sw,ext} = E_{\rm on} + E_{\rm off} + E_{\rm rec} \tag{27}$$

The extra switching energies of the FBSM and CDSM can be obtained similarly, as shown in Table 4. Substituting the switching energies of the SMs in Table 4 into (24), the total extra switching losses of the MMC can be expressed as:

$$P_{\rm sw,ext_MMC} = 6P_{\rm sw,ext_arm}$$
(28)

4 A low switching frequency capacitor voltage balancing method

From the above analysis, the extra switching actions of the SMs are the main reason for the high losses of an MMC. To solve the problem, a low switching frequency capacitor voltage balancing method without sorting is proposed.

The proposed capacitor voltage balancing method takes the capacitor voltage dispersion as the direct control object, and the "voltage allowable distribution



Fig. 8 The voltage allowable distribution band and SM input priority

band" and "SM input priority" are introduced. In each control cycle, the SM status in the previous control cycle remains unchanged, if possible, to avoid unnecessary switching actions, as shown in Fig. 8. The width of the capacitor voltage distribution band is determined by the voltage dispersion threshold $\sigma_{\rm m}$, and the upper and lower limits can be obtained as:

$$\begin{cases} U_{c_upper} = U_{c_avg} + \sigma_m U_{cN} / 2 \\ U_{c_lower} = U_{c_avg} - \sigma_m U_{cN} / 2 \end{cases}$$
(29)

Taking the arm current $i_{arm} > 0$ as an example, there are three cases:

Case 1) if SM capacitor voltages are less than the lower limit value of the voltage allowable distribution band, the SMs should be in the ON state as much as possible to increase their voltages into the voltage allowable distribution band as soon as possible. In order to avoid unnecessary switching actions, the SMs of the ON state group should remain in the ON state in the current control cycle, and their input priority is P_{1_oon} . Then, the SMs in the OFF state group should be changed to the ON state, and their input priority is P_{1_oon} .

Case 2) if the SM capacitor voltages are within the voltage allowable distribution band, the SMs should selectively maintain the original switching states according to the actual number of SMs in the ON state of the arm given from the modulation. The input priorities of the SMs are divided into $P_{2_{\text{ON}}}$ and $P_{2_{\text{OFF}}}$ according to their states.

Case 3) If the SM capacitor voltages are greater than the upper limit of the voltage allowable distribution band, the SMs should be in the OFF state if possible to avoid further increase of the capacitor voltages. Therefore, the SMs of the ON state group should be changed to the OFF state, and their input priority is $P_{3_{\text{OFF}}}$. The SMs of the OFF state group should remain in the OFF state in the current control cycle, and their input priority is $P_{3_{\text{OFF}}}$.

To sum up, for each input priority divided above, the smaller the value, the higher the priority, and the greater the possibility of the SMs being in the ON state. SMs maintain the switching states of the previous control cycle in the current control cycle as much as possible. The switching states of some SMs are changed only when their capacitor voltages exceed the upper and lower limits of the voltage allowable distribution band. In addition, for the SMs with the same priority (*P*1, *P*2 and *P*3), the priority of the ON state group is always higher than that of the OFF state group when the current is positive.

5 Simulation

In order to verify the proposed MMC valve loss calculation method, based on the actual parameters of the Luxi±350 kV/1000 MW HVDC Project in China, an MMC electromagnetic transient simulation model is built in the PSCAD/EMTDC simulation software, and the loss calculation method proposed is implemented in MATLAB software. This has two parts: the static loss calculation and the switching loss models. The detailed simulation parameters are shown in Table 2. First, the calculated and simulation values are compared in various conditions for the three typical topologies of HBMMC, FBMMC, and CDMMC to verify the correctness and accuracy of the proposed method. Then, the three voltage balancing control methods are adopted to compare the proposed loss calculation method with the simulation results. Finally, the calculation results of MMC losses in different operating conditions are analysed and verified.

5.1 Static loss distribution of SM

The MMC operates at a rated power of 1000 MW in a rectified state, with a power factor of 1. All SMs only output positive and zero levels. The numbers of HBMMC and FBMMC arm SMs are N=468, and the number of CDMMC arm SMs is N/2=234, which ensures the same output voltage levels. The steady-state operation waveforms of the HBMMC are shown in Fig. 9. The AC output voltages and currents are shown in Fig. 9a, c, and the arm output voltages are shown in Fig. 9b. These are step waves according to the reference values of arm voltages and the control sampling frequency. The arm currents only contain the fundamental and DC components since the circulating current suppressing strategy is adopted in the simulation, as shown in Fig. 9d.

The instantaneous conduction losses of each switching device of the three topologies are shown in Figs. 10, 11, 12. The red curves and blue curves represent the instantaneous conduction losses of the IGBTs and diodes respectively. These are determined by the current direction and switching function, and are similar to the



Fig. 9 The steady-state operation waveforms of the HBMMC. **a** AC output voltages. **b** Arm voltages. **c** AC output currents. **d** Arm currents



Fig. 10 The transient conduction loss of HBSM



Fig. 11 The transient conduction loss of FBSM

current half-wave. The conduction loss distributions are uneven since the MMC arm currents contain a DC component under the rated active power. In the HBSM case, the peak conduction losses of D1 and T2 are approximately 2.4 kW and 3.5 kW, while those of T1 and D2 are about 0.85 kW and 0.55 kW, respectively, as shown in Fig. 10. The conduction loss characteristics of FBSM shown in Fig. 11 and CDSM shown in Fig. 12 are similar to those of HBSM, with the following main differences: 1)



Fig. 12 The transient conduction loss of CDSM

the conduction losses of FBSM are twice those of HBSM due to T1 (D1) and T4 (D4), T2 (D2) and T3 (D3) having the same characteristics; and 2) T5 (D5) are in conduction continuously, and the peak conduction losses are about 5.5 kW and 1.3 kW, which are significantly higher than in other switching devices.

The waveforms of the instantaneous off-state losses of the three types of SMs are shown in Fig. 12d. Similar to the conduction losses, the FBSM off-state losses are also twice those of the HBSM, and the off-state losses of the CDSM are relatively high since the diodes D6 and D7 in the CDSM remain cut-off. The off-state losses of the three types of SMs are much smaller than the conduction losses. The above simulation results verify the correctness of the loss distribution characteristics of various MMC topologies.

5.2 Switching loss characteristic

The instantaneous switching loss characteristics of the four switching devices in a single HBSM are shown in Fig. 13, with the traditional sorting-based capacitor voltage balancing strategy adopted under rated conditions. The blue curves represent the instantaneous losses, which are determined by the arm currents and the switching functions. Similar to the conduction losses, the instantaneous switching losses are also unevenly distributed since the DC components existed in the arm currents. The red and yellow curves represent the equivalent instantaneous switching losses obtained by the methods proposed here and [12], respectively. Different from the blue curves, the proposed method decouples the instantaneous switching losses from the switching functions, which are similar to the half wave of arm currents. The instantaneous switching loss peaks of T1, T2, D1 and D2 in HBSM are 1.79 kW, 4.60 kW, 1.29 kW and 0.73 kW,



Fig. 13 The instantaneous switching losses. a T1. b T2 c D1. d D2



Fig. 14 The energies of the switching devices

respectively. However, the method in [12] cannot accurately reflect the switching losses in real time according to the arm currents although it realizes the decoupling of switching losses and functions.

The switching energies accumulated by the four switching devices in an HBSM during two power frequency cycles obtained by the proposed method and [12] are compared in Fig. 14. The switching loss energy variation range of the proposed method is largely the same as the simulation results. The switching loss energies of T1, T2, D1 and D2 in two power frequency cycles are 0.017 kJ, 0.061 kJ, 0.019 kJ and 0.008 kJ respectively and the total switching loss energy is 0.105 kJ. Compared with the simulation results, the respective errors are 11.20%, 0.59%, 7.50%, and 7.45%, and the total switching loss energy error is about 4.1%. These are quite different from the results calculated in [12]. The source of error in the proposed method is that the calculation of switching losses is relatively conservative for the purpose of meeting the needs of MMC reliability analysis. That is, the larger instantaneous value of the arm current in the adjacent control period is selected for calculation to avoid the possible loss reduction caused by the SM switching times lagging behind the current sampling point.

5.3 Analysis of loss calculation accuracy

According to the above analysis, the switching loss calculation method proposed in [12] is too conservative since it uses the estimated extra switching frequency $f_{\rm sw,extra}$ of power device and the switching energy $E_{\rm sw,max}$ corresponding to the peak value of the arm current as the basis for calculating switching losses, and this causes significant calculation errors, as:

$$\begin{cases} f_{\text{sw,extra}} = f_{\text{sw}} - mf_1 \\ I_{\text{max}} = \max \left[abs[i_{\text{pa}}(t)] \right] \\ P_{\text{sw,extra}} = f_{\text{sw,extra}} \times \left[E_{\text{on}}(I_{\text{max}}) + E_{\text{off}}(I_{\text{max}}) + E_{\text{ref}}(I_{\text{max}}) \right] \end{cases}$$
(30)

Therefore, another commonly used method for calculating switching losses in [31–33] is selected for comparison. The common method is to calculate the average switching frequency $f_{sw,avg}$ of power devices and the switching energy $E_{sw,eff}$ corresponding to the effective value of the equivalent currents flowing through the power devices respectively during a power cycle, and multiply them to obtain the switching losses of MMC power devices, as:

$$\begin{cases} I_{\text{eff}} = RMS[i_{\text{pa}}(t)] \\ P_{\text{sw,extra}} = f_{\text{sw,avg}} \times [E_{\text{on}}(I_{\text{eff}}) + E_{\text{off}}(I_{\text{eff}}) + E_{\text{ref}}(I_{\text{eff}})] \end{cases}$$
(31)

Under the rated operating conditions, the loss calculation results of the proposed method, the commonly used method and the method in [12] are compared with the three MMC topologies and the three voltage balancing control methods, as shown in Figs. 15 and 16.

The loss calculation results of HBMMC with the traditional sorting-based capacitor voltage balancing method are shown in Fig. 15a. In terms of conduction losses and off-state losses, the proposed method is basically consistent with the existing methods, which are not shown. However, for switching losses, the three methods are quite different. The switching losses of the four groups of switching devices (T1, T2, D1 and D2) calculated by the proposed method are 1317 kW, 4114 kW, 1443 kW and 581 kW respectively and the total switching losses of the converter valve are 7445 kW. Compared with the simulation results, the errors are 6.9%, 4.8%, 11.2% and 7.4% respectively, and the total switching loss error is about 6.8%. The loss calculation results with the two low switching frequency voltage balancing methods are shown in Fig. 15b, c, and are largely the same. Compared with the results of Fig. 15a, the switching losses are greatly reduced since the low switching frequency voltage balancing method is adopted. The total switching losses of the converter valve are 899 kW and the error is about 3.4%.

The value loss calculation results of the three MMC topologies with the three voltage balancing control methods are shown in Fig. 16. With the traditional sorting-based capacitor voltage balancing method, the errors of calculated conduction losses and off-state losses are less than 1%, and the maximum error of switching losses is 6.8%. The switching losses of HBMMC and FBMMC are largely equal, and the ratio of conduction losses is about 1:2, which is consistent with the theoretical analysis. The switching losses of CDMMC is largely equal to that of HBMMC, but the static losses (conduction losses + other losses) are about 60% higher than the latter. The detailed loss distributions of the three MMC topologies with the other two voltage balancing methods are shown in Table 5.



Fig. 15 The SM losses results under three voltage balancing methods. a The traditional method. b The LSF1 method. c The LSF2 method



Fig. 16 The valve losses results of three kinds of SMs under three voltage balancing methods. **a** The traditional method. **b** The LSF1 method. **c** The LSF2 method

Table 5 The MMC valve loss composition and loss rate

Loss type	НВММС	FBMMC	CDMMC
Off-state loss (kW)	72	144	108
Conduction loss (kW)	4833	9665	7817
Switching loss (kW) Traditional/LSF1/LSF2	6981/929/997	6981/929/997	6981/929/997
Energy storage capacitor loss (kW)	1.4	1.4	1.4
Arm inductor loss (kW)	11	11	11
Constant power load loss (kW)	112	112	56
Total loss rate (%)	1.20/0.59/0.60	1.69/1.08/1.09	1.49/0.89/0.90

The capacitor and inductor losses refer to [29]

5.4 Loss calculation under different control strategies and operating conditions

In order to further verify the accuracy of the MMC loss calculation method proposed in this paper, the MMC is simulated using different control strategies and operating conditions. The electromagnetic transient simulation and numerical calculation by adopting the traditional sorting-based voltage balancing method and the low switching frequency voltage balancing methods of LSF1 and LSF2 are carried out. Taking the HBMMC as an example, the system runs at unity power factor and the active power gradually increases from no-load to the rated power. The simulation and calculation results are shown in Figs. 17, 18, 19.

The selected capacitor voltages of the upper arm of phase A by adopting the traditional sorting voltage balance method under the rated power condition are shown in Fig. 17b. As seen, the capacitor voltage balancing control effect is better, but the SM switching actions are frequent, resulting in large switching losses, as shown in Fig. 17c. The switching loss ratio with the rated power of the traditional sorting-based capacitor voltage balancing method is as high as 0.70%, and the loss rate increases



Fig. 17 The results under the traditional method

accordingly when the active power of MMC gradually increases from no-load to the rated value. The simulated loss ratio is $0.31\% \sim 0.70\%$ and the calculated loss ratio is $0.31\% \sim 0.74\%$. The maximum calculation error is about 5.7%, which is significantly lower than the existing calculation method.

By contrast, the MMC capacitor voltage balancing control effect is relatively poor using the LSF1 and LSF2 methods, as shown in Figs. 18b and 19b. However, the switching losses are significantly reduced as can be



Fig. 18 The results under the LSF1 method



Fig. 19 The results under the LSF2 method

seen from Figs. 18c and 19c. The maximum loss ratio is reduced from about 0.70% to 0.09% compared with the traditional sorting-based capacitor voltage balancing method. The switching loss ratio of the LSF1 method is relatively less affected by power change as the switching frequency is fixed. The switching loss ratio of the LSF2 method is closely related to system power because the number of alternating SMs in real time is adjusted according to the MMC transmission power, so the losses are relatively lower under light load conditions, as shown in Figs. 18c and 19c. The calculated values of the proposed method match the simulation results well in the three control strategies, and the accuracy is significantly improved compared with the existing methods. The simulation results show that the MMC valve loss calculation method proposed in this paper is suitable for HBSM, FBSM and CDSM and other topological structures. The calculation results are consistent with the simulation results using various voltages balance strategies and operating conditions.

From the above results, the proposed loss calculation method can achieve decoupling of switching losses and pulse under the commonly used method. However, it cannot reflect the change characteristics of switching losses with arm currents in real time. Therefore, switching loss calculation error still exists although taking the effective values of equivalent arm currents reduces the loss calculation error.

5.5 The effect of the proposed voltage balancing method

With the traditional voltage balancing method and the proposed method, the SM capacitor voltages, the frequencies and the switching losses of power devices are shown in Figs. 20, 21, 22.

With the traditional method, the peak and valley capacitor voltages are 1.77 kV and 1.55 kV respectively, and the ripple coefficient of the capacitor voltages is 6.6%. In comparison, with the proposed method, the ripple coefficient of the capacitor voltages is 7.3%, indicating an increase of 10.6%. However, it is still within the acceptable range, meeting the requirements of practical engineering application (10% of rated capacitor voltage). On the other hand, with the two methods, the average switching frequencies of the first 10 SMs are 1.03 kHz and 0.23 kHz, respectively. Compared with the traditional method, the average switching frequency of the SM decreases by 78.04% and the unnecessary switching of the power devices are mostly eliminated in the proposed method.



Fig. 20 Capacitor voltages under the traditional method



Fig. 21 Capacitor voltages under the proposed method

6 Conclusion

Accurate evaluation of power losses is significant for the parameter design and reliability analysis of an MMC-HVDC. In this paper, the loss distribution characteristics of the HBSM, FBSM and CDSM are analysed. An accurate calculation method for converter power losses is proposed to obtain the extra switching losses caused by the voltage balancing strategy. This has not been calculated in detail in



Fig. 22 Capacitor voltages under the proposed method

existing methods. The proposed method is suitable for various types of MMC topologies and has good performance with different voltage balancing strategies and operating conditions. Compared with the existing power loss calculation methods, the electromagnetic transient simulation results show that the switching loss calculation accuracy of the proposed method with the three voltage balancing strategies can reach 94.3%, which is significantly higher than that of the existing methods.

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Author contributions

XX contributed to the conception of the study. YL performed the experiment and contributed to analysis and manuscript preparation. YS performed the data analyses and wrote the manuscript.

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Availability of data and materials

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Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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