

Capacitance Reduction Method on Hybrid MMC Topology with High Modulation Ratio

Qiang Fan, *Student Member, IEEE*, Jianzhong Xu, *Senior Member, IEEE*, Tian Liang, *Member, IEEE*, Venkata Dinavahi, *Fellow, IEEE*, and Chengyong Zhao, *Senior Member, IEEE*

Abstract—Hybrid MMC (Hy-MMC) has broad application prospects because of the negative level output ability in its bridge arm. A Hy-MMC topology with a high-modulation ratio is designed in this paper. A second-harmonic current injection (SHCI) strategy based on Hy-MMC in high-modulation operation is also proposed to improve the power density of Hy-MMC effectively in steady-state operation. The amplitude of SHCI is determined from the perspective of the root mean square (RMS) value of bridge arm current, and the optimal initial phase angle is determined from the multi-objective optimization (capacitor voltage ripple of sub-modules (SMs), power loss, and peak value of bridge arm current). The effectiveness and engineering practicability of the proposed SHCI strategy based on Hy-MMC in high-modulation operation is verified by the electromagnetic transient (EMT) simulation using PSCAD/EMTDC®. The simulation results show that the capacitor voltage ripple of SMs can be effectively decreased by 61.98% or the capacitance can be decreased by 40%. The power loss is also analyzed. In addition, little influence of low capacitance on multi-operation conditions of Hy-MMC is verified by EMT simulation.

Index Terms—Capacitor voltage ripple, harmonic current injection, high-modulation operation, hybrid MMC (Hy-MMC), low capacitance, multi-objective optimization, power density.

LIST OF ACRONYMS

CCSC	Circulating Current Suppressing Controller.
FBSM	Full-Bridge Sub Module.
HBSM	Half-Bridge Sub Module.
HVDC	High Voltage Direct Current.
Hy-MMC	Hybrid MMC.
NBRT	Non-Blocking Ride Through.
RMS	Root Mean Square.
SHCI	Second-Harmonic Current Injection.
SM	Sub Module.
ZSVI	Zero Sequence Voltage Injection.

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Q. Fan (corresponding author, email: 13910548020@163.com), J. Z. Xu, and C. Y. Zhao are with the State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China.

T. Liang and V. Dinavahi are with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta T6G 2V4, Canada.

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I. INTRODUCTION

MODULAR multilevel converter (MMC) has attracted extensive attention because of its high symmetry and scalability. The high-voltage direct current (HVDC) transmission technology based on MMC has been used in practical projects for grid connection of clean energy, which can effectively reduce carbon emissions [1]–[3].

The traditional MMC (T-MMC) is composed of six bridge arms, and each bridge arm is cascaded by many half-bridge sub-modules (HBSMs), which makes the big volume and huge weight of MMC. Therefore, the lightweight MMC is imperative [4], [5]. For the sub-modules (SMs) in MMC, the capacitance volume accounts for a large proportion, and the parameter value of the capacitance is related to the capacitor voltage ripple of the SMs [6], [7]. Therefore, the reduction of the capacitor voltage ripple can reduce the demand for the capacitance of SMs and then realize the lightweight MMC [8], [9].

The hybrid MMC (Hy-MMC), which is composed of HB-SMs and full-bridge SMs (FBSMs), has the negative level output capability of its bridge arm. Thus, Hy-MMC has better performance than T-MMC, which has attracted extensive attention. For example, Hy-MMC topology has been used in a practical project in China (Fig. 1), which transmits power from the Wudongde hydropower station to the Guangdong

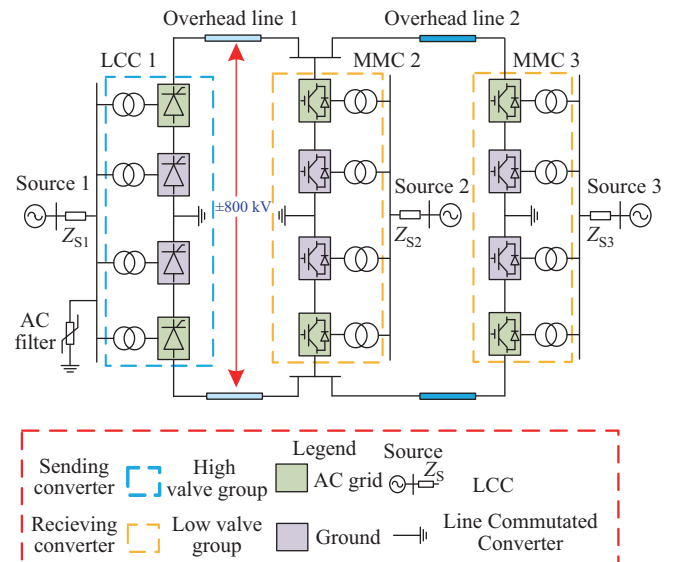


Fig. 1. System topology of HVDC project with Hybrid MMC.

and Guangxi grid [10], [11]. The FBSMs proportion of Hy-MMC is 70% (MMC2 and MMC3 in Fig. 1, and the detailed topology of Hy-MMC is shown in Fig. 2). The start-up scheme [12], steady-state operation strategy [13], low DC voltage operation [14], and non-blocking ride through (NBRT) strategy [15], [16] of Hy-MMC have been actively explored. The lightweight problem based on Hy-MMC is a timely topic in current research.

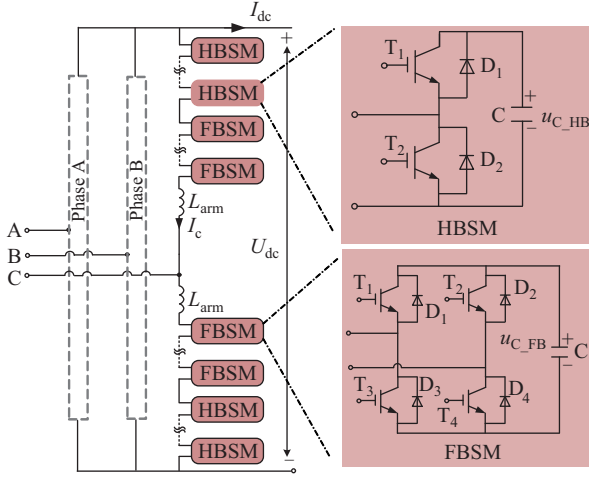


Fig. 2. Topologies of Hy-MMC and SMs.

Many control schemes of capacitor voltage ripple reduction for half-bridge MMC can be directly used in Hy-MMC because they do not need the negative level output capability of FBSMs. The classical circulating current suppressing controller (CCSC) is proposed in [17], and the circulating current of MMC is suppressed to zero by the CCSC. In contrast to [17], utilizing circulating current instead of suppressing it to zero is also an effective scheme to reduce the capacitor voltage ripple of SMs in MMC. The second harmonic current is the main component of the circulating current in MMC. Various methods to determine the amplitude and initial phase angle of the second harmonic current injection (SHCI) are proposed [18], [19]. The capacitor voltage ripple of the SMs is aimed as the objective function to get the optimal second harmonic current. Based on the instantaneous information of MMC, an improved method of SHCI is proposed in [18]. Based on [18], a unified online calculation scheme of SHCI by using the instantaneous information of MMC is proposed in [19], and the impact of SHCI on power loss and root mean square (RMS) value of arm current is also considered.

Furthermore, the zero-sequence voltage injection (ZSVI) scheme is proposed in [20], which can improve the modulation ratio and reduce the capacitor voltage ripple of SMs. The average capacitor voltage control of SMs is proposed in [21], which can reduce the MMC energy storage requirements. However, the DC voltage may be adjusted, which is not easy to realize in the practical project.

Based on the negative level output capability of the FBSMs, many new schemes have been proposed. In [22], a scheme to reduce the fundamental frequency ratio of capacitor voltage ripple is proposed, which is useful to decrease the capacitor

voltage ripple. Moreover, SHCI is proposed to suppress the ripple caused by reactive power in [22]. Based on the state trajectory analysis, a novel SHCI method is proposed in [23] to eliminate both the fundamental frequency and the second-order harmonic of the capacitor voltage ripple. A special modulation index of 1.15 is also needed in [23]. The modulation index is up to 1.414 to further decrease the capacitor voltage ripple of SMs [24]. Both second-order harmonic and third-order voltage are considered in [25] to reduce the capacitor voltage ripple. Based on [25], the determined scheme of second-order harmonic and third-order voltage is proposed in [26] to suppress the fundamental and second-harmonic components of instantaneous power. In addition, the schemes of single-line-to-ground fault based on Hy-MMC reduce the capacitor voltage ripple of SMs are proposed in [27], [28], fundamental-frequency reactive circulating current injection [29] is proposed to balance the capacitor voltage in Hy-MMC under DC faults. Based on the negative level output capability of FBSMs, fewer SMs will be used under the condition that the amplitude of MMC AC voltage remains unchanged in [30]. The optimum injection of SHCI for the reduction of capacitor voltage ripple in over-modulated MMC is proposed in [31].

The above contents have actively explored the capacitance reduction schemes of SMs in Hy-MMC and make full use of the negative level of FBSMs to reduce significantly the capacitor voltage ripple of SMs. However, the following points need to be further studied and discussed: 1) how does the harmonic injection affect the peak value and RMS value of the bridge arm current. When selecting the harmonic injection, the peak value and RMS value of bridge arm current should be considered quantitatively; 2) how to optimize the proportion of the FBSMs to reduce the construction cost of the whole Hy-MMC with a high-modulation ratio; 3) verify the influence of low capacitance on the transient state and the steady-state of Hy-MMC by electromagnetic transient (EMT) simulation.

Based on the above analysis, the high-modulation operation of Hy-MMC (HMH-MMC) with a capacitance reduction method is proposed in this manuscript. The main contributions of this manuscript are as follows: 1) The FBSMs proportion of HMH-MMC is optimized by adding extra HBSMs, which can operate in the high-modulation mode and decrease the usage of power electronic devices. 2) The determination method of SHCI is proposed. The amplitude of SHCI is determined from the perspective of the RMS value of the bridge arm current, and the optimal initial phase angle is determined from the multi-objective optimization (capacitor voltage ripple of SMs, power loss, and peak value of bridge arm current). 3) Furthermore, the operations (low DC voltage operation in steady-state and NBRT process under DC fault state) of Hy-MMC under low capacitance are also verified by EMT simulation.

The rest of this paper is organized as follows: Section II introduces the HMH-MMC. Based on Section II, the optimal determination method of amplitude and initial phase angle of the SHCI is obtained in Section III. The EMT simulation verification in PSCAD/EMTDC[®] and the economic analysis of SHCI the method based on HMH-MMC are shown in Section IV. Section V gives the conclusion of the work.

II. HIGH-MODULATION OPERATION OF HY-MMC

The topology of the Hy-MMC is shown in Fig. 2. Hy-MMC is composed of 6 identical bridge arms. Each bridge arm contains bridge arm inductance (L_{arm}) and numerous SMs. There are two types of SMs in Hy-MMC: HBSM and FBSM. HBSM is composed of IGBTs (T_1 and T_2), diodes (D_1 and D_2), and capacitors (C), while the number of power electronic devices in FBSM is twice that of HBSM. It is noted that phase A will be used for analysis if there is no special description.

The bridge arm voltage (phase a) of T-MMC can be obtained from (1):

$$\begin{cases} U_{pa} = \frac{U_{dc}}{2} - U_a \sin(\omega t) \\ U_a = \frac{m}{2} U_{dc} = \frac{m}{2} N \cdot u_{cave} \end{cases} \quad (1)$$

where U_{pa} is the upper bridge arm voltage, U_{dc} is the DC voltage, U_a is the amplitude of modulation voltage, m is the modulation ratio, ω is the system angular frequency, t is the time variable. u_{cave} is the average voltage of the capacitor in SMs, and N is the number of SMs that support DC voltage.

Due to the negative level output capability of the FBSM, the bridge arm voltage of Hy-MMC can also be negative. Two modes can make the bridge arm voltage negative from (1): high amplitude of modulation voltage and low DC voltage, which are shown in Fig. 3, where U'_{dc} is the DC voltage of Hy-MMC, U'_a is the amplitude of modulation voltage of Hy-MMC, the relationships of these variables are shown in (2):

$$\begin{cases} U'_a > U_a \\ U'_{dc} < U_{dc} \end{cases} \quad (2)$$

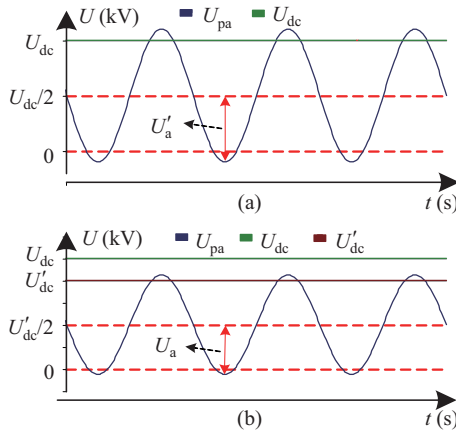


Fig. 3. Two modes of negative bridge arm voltage. (a) High amplitude of modulation voltage. (b) Low DC voltage.

Mode A: DC voltage is constant and the amplitude of modulation voltage is increased, bridge arm voltage will be negative (Fig. 3(a)), which often happens in high modulation ratio conditions in steady-state operation. Extra SMs will be added to the bridge arm to keep a high modulation ratio under constant DC voltage.

Mode B: The amplitude of modulation voltage is constant and DC voltage is decreased; bridge arm voltage will also be

negative (Fig. 3(b)). No extra SMs are needed, which often happens in low DC voltage conditions in a steady state.

The proportion of FBSM is at least 50% when the DC fault can be cleaned without blocking the Hy-MMC. A higher proportion of FBSM is required or SHCI [32] is used when the DC voltage of Hy-MMC ramps from rated value to zero with constant amplitude of modulation voltage. If a high modulation ratio in steady-state and clearing DC fault without blocking converter are both required in Hy-MMC, the total number of SMs in the bridge arm in Hy-MMC will be over N [26] and the FBSM proportion of Hy-MMC is ζ ($\zeta \geq 0.5$).

Two types of Hy-MMC are defined and compared below:

Normal-modulation Hy-MMC (NMH-MMC): Hy-MMC with NBRT capability ($\zeta \geq 0.5$).

High-modulation Hy-MMC (HMH-MMC): based on NMH-MMC, high modulation ratio operation (Mode A) in steady-state is also included.

The comparison of three topologies (T-MMC included) is shown in Table I. The modulation ratio of NMH-MMC usually does not operate at its maximum value to keep some safety margin. Based on the rule of the safety margin ratio, the maximum value of the modulation ratio in HMH-MMC can be obtained from (3):

$$\frac{m}{1} = \frac{m'}{m_{max}} = \eta \quad (3)$$

where m is the modulation ratio of NMH-MMC, m' is the high modulation ratio of HMH-MMC ($m' > m$). m_{max} is the maximum value of modulation ratio in HMH-MMC, η is the safety margin ratio.

TABLE I
COMPARISON OF THREE TOPOLOGIES

Topologies		T-MMC	Hy-MMC	
			NMH-MMC	HMH-MMC
Types of SMs	HBSM	★	★	★
	FBSM	☆	★	★
NBRT DC fault		☆	★	★
Low DC voltage in steady state		☆	★	★
High modulation in steady state		☆	☆	★

Note: YES ★ NO ☆

When the value of m' is selected, m_{max} can be obtained from (3). Substitute m_{max} into (1), ωt is assigned $-\pi/2$, the total number of SMs in the bridge arm can be obtained from (4):

$$\begin{cases} \frac{U_{dc}}{2} + \frac{U_{dc}}{2} m_{max} = U_{pamax} \\ U_{pamax} = N' \cdot u_{cave} \end{cases} \quad (4)$$

where U_{pamax} is the maximum positive output voltage of the bridge arm, it is the total number of bridge arms. The relationship between N' and m_{max} is shown in (5):

$$N' = (1 + m_{max}) \frac{N}{2} \quad (5)$$

where N is the instantaneous value of the input phase SM number (the same meaning as N in (1)). The number of HBSM and FBSM in the bridge arm of HMH-MMC can be obtained from (6):

$$\begin{cases} N_{\text{FBSM}} = \zeta N \\ N_{\text{HBSM}} = \left(\frac{1 + m_{\text{max}}}{2} - \zeta \right) N \end{cases} \quad (6)$$

where N_{HBSM} is the number of HBSM, N_{FBSM} is the number of FBSM, ζ is the FBSM proportion of Hy-MMC.

III. OPTIMAL DETERMINATION METHOD OF SHCI

A. Amplitude Determination Method of SHCI

The SHCI can increase the RMS value of the bridge arm current and increase the power loss of the converter. The amplitude of SHCI can be determined from the perspective of the RMS value of MMC's bridge arm current.

The bridge arm current of NMH-MMC and HMH-MMC are shown in (7): (take the phase a as an example)

$$\begin{cases} i_{\text{aupNMH}} = \frac{I_{\text{dcNMH}}}{3} + I_{\text{asNMH}} \sin(\omega t + \varphi_{1\text{NMH}}) \\ i_{\text{aupHMH}} = \frac{I_{\text{dcHMH}}}{3} + I_{\text{asHMH}} \sin(\omega t + \varphi_{1\text{HMH}}) \\ \quad + I_{2\text{as}} \sin(2\omega t + \varphi_{2\text{as}}) \end{cases} \quad (7)$$

where i_{aupNMH} is the bridge arm current of NMH-MMC (when CCSC is used in NMH-MMC, no second component is included in i_{aupNMH}). I_{dcNMH} is the DC current of NMH-MMC. I_{asNMH} is the peak value of the bridge arm's fundamental phase current in NMH-MMC and $\varphi_{1\text{NMH}}$ is the initial phase angle of the fundamental phase current in NMH-MMC. i_{aupHMH} is the bridge arm current of HMH-MMC. I_{dcHMH} is the DC current of HMH-MMC. I_{asHMH} is the peak value of the bridge arm fundamental phase current in HMH-MMC and $\varphi_{1\text{HMH}}$ is the initial phase angle of the fundamental phase current in HMH-MMC. $I_{2\text{as}}$ is the amplitude of SHCI in HMH-MMC, $\varphi_{2\text{as}}$ is the initial phase angle of SHCI in HMH-MMC.

The RMS value of the bridge arm in NMH-MMC and HMH-MMC are obtained from (8), where $I_{\text{aupNMHrms}}$ is the RMS value of the bridge arm in NMH-MMC, the RMS value of the bridge

$$\begin{cases} I_{\text{aupNMHrms}}^2 = \left(\frac{I_{\text{dcNMH}}}{3} \right)^2 + \frac{I_{\text{asNMH}}^2}{2} \\ I_{\text{aupHMHrms}}^2 = \left(\frac{I_{\text{dcHMH}}}{3} \right)^2 + \frac{I_{\text{asHMH}}^2}{2} + \frac{I_{2\text{as}}^2}{2} \end{cases} \quad (8)$$

arm in HMH-MMC is $I_{\text{aupHMHrms}}$.

Under the same working conditions of DC voltage and active power, I_{dcNMH} and I_{dcHMH} are equal. Compared with NMH-MMC, the modulation ratio of HMH-MMC is increased, I_{asHMH} is less than I_{asNMH} . The value of $I_{2\text{as}}$ can be determined by making the value of $I_{\text{aupNMHrms}}$ and $I_{\text{aupHMHrms}}$ equal, which can be obtained from (9):

$$\begin{cases} I_{\text{aupNMHrms}} = I_{\text{aupHMHrms}} \\ I_{2\text{as}} = \sqrt{1 - \left(\frac{m}{m'} \right)^2} I_{\text{asNMH}} \end{cases} \quad (9)$$

where m and m' have the same meaning of that in (3).

Assuming the power factor of NMH-MMC and HMH-MMC is both 1, then I_{asNMH} can be obtained from (10):

$$\begin{cases} P = \frac{3}{2} U_{\text{ac}} I_{\text{ac}} \\ U_{\text{ac}} = m \frac{U_{\text{dc}}}{2} \\ I_{\text{asNMH}} = \frac{I_{\text{ac}}}{2} \end{cases} \quad (10)$$

where P is an active power, U_{ac} is the amplitude of phase voltage at the AC side in NMH-MMC. I_{ac} is the amplitude of phase current at the AC side in NMH-MMC. Substituting (10) into (9), we obtained (11):

$$I_{2\text{as}} = \sqrt{1 - \left(\frac{m}{m'} \right)^2} \frac{2P}{3mU_{\text{dc}}} \quad (11)$$

The inherent physical quantity of the system determines $I_{2\text{as}}$.

The final optimal value $I_{2\text{asf}}$ of the $I_{2\text{as}}$ can be obtained from (12):

$$I_{2\text{asf}} = k_1 \cdot \sqrt{1 - \left(\frac{m}{m'} \right)^2} \frac{2P}{3mU_{\text{dc}}} \quad (0.5 < k_1 < 1) \quad (12)$$

where k_1 is a coefficient of correction, which can expand the selection range of $I_{2\text{as}}$ and ensure that $I_{\text{aupHMHrms}}$ is not greater than $I_{\text{aupNMHrms}}$. k_1 is determined and chosen by many factors (e.g., power loss, the peak value of bridge current, capacitor voltage ripple).

B. Operational Initial Phase Angle Determination Method of SHCI

The injection of second-harmonic current will increase the peak value of the bridge arm current of HMH-MMC, which can deteriorate the current stress environment of IGBT devices in SMs. When the amplitude of the second-harmonic current is determined, the peak value of the bridge arm current is mainly affected by the initial phase angle of the SHCI. Therefore, the peak value of the bridge arm current can be considered one of the conditions for selecting the initial phase angle of the SHCI.

To expand the selectable range of the initial phase angle of the SHCI as much as possible, the bridge arm current peak value of HMH-MMC is limited to no more than 1.2 times the bridge arm current peak value of NMH-MMC. The inequality constraints about $\varphi_{2\text{as}}$ can be obtained from (13):

$$|i_{\text{aupHMH}}|_{\text{max}} < 1.2 |i_{\text{aupNMH}}|_{\text{max}} \quad (13)$$

At the same time, when the amplitude of the second-harmonic current is determined, the capacitor voltage fluctuation of the SMs will be determined by the $\varphi_{2\text{as}}$ (when other system parameters are determined). Therefore, the minimum peak value of capacitor voltage fluctuation of SMs can be regarded as one condition of the optimal $\varphi_{2\text{as}}$, which is shown in (14):

$$f(\varphi_{2\text{opt}})|_{\text{max}} \leq f(\varphi_{2\text{as}})|_{\text{max}} \quad (14)$$

where $f(\varphi_{2\text{as}})$ is the function of capacitor voltage fluctuation of SMs with $\varphi_{2\text{as}}$. $\varphi_{2\text{opt}}$ is the optimal $\varphi_{2\text{as}}$. Substituting (7) and (9) into (13), two inequality constraints of $\varphi_{2\text{as}}$ are shown in (15):

$$\begin{cases} \left| \left(\frac{m}{m'} - 1.1 \right) \sin(\omega t) + k_I \cdot \sqrt{1 - \left(\frac{m}{m'} \right)^2} \sin(2\omega t + \varphi_{2\text{opt}}) \right|_{\max} \leq \frac{m}{20} \\ f(\varphi_{2\text{opt}})|_{\max} \leq f(\varphi_{2\text{as}})|_{\max} \end{cases} \quad (15)$$

The $\varphi_{2\text{opt}}$ can be obtained by (15).

IV. EMT SIMULATION RESULTS AND DISCUSSION

A simulation case is established in PSCAD/EMTDC® to verify the effectiveness of HMH-MMC and its SHCI method. To be more suitable for practical engineering scenarios, $\zeta = 0.7$ [10]. The whole system structure is shown in Fig. 4, where Z_s is the system impedance of the AC system. NMH-MMC is taken as the control group ($m = 0.9$, maximum modulation ratio is 1, $N = 200$). Supposing the $m' = 1$ of HMH-MMC is taken as an example. The $m_{\max}$ of HMH-MMC is 1.1 (actually $m_{\max} = 10/9$, for the convenience of calculation, $m_{\max} = 1.1$). The number of HBSM and FBSM in the bridge arm of HMH-MMC can be obtained by (6) and Table II.

$$\begin{cases} N_{\text{FBSM}} = 140 \\ N_{\text{HBSM}} = 70 \end{cases} \quad (16)$$

The other system parameters of HMH-MMC are the same as those of NMH-MMC.

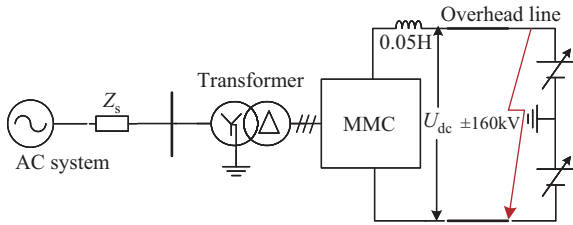


Fig. 4. System structure of simulation case.

TABLE II
PARAMETERS OF NMH-MMC AND HMH-MMC

Parameter	NMH-MMC	HMH-MMC
Rated DC voltage (kV)	320	320
Rated active power (MW)	-500	-500
Number of SMs		
HBSM	60	70
FBSM	140	140
Inductance of arm bridge (H)	0.06	0.06
The capacitance of SMs (mF)	10	10
Proportion of FBSM	0.7	0.67
Second harmonic current	0	$i_{2\text{as}}$

A. Verification of Capacitor Reduction Strategy

The system parameters are shown in Table II. The influence of the amplitude $I_{2\text{as}}$ and initial phase angle $\varphi_{2\text{as}}$ of SHCI on the peak value of capacitor voltage ripple U_{cmax} and power loss [33] of SMs P_{Loss} is shown in Fig. 5, where all the system parameters are from Table II. The relationship between U_{cmax} and $\varphi_{2\text{as}}$ can be obtained from Fig. 5(a), the same trend can be obtained by changing different $I_{2\text{as}}$. When $\varphi_{2\text{as}}$ changes from 0° to 360° , U_{cmax} first increases and then decreases. The value of U_{cmax} is relatively small when $\varphi_{2\text{as}}$ is in the range

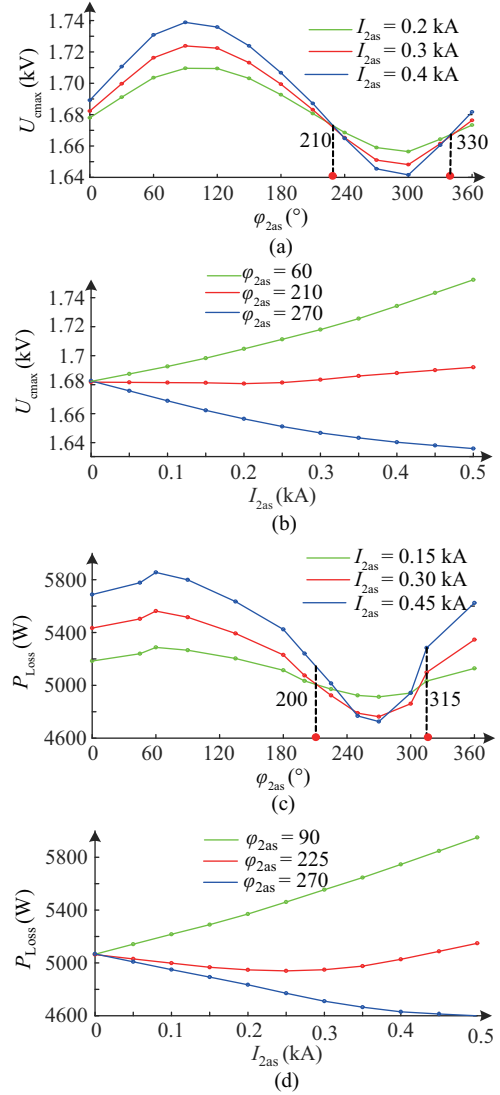


Fig. 5. The influence of $I_{2\text{as}}$ and $\varphi_{2\text{as}}$ of SHCI on the U_{cmax} and P_{Loss} . (a) Relationship between U_{cmax} and $\varphi_{2\text{as}}$. (b) Relationship between U_{cmax} and $I_{2\text{as}}$. (c) Relationship between P_{Loss} and $\varphi_{2\text{as}}$. (d) Relationship between P_{Loss} and $I_{2\text{as}}$.

of 210° to 330° . The relationship between U_{cmax} and $I_{2\text{as}}$ can be obtained from Fig. 5(b). Different $\varphi_{2\text{as}}$ has great influence on the relationship between U_{cmax} and $I_{2\text{as}}$. The relationship between P_{Loss} and $\varphi_{2\text{as}}$ can be obtained from Fig. 5(c), the same trend can be obtained by changing different $I_{2\text{as}}$. When $\varphi_{2\text{as}}$ changes from 0° to 360° , P_{Loss} first increases and then decreases. The value of P_{Loss} is relatively small when $\varphi_{2\text{as}}$ is in the range of 200° to 315° . The relationship between P_{Loss} and $I_{2\text{as}}$ can be obtained from Fig. 5(d). Different $\varphi_{2\text{as}}$ has great influence on the relationship between P_{Loss} and $I_{2\text{as}}$.

The SHCI $i_{2\text{as}}$ of HMH-MMC can be obtained from (12), (15) and Fig. 5 ($k_1 = 0.8$):

$$i_{2\text{as}} = 0.4 \sin(2\omega t - 45^\circ) \quad (17)$$

The corresponding controller of SHCI is shown in Fig. 6, where ω_0 is the system angular frequency, t is the time, $T_{\text{abc}/\text{dq}}$ is the matrix of the Park transformation, $T_{\text{dq}/\text{abc}}$ is the inverse matrix of the Park transformation. i_{2sj} ($j = a, b, c$) is

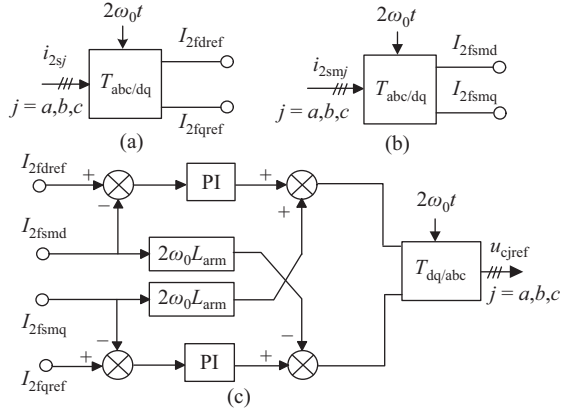


Fig. 6. Controller diagram of SHCI. (a) Reference value of SHCI in dq coordinate. (b) Measuring value of SHCI in dq coordinate. (c) Main controller of SHCI.

Note: i_{2as} is the quantity of the SHCI.

the reference value of second harmonic component of bridge arm current in MMC. I_{2fdref} is the component of i_{2sj} in d axis of dq coordinate system and I_{2fqref} is the component of i_{2sj} in q axis of dq coordinate system. i_{2smj} ($j = a, b, c$) is the measured value of second harmonic component of bridge arm current in MMC after SHCI. I_{2fsmd} is the component of i_{2smj} in d axis of dq coordinate system and I_{2fsmq} is the component of i_{2smj} in q axis of dq coordinate system. L_{arm} is the bridge arm reactance. PI is a proportional integration controller. u_{cjref} ($j = a, b, c$) is the harmonic voltage output of the whole controller, which is superimposed on the modulation wave of the main controller of MMC to realize the closed-loop control of SHCI.

For effective verification of the capacitor reduction strategy of HMH-MMC, the comparison and verification of

Two operations of equal capacitance and low capacitance will be carried out in this section.

Equal capacitance operation: capacitor voltage ripple reduction of SMs in HMH-MMC based on the same capacitance as NMH-MMC (control group).

Low capacitance operation: The capacitance reduction of SMs in HMH-MMC based on the capacitor voltage ripple is no more significant than that of NMH-MMC.

The ratio of capacitor voltage ripple reduction (equal capacitance operation) $\Delta u_{cp}\%$ and the ratio of capacitance reduction (low capacitance operation) $\Delta C_r\%$ are defined in (18):

$$\begin{cases} \Delta u_{cp}\% = \frac{u_{cp1} - u_{cp2}}{u_{cp1} - u_{cN}} \\ \Delta C_r\% = \frac{C_{r1} - C_{r2}}{C_{r1}} \end{cases} \quad (18)$$

where u_{cpj} ($j = \text{HMH-MMC, NMH-MMC}$) is the peak value of the capacitor voltage ripple of SMs in j MMC. u_{cN} is the DC part of capacitor voltage ripple in SMs. C_{rj} ($j = \text{HMH-MMC, NMH-MMC}$) is the capacitance value of SMs in j MMC.

(1) Verification of equal capacitance operation

The waveforms comparison of key measuring points of different types of MMC under equal capacitance operation is shown in Fig. 7, where U_{capave} is the average voltage of all

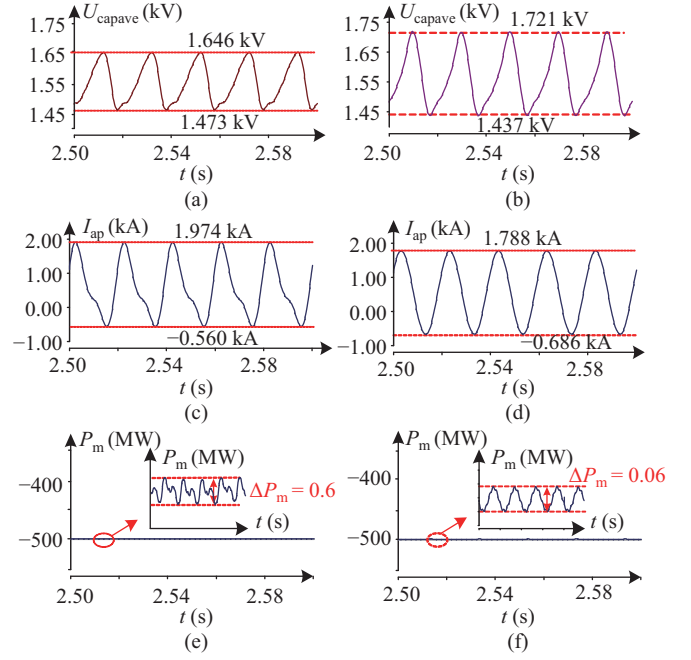


Fig. 7. Waveform comparison of key measuring points under equal capacitance operation. (a) Capacitor voltage ripple of SMs in HMH-MMC. (b) Capacitor voltage ripple of SMs in NMH-MMC. (c) Bridge arm current in HMH-MMC. (d) Bridge arm current in NMH-MMC. (e) Active power of HMH-MMC. (f) Active power of NMH-MMC.

SMs in the upper bridge arm of phase a. I_{ap} is the upper bridge arm current of phase a. P_m is the active power. The U_{capave} of HMH-MMC is 1.473 kV~1.646 kV from Fig. 7(a), and the U_{capave} of NMH-MMC is 1.437 kV~1.721 kV from Fig. 6(b). The $\Delta u_{cp}\%$ of HMH-MMC is 61.98% according to (18). The I_{ap} of HMH-MMC is -0.560 kA~1.974 kA from Fig. 7(c), and the I_{ap} of NMH-MMC is -0.686 kA~1.788 kA from Fig. 7(d).

The peak values of I_{ap} between HMH-MMC and NMH-MMC meet the (13). SHCI does not have an obvious influence on the active power by comparing Fig. 7(e) and Fig. 7(f).

On the one hand, the capacitor voltage ripple of SMs can be effectively reduced by the topology improvement method. On the other hand, the capacitor voltage ripple of SMs can be further reduced by the method of second harmonic injection. Both of these two methods have the superposition effect.

(2) Verification of low capacitance operation

To verify the effectiveness of the capacitor reduction strategy more effectively, the capacitance of SMs in Table II is reduced from 10mF to 6mF ($\Delta C_r\% = 40\%$), and the other parameters remain unchanged.

The waveforms comparison of key measuring points of HMH-MMC under low capacitance operation are shown in Fig. 8. The U_{capave} of HMH-MMC is 1.405 kV~1.691 kV from Fig. 8(a). The $\Delta u_{cp}\%$ is 24.79% when $\Delta C_r\%$ is 40%. The I_{ap} of HMH-MMC is -0.564 kA~1.980 kA from Fig. 8(b), which still meets the (13).

B. Verification of Other Operations

Due to the negative level output capability of FBSMs, there are many additional operations in HMH-MMC. It is necessary

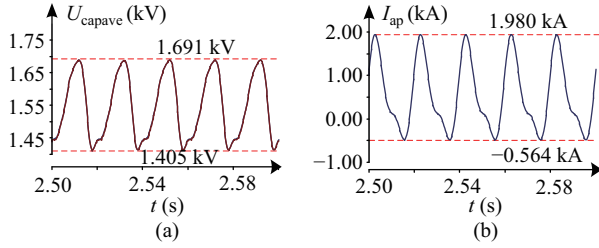


Fig. 8. Waveform comparison of key measuring points under low capacitance operation. (a) Capacitor voltage ripple of SMs. (b) Bridge arm current.

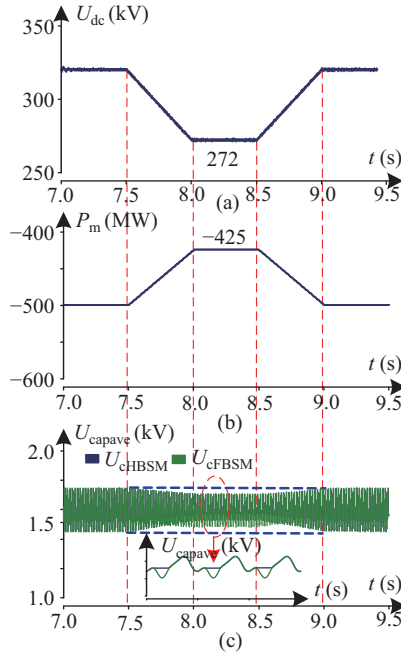


Fig. 9. Waveform of key measuring points under low DC voltage operation in steady-state. (a) DC voltage. (b) Active power. (c) Capacitor voltage ripple of SMs.

to verify the impact of low capacitance on these operations ($\Delta C_r\% = 40\%$) by EMT simulation.

1) Low DC Voltage Operation under Steady-state

HMH-MMC needs to reduce DC voltage under extreme environments to improve safety. Considering the current carrying capacity of power electronic devices, the DC current of HMH-MMC needs to remain unchanged before and after the low DC voltage operation. Therefore, the actual active power P_{act} and actual DC voltage U_{dact} meet the (19):

$$\frac{P_{act}}{U_{dact}} = \frac{P_{rate}}{U_{dcrate}} = I_{dcrate} \quad (19)$$

where P_{rate} is the rate value of active power, U_{dcrate} is the rate value of DC voltage. I_{dcrate} is the rate value of DC current. DC voltage is reduced to 85% U_{dcrate} in the form of a slope wave.

The waveforms of key measuring points are shown in Fig. 9, where P_m and U_{capave} have the same meaning as that in Fig. 7, U_{dc} is the DC voltage. The whole timeline of low DC voltage operation is as follows: The U_{dc} reduces to 85% U_{dcrate} in the form of slope wave within 7.5 s~8 s and increases to the U_{dcrate} within 8.5 s~9 s. HMH-MMC can still effectively

operate in a low DC voltage state under low capacitance of SMs from Fig. 9. The capacitor voltage ripple between FBSM and HBSM diverges because HBSM does not have the output capability of negative voltage.

2) NBRT Capability Under DC Fault Operation

NBRT capability is a key property for HMH-MMC. It is necessary to verify the NBRT capability of HMH-MMC under low capacitance operation. The NBRT capability strategy based on [16] is implemented in this work. The waveforms of key measuring points of NBRT capability of HMH-MMC under low capacitance operation are shown in Fig. 10, where Q_m is reactive power, U_{pa} is the upper bridge arm voltage of phase a, U_{dhalf} is the half value of U_{dc} . The timeline is as follows: the whole system is running in steady-state before 2 s, then the pole-to-pole DC fault (in Fig. 4) occurs at 2 s, and the fault is detected at 2.001 s. Within 2.001 s to 2.5 s, DC voltage

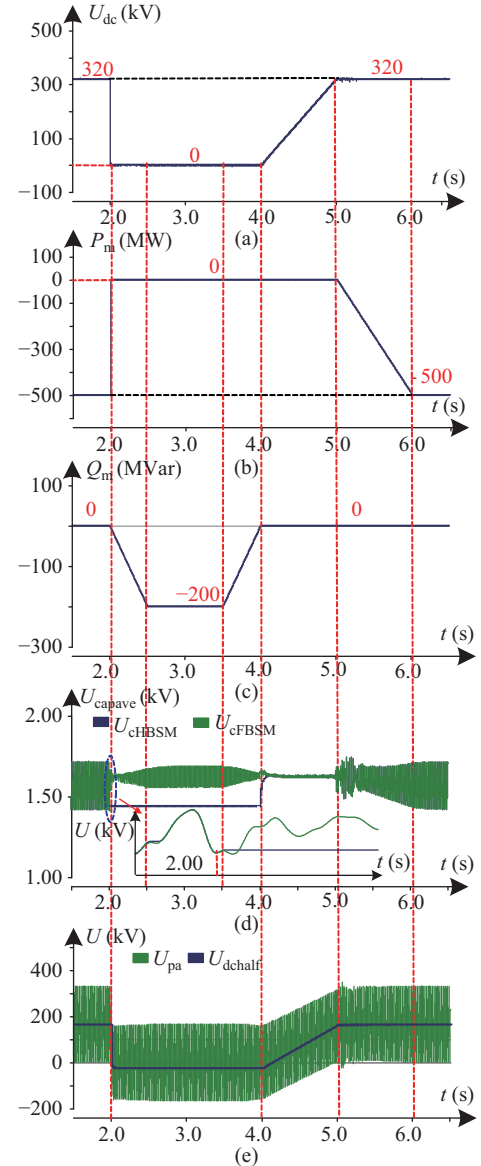


Fig. 10. Waveforms of key measuring points of no block through DC fault capability of HMH-MMC. (a) DC voltage. (b) Active power. (c) Reactive power. (d) Capacitor voltage ripple of SMs. (e) Bridge arm voltage.

U_{dc} and active power P_m are assigned 0, and Reactive power Q_m changes from 0 to -200 MVar in the form of the slope. After the DC fault is cleared, Reactive power Q_m changes from -200 MVar to 0 Mvar in the form of a slope within 3.5 s to 4 s.

Within 2.001 s~4 s, all HBSMs are bypassed. Only FBSMs are in use. Only the sinusoidal component is included in the bridge arm voltage U . Within 4 s~5 s, DC voltage U_{dc} is reestablished, and DC bias reappears in the bridge arm voltage U ; HBSMs and FBSMs are both in use. Within 5 s~6 s, active power P_m changes from 0 to -500 MW in the form of slope. The CCSC is in use within 2.001 s~4 s, and the SHCI method is in use in the other periods. The low capacitance value ($\Delta C_r\% = 40\%$) has little influence on the NBRT capability of HMH-MMC, as shown in Fig. 10.

V. ECONOMIC ANALYSIS OF HMH-MMC

The economic analysis of HMH-MMC includes construction investment and operation costs (power loss).

HMH-MMC is an improvement of NMH-MMC (Table I). The comprehensive comparison between HMH-MMC and NMH-MMC is shown in Table III, where all the system parameters are based on Table II. The power loss of FBSM is twice that of HBSM.

TABLE III
COMPARISON BETWEEN HMH-MMC AND NMH-MMC

MMC type	Construction part			Power loss (W)	
	HBSM	FBSM	C (mF)	HBSM	Six bridge arms
NMH-MMC	6×60	6×140	10	5535.33	1.13×10^7
HMH-MMC	6×70	6×140	6	4923.05	1.03×10^7

In comparison to NMH-MMC, the merits of HMH-MMC are lower power loss (10^6 W reduced) and lower capacitance ($\Delta C_r\% = 40\%$), while the demerit of HMH-MMC is that extra 60 HBSMs are needed.

A. Comparison With Other Capacitor Voltage Ripple Methods

To verify the effectiveness of the proposed method more effectively, the comparison between the dual harmonic injection [26] method and the proposed method is shown in Table IV.

TABLE IV
COMPREHENSIVE COMPARISON OF DIFFERENT METHODS

Serial number	Capacitor reduction method	Capacitor voltage ripple (kV)	Bridge arm current (kA)	Inputting the number of SMs
I	CCSC	1.471~1.687	$-0.547 \sim 1.625$	$-3 \sim 200$
II	dual harmonic injection	1.520~1.655	$-0.264 \sim 2.016$	$-7 \sim 210$
III	proposed method	1.473~1.646	$-0.560 \sim 1.974$	$3 \sim 197$

The three methods are all based on the hybrid MMC topology, with the modulation ratio $m = 1$, power factor angle $\cos \varphi = 1$ —method I is used as the blank control group. Methods II and III can both decrease the capacitor voltage ripple of SMs. Method III can reduce the amplitude of the

capacitor voltage ripple of SMs to a greater extent than that of Method II. According to (18), the $\Delta u_{cp}\%$ of Methods II and III is 36.78% and 47.13% respectively.

The range of the bridge arm current in Method II is -0.264 kA~ 2.016 kA, which is larger than that of Method III (-0.560 kA~ 1.974 kA). The range of the inputting number of SMs in Method II is $-7 \sim 210$, which is a more extensive range than that of Method III. What's more, more SMs are used, which means there is a lower margin for the number of SMs which affects the input of other types of additional controllers. The transformer connection mode of Method II is Y/ Δ because of the injection of the third harmonic voltage, which also affects some application scenarios of Method II.

VI. CONCLUSION

Hy-MMC has broad application prospects because of the negative voltage output capacity in the bridge arm. In this paper, the HMH-MMC is proposed to improve the power density of Hy-MMC. The optimal SHCI based on HMH-MMC is also proposed. The following conclusions can be drawn:

1) HMH-MMC can be obtained by adding some HBSMs based on the NMH-MMC, which can operate in the high-modulation mode.

2) The optimal SHCI method based on HMH-MMC can effectively reduce the capacitor voltage ripple (61.98%) or capacitance value (40%) of SMs in HMH-MMC. And the power loss of the optimized HMH-MMC is not greater than that of NMH-MMC.

3) The low capacitance of HMH-MMC has little effect on low DC voltage operation in steady-state and NBRT processes under DC fault states by EMT simulation.

In comparison to NMH-MMC, extra HBSMs are needed in HMH-MMC, which increases some construction investment. Furthermore, more SMs means a sophisticated sorting process of SMs in HMH-MMC, which means the requirement of more extensive computing resources. Through the above analysis, the ripple and capacitance reduction strategy based on HMH-MMC has certain innovation and engineering application value.

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Qiang Fan received the B.S. degree in Power System and Automation from China University of Mining and Technology, Beijing, China, in 2016 and received the Ph.D. degree from the School of Electrical and Electronic Engineering, North China Electric Power University, Beijing, China, in 2023. He is currently employed at the DC Technology Consulting Center, State Grid Economic and Technological Research Institute Co., Ltd., with his research focus on control and protection system of VSC-HVDC.



Jianzhong Xu received the Ph.D. in electrical engineering from NCEPU, Beijing, China, in 2014. He is currently a professor with the State Key Laboratory of Alternate Electrical Power System with Renewable Energy Resources, NCEPU. His research interests include electromagnetic transient equivalent modeling, simulation, and analysis of HVdc grid.



Tian Liang received the B.Eng. degree in Electrical Engineering from Nanjing Normal University, Nanjing, Jiangsu, China, in 2011, the M.Eng. degree from Tsinghua University, Beijing, China, in 2014, the Ph.D. degree in Energy Systems from the University of Alberta, Edmonton, AB, Canada, in 2020. He was with RTDS Technologies Inc., Winnipeg, MB, Canada. He is now with CSG Electric Power Research Institute Co., Ltd., Guangzhou, Guangdong, 510663, China. His research interests include real-time simulation of power systems, power electronics, artificial intelligence, field-programmable gate arrays, and system on chip.



Venkata Dinavahi received the B.Eng. degree in Electrical Engineering from the Visvesvaraya National Institute of Technology (VNIT), Nagpur, India, in 1993, the M.Tech. degree in Electrical Engineering from the Indian Institute of Technology (IIT) Kanpur, Kanpur, India, in 1996, and the Ph.D. degree in Electrical and Computer Engineering from the University of Toronto, Toronto, ON, Canada, in 2000. He is currently a Professor in energy systems with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada. His research interests include real-time simulation of large-scale power systems and power electronic systems, electromagnetic transients, device-level modeling, machine learning, artificial intelligence, and parallel and distributed computing. Dr. Dinavahi is a Fellow of the Engineering Institute of Canada (EIC) and Asia-Pacific Artificial Intelligence Association (AAIA). He is a Professional Engineer in the Province of Alberta, Canada.



Chengyong Zhao received the B.S., M.S., and Ph.D. degrees in Power Systems and Its Automation from NCEPU, Beijing, China, in 1988, 1993, and 2001, respectively. From January 2013 to April 2013 and September 2016 to October 2016, he was a Visiting Professor with the University of Manitoba, Winnipeg, MB, Canada. Currently, he is a Professor with the School of Electrical and Electronic Engineering, NCEPU. His research interests include HVDC systems and DC grid.