A Simple and Cost-effective Precharge Method for Modular Multilevel Converters by Using a Low-Voltage DC Source

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***Abstract*—A simple and cost-effective precharge method for modular multilevel converter (MMC) by using a low-voltage direct current (dc) source is proposed in this paper. The submodule (SM) capacitors in MMC are required to be precharged to their nominal voltage values at start-up to ensure MMC work normally. Conventional methods perform the precharging either through grid side or dc side by using costly high-voltage bypass breakers, charging resistors or a high-voltage dc source. Voltage of the high-voltage dc source must be equal to SM capacitor voltage and could be as high as thousands of volts. By contrast, the proposed method employs a very low voltage dc source on dc bus through a series-connected blocking diode, and requires no charging resistor and bypass breakers. It takes advantages of the existing power devices, arm inductors, and SM capacitors in MMC, and configures them into boost circuit for the precharging. The proposed method is simple and cost-effective. Moreover, the characteristics of the boost circuit render the proposed method flexible. For instance, the voltage selection of the dc source is flexible and not restricted to a fixed value. The SM capacitors can be charged in different groups. In addition, the method is applicable to different MMC SMs, including SM with different capacitor voltages. The effectiveness of the proposed method is verified through simulation and experiment.**

***Index Terms*—Boost circuit, low-voltage dc source, modular multilevel converter, precharge.**

I. INTRODUCTION

MODULAR multilevel converter (MMC) has attracted increasing attention in high- and medium-voltage applications [1]. Compared with other multilevel converter topologies, MMC displays modularity and scalability that satisfy any voltage level requirements, superior harmonic performance, small or no ac-side filters, and no direct current (dc)-link capacitor [2]. MMC is applicable to high-voltage dc transmission, medium-voltage motor drives, static synchronous compensator, energy storage systems, and electric railway supplies [3]–[9].

Over the past few years, various techniques have been applied to address the technical challenges associated with the operation and control of MMC, including modeling [10], [11], control methods [12], [13], modulation strategies [14], [15], fault-tolerant management [16], and loss evaluation [17]. The precharge of submodule (SM) capacitors of MMC is another key issue. MMC is comprised of a number of series-connected SMs. Each SM contains one or more capacitors depending on SM topologies. These SM capacitors are required to be precharged to their nominal voltage values at start-up to ensure MMC work normally.

Several methods have been developed in literature to precharge SM capacitors in MMC. These methods can be divided into three categories. Methods in the first category charge the SM capacitors through the grid side (ac side) [18]–[24]. These methods are suitable for grid-connected MMC. Grid voltage is used for precharging. Additional charging resistors are used to limit charging current. To bypass the charging resistors after precharging, additional bypass breakers are used parallel with the resistors. In [18]–[23], the resistors and breakers are connected on the ac side in series with the grid. In [24], they are placed in MMC arms, in which more resistors and breakers are required. The resistors and breakers are at the same voltage rating with the grid and very costly in high- and medium-voltage applications where the voltage ratings are very high. Meanwhile, the bypass breakers consistently stay in the power circuit in normal operation, which reduces the system reliability. Methods in the second category conduct precharging by using separate charging circuits for each SM capacitor [25]. Each capacitor requires one charging circuit. Each charging circuit consists of several power switches and shares a common dc voltage source. This method requires a large number of additional power switches and thus is not cost-effective. Methods in the third category charge the SM capacitors through the dc bus of MMC. In [26], a dc voltage source is used on the dc bus to do precharging. However, the dc-source voltage in this method must be equal to the nominal SM capacitor voltage and could be as high as thousands of volts. The use of a high-voltage dc source is very costly. Moreover, this method does not work for SMs with different capacitor voltages.

This paper proposes a simple and cost-effective precharge method for MMC by using a low-voltage dc source. The low-voltage dc source is connected to the dc bus of MMC through a series-connected blocking diode. The method does not require charging resistors and bypass breakers. It takes advantage of the existing power devices, arm inductors, and SM capacitors in MMC, and configures them into boost circuits for the

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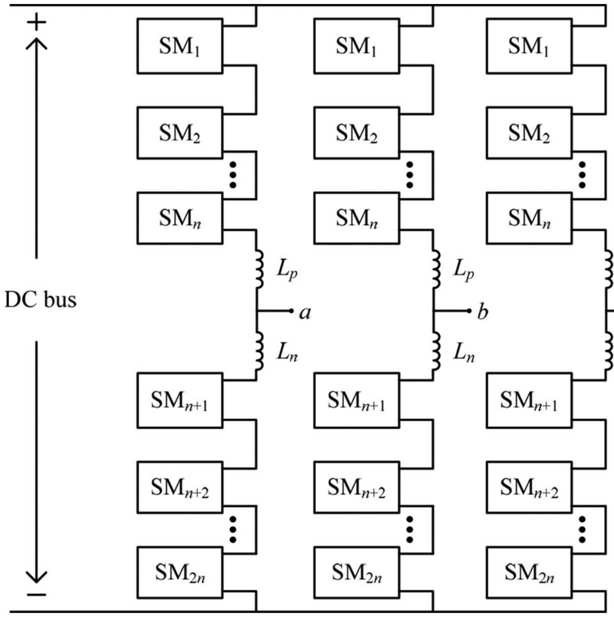

Fig. 1. Schematic of three-phase MMC.

precharging. The proposed method is simple and cost-effective. Moreover, the characteristics of the boost circuit render the proposed method flexible. For instance, the voltage selection of the dc source is flexible and not restricted to a fixed value. The SM capacitors can be charged in different groups. In addition, the method is applicable to different MMC SMs, including SM with different capacitor voltages. The effectiveness of the proposed method is verified through simulation and experiment.

II. MMC

A three-phase MMC is shown in Fig. 1. It consists of $2n$ series-connected SMs and two arm inductors in each phase. The SMs and inductors are divided into two arms, namely, top arm and bottom arm. Each arm is composed of n series-connected SMs and a series-connected arm inductor. As shown in Fig. 1, $\mathrm{SM}_1 - \mathrm{SM}_n$ and inductor L_p comprise the top arm, and $\mathrm{SM}_{n+1} - \mathrm{SM}_{2n}$ and inductor L_n comprise the bottom arm.

Each SM of MMC in Fig. 1 can be realized by different topologies [2], [27], [28]. Fig. 2 shows a few SM topologies, including half-bridge SM, full-bridge SM, clamp-double SM, three-level neutral point clamped SM, and three-level flying capacitor (FC) SM.

The half-bridge SM, which is shown in Fig. 2(a), consists of two switches S_1 and S_2, and a capacitor C. For the half-bridge SM, the relationship between the nominal dc-bus voltage of MMC and the nominal capacitor voltage of SM can be expressed as

$$V_c = V_d/n \tag{1}$$

where V_c is the nominal capacitor voltage of SM, V_d is the nominal dc-bus voltage of MMC, and n is the number of SMs per arm.

If the three-level FC SM, which is shown in Fig. 2(e), is considered, the case will be different. There are two capacitors C_L and C_H in this SM, and their voltages are denoted by V_{cL} and V_{cH}, respectively. The nominal value of V_{cH} is twice the value of V_{cL}. Their relationship with the dc-bus voltage can be expressed as

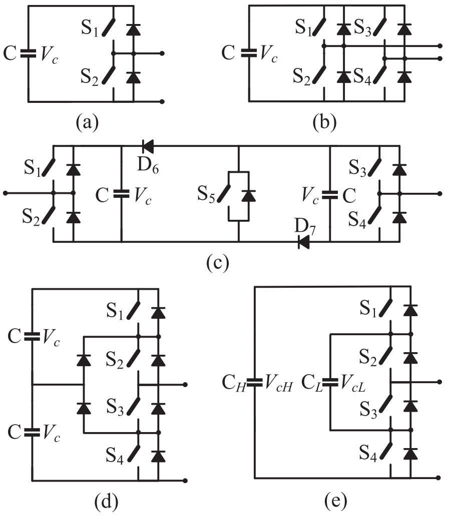

Fig. 2. Schematics of different SM topologies: (a) half-bridge SM, (b) full-bridge SM, (c) clamp-double SM, (d) three-level neutral point clamped SM, and (e) three-level FC SM.

$$V_{\mathrm{cH}} = 2V_{\mathrm{cL}} = V_d/n. \tag{2}$$

It should be noted that the value of n in (1) is twice that in (2) for the same dc-bus voltage and voltage rating of employed power devices. Power devices with voltage rating equal to 1700 or 3300 V are commonly used in MMC. If a certain margin is considered, the nominal capacitor voltage V_c in the half-bridge SM is usually around 1000 if 1700 V power devices are employed. Meanwhile, V_c is usually around 2000 if 3300 V power devices are considered. For the three-level FC SM, V_{cL} and V_{cH} are approximately 1000 and 2000 V, respectively, in the case of 1700 V power devices. If 3300 V power devices are employed in the three-level FC SM, V_{cL} and V_{cH} are approximately 2000 and 4000 V, respectively. In MMC, the voltage of SM capacitors depends on the SM topologies and voltage rating of employed power devices. The SM capacitor voltage could be as high as thousands of volts.

A dc voltage source is employed on the dc bus of MMC to precharge SM capacitors in [26]. In this method, the voltage of the dc source must be equal to the SM capacitor voltage. Because the SM capacitor voltage is as high as thousands of volts, the employed dc voltage source is a high-voltage dc source with a specified value. The use of the high-voltage dc source is costly. A charging resistor is required for limiting the charging current because of the high dc voltage. Meanwhile, this precharge method does not work for SMs with different capacitor voltage values, such as the three-level FC SM, because the value of the dc-source voltage is restricted to one SM capacitor voltage only.

III. PROPOSED PRECHARGE METHOD

A. Precharge Circuit

This paper proposes a precharge method that uses a low-voltage dc source. The precharge circuit is shown in Fig. 3. A

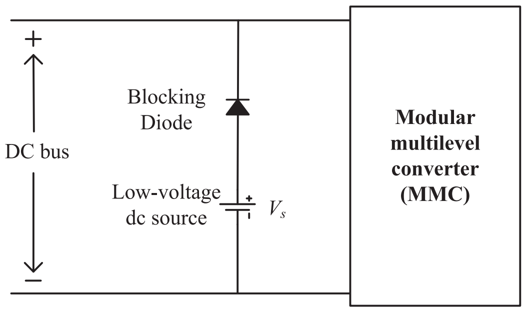

Fig. 3. Precharge circuit using a low-voltage dc source.

dc voltage source in series with a blocking diode is connected to the dc bus of MMC for precharging.

Different from the method that uses a high-voltage dc source with a voltage equal to SM capacitor voltage, the proposed method employs a low-voltage dc source. For example, a 100 V dc source can charge the SM capacitors to 1000 or 2000 V in the proposed method. The voltage selection of the dc source is flexible and not restricted to a specific value. For example, a 200 V dc source can also charge the SM capacitors to 1000 or 2000 V with the proposed method. Compared with a high-voltage dc source with a specified value, the low-voltage dc source is more flexible and cost-effective.

The blocking diode in the precharge circuit is used to block the current flowing from the dc bus to the dc voltage source after precharging. In normal operation, the dc bus voltage is higher than the dc-source voltage. The blocking diode can block the energy from the dc bus to the dc source. The blocking diode is not needed if the dc voltage source can be removed or disconnected manually after precharging, such as during the temporary test of a MMC because of fault identification or unit test, among other reasons.

B. Control Method

The dc-source voltage in the proposed method is lower than the nominal SM capacitor voltage. To charge the SM capacitors to nominal value, the voltage should be boosted. The proposed method takes advantages of the existing power devices, arm inductors, and SM capacitors in MMC, and configures them into boost circuit for the precharging. To demonstrate the control method, the MMC with half-bridge SMs is employed as an example in this section. The control principle is presented, and different charging strategies are developed.

The first charging strategy is to charge the SM capacitors one by one. The control principle can be divided into two operation modes, namely, bypass mode and insert mode, which are illustrated in Fig. 4(a) and (b), respectively. Four SMs are illustrated for each arm in Fig. 4 for simplicity. The two operation modes are described as follows.

1) *Bypass mode*: As shown in Fig. 4(a), in this mode the bottom switches ($S_{1n} - S_{8n}$) of all SMs are ON, while all top switches ($S_{1p} - S_{8p}$) are OFF. All SM capacitors are bypassed. Arm inductor current will increase, and energy will be stored in arm inductors.
2) *Insert mode*: In this mode, one SM capacitor is selected and inserted into the charging circuit to get charged, while all other SMs remain bypassed. In the example shown in Fig. 4(b), the capacitor C_1 is inserted into the charging circuit by turning off S_{1n}. In this case, the energy accumulated in arm inductors will be transferred into capacitor C_1, making the voltage of C_1 increase.

With the two operation modes, the dc voltage source, power switches, arm inductors, and SM capacitors work together as a boost circuit. With the boost circuit, the dc-source voltage can be boosted and SM capacitors can be charged to their nominal value. The control of the charging is simple since it follows the principle of boost circuit. The voltage of the dc source can be very low and is not restricted to a certain value because of the characteristics of the boost circuit.

When charging C_1, switch S_{1n} works in pulse width modulation (PWM) mode when the circuit operates between the bypass and insert modes. Turn on S_{1n} to bypass C_1 after charging it to nominal value, and control S_{2n} in the second SM work in PWM mode, consequently, C_2 can be charged. Following the same principle, all SM capacitors can be charged one by one.

The method can also charge the SM capacitors in different groups. Fig. 5 shows an example on how to charge the SM capacitors two by two. As shown in Fig. 5(b), C_1 and C_5 in the top and bottom arms, respectively, are paired as a group. The two capacitors are charged simultaneously by being bypassed or inserted into the charging circuit together. Similarly, C_2 and C_6, C_3 and C_7, C_4 and C_8 can also be grouped and charged simultaneously. Consequently, all SM capacitors can be charged two by two. Following the same principle, SM capacitors can also be charged in other groups. For instance, three or more or all capacitors can be simultaneously charged. This method is highly flexible when choosing charging strategies.

C. Applicable to Different SM Topologies

The proposed precharge method is applicable to different SM topologies. To charge a SM with the proposed method, the SM capacitor should be able to be bypassed or inserted into charging circuit. A few SM topologies are shown in Fig. 2. Apparently, all these SM topologies satisfy this requirement. They all can be charged with the proposed method.

The proposed precharge method has advantages when applied to charge SMs with different capacitor voltages, such as the three-level FC SM. As shown in Fig. 6, the three-level FC SM contains two capacitors, C_L and C_H, with voltages of V_{cL} and V_{cH}, respectively. V_{cH} is twice V_{cL}, as given in (2). Conventional precharge method does not work for this type of SM because of the voltage difference of the two capacitors. In contrast, the proposed method can charge this type of SM easily.

Fig. 6 illustrates three operation modes, namely bypass mode, insert mode I, and insert mode II, respectively, of the three-level FC SM. The three operation modes are described as follows.

1) In bypass mode [see Fig. 6(a)], switches S_3 and S_4 are turned on, while S_1 and S_2 are turned off. Current passes through S_3 and S_4. Capacitors C_L and C_H are bypassed.

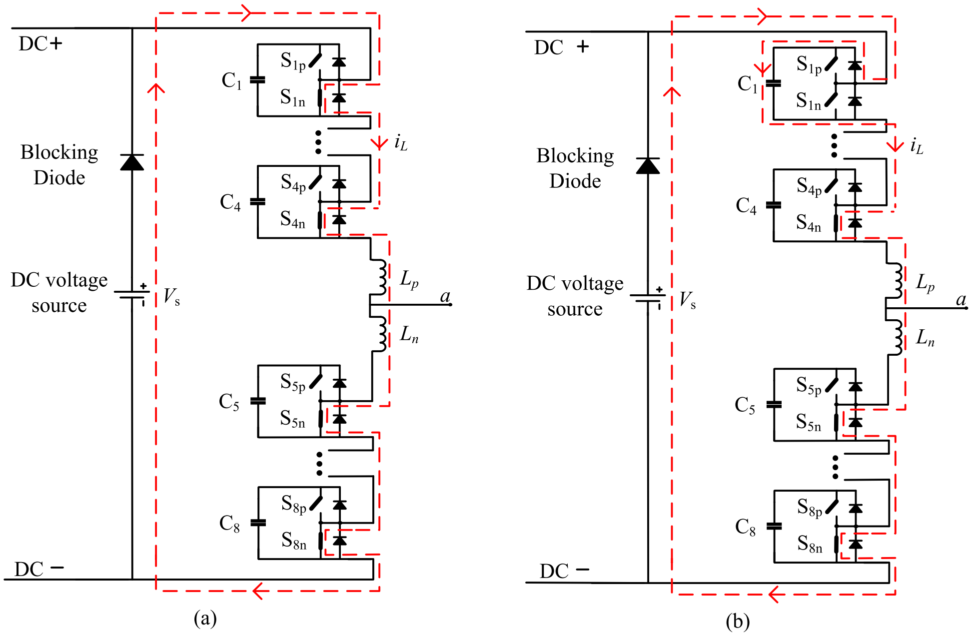

Fig. 4. Two operation modes for charging SM capacitors one by one: (a) bypass mode and (b) insert mode.

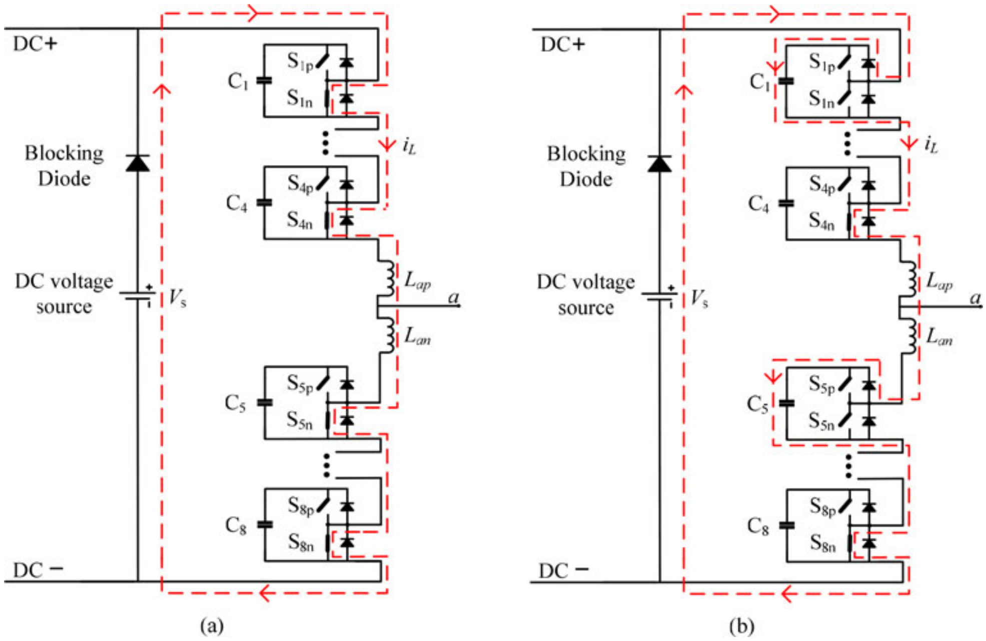

Fig. 5. Two operation modes for charging SM capacitors two by two: (a) bypass mode and (b) insert mode.

2) In insert mode I [see Fig. 6(b)], S_1, S_2, and S_3 are turned off, and S_4 is turned on. Current passes through C_L and C_H. The two capacitors are charged simultaneously.
3) In insert mode II [see Fig. 6(c)], all of the four switches S_1, S_2, S_3, and S_4 are turned off. Current passes through C_H, and only C_H is charged.

The charging procedure for the three-level FC SM can be divided into the following two steps:

1) first, C_L and C_H are charged simultaneously to the nominal value of V_{cL} by operating between the bypass mode and insert mode I;
2) second, C_H is charged to the nominal value of V_{cH} by operating between the bypass mode and insert mode II.

The previous analyses show that the proposed method is suitable for different SM topologies, including SMs with different capacitor voltages.

IV. SIMULATION RESULTS

Simulation studies have been performed by using MATLAB/Simulink to verify the proposed method. Both of the half-bridge SM and the three-level FC SM have been studied.

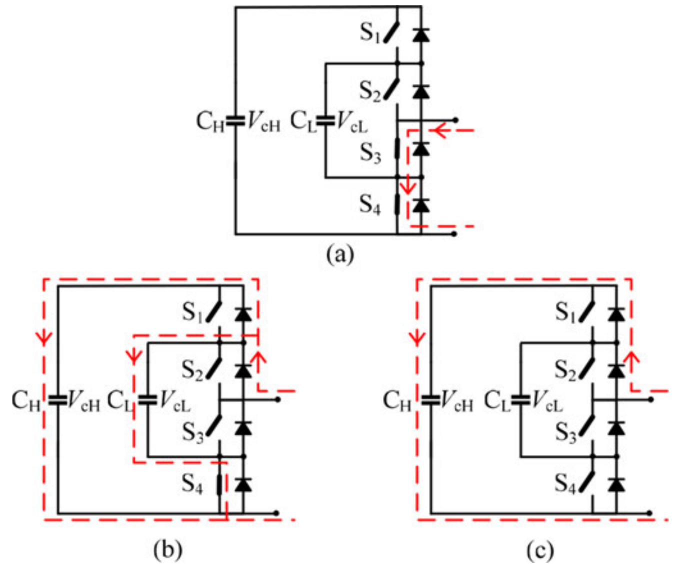

Fig. 6. Three-level FC SM: (a) bypass mode, (b) insert mode I, and (c) insert mode II.

TABLE I
SIMULATION PARAMETERS FOR HALF-BRIDGE SM

Simulation parameter	Value
Topology of SM	Half-bridge SM
Number of SMs per arm	4
Nominal SM voltage	1000 V
DC-source voltage for precharging	100 V
Capacitance of SM capacitor	4500 μF
Arm inductance	2.5 mH

A. *Precharge for Half-Bridge SM*

Table I lists the simulation parameters for precharging MMC with half-bridge SMs. Four SMs are employed in the top arm, and four SMs are employed in the bottom arm in the simulation. The SM capacitance is 4500 μF, arm inductance is 2.5 mH, nominal SM capacitor voltage is 1000 V, and the dc-source voltage for precharing is 100 V.

Two precharge strategies have been studied. One is to precharge SM capacitors one by one. The other is to precharge SM capacitors two by two.

Fig. 7 shows the results of precharging SM capacitors one by one. The dc-source voltage and the charging current are shown in Fig. 7(a) and (b), respectively. The dc-source voltage is 100 V. The charging starts at $t = 0.5$ s, and the charging current is approximately 70 A. Fig. 7(c) shows the waveforms of the SM capacitor voltages. $V_{c1} - V_{c4}$ are the four capacitor voltages in the top arm, whereas $V_{c5} - V_{c8}$ are the four capacitor voltages in the bottom arm. It can be seen from the waveforms that the eight SM capacitors are charged to 1000 V one by one.

Fig. 8 shows the results of precharging SM capacitors two by two. The dc-source voltage and the charging current are shown in Fig. 8(a) and (b), respectively. The dc-source voltage is 100 V, and the charging current is approximately 70 A. The charging starts at $t = 0.5$ s. The waveforms of the four capacitor voltages in the top arm are shown in Fig. 8(c), and the waveforms of the four capacitor voltages in the bottom arm are shown in Fig. 8(d). As shown in the waveforms, V_{c1} and V_{c5} are charged simultaneously. After charging V_{c1} and V_{c5} to the nominal value, V_{c2} and V_{c6}, V_{c3} and V_{c7}, and V_{c4} and V_{c8} are charged sequentially.

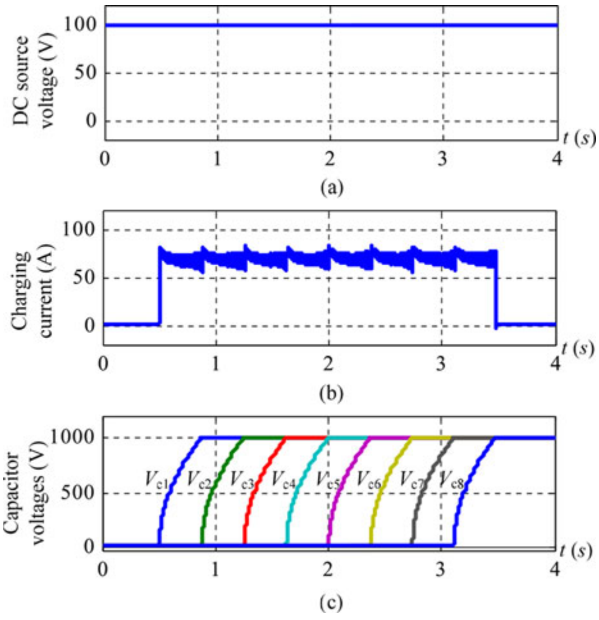

Fig. 7. Simulation results of precharging half-bridge SMs one by one: (a) dc-source voltage, (b) charging current, and (c) capacitor voltages $V_{c1} - V_{c8}$.

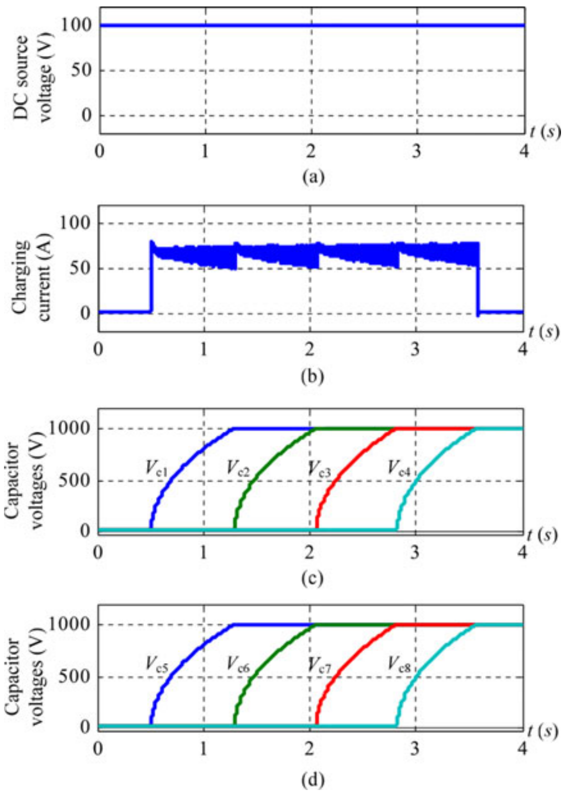

Fig. 8. Simulation results of precharging half-bridge SMs two by two: (a) dc-source voltage, (b) charging current, (c) capacitor voltages $V_{c1} - V_{c4}$, and (d) capacitor voltages $V_{c5} - V_{c8}$.

TABLE II
SIMULATION PARAMETERS FOR THREE-LEVEL FC SM

Simulation parameter	Value
Topology of SM	Three-level FC SM
Number of SMs per arm	2
Nominal SM voltage V_{cL}	1000 V
Nominal SM voltage V_{cH}	2000 V
DC-source voltage for precharging	100 V
Capacitance of SM capacitor C_L	4500 μF
Capacitance of SM capacitor C_H	2250 μF
Arm inductance	2.5 mH

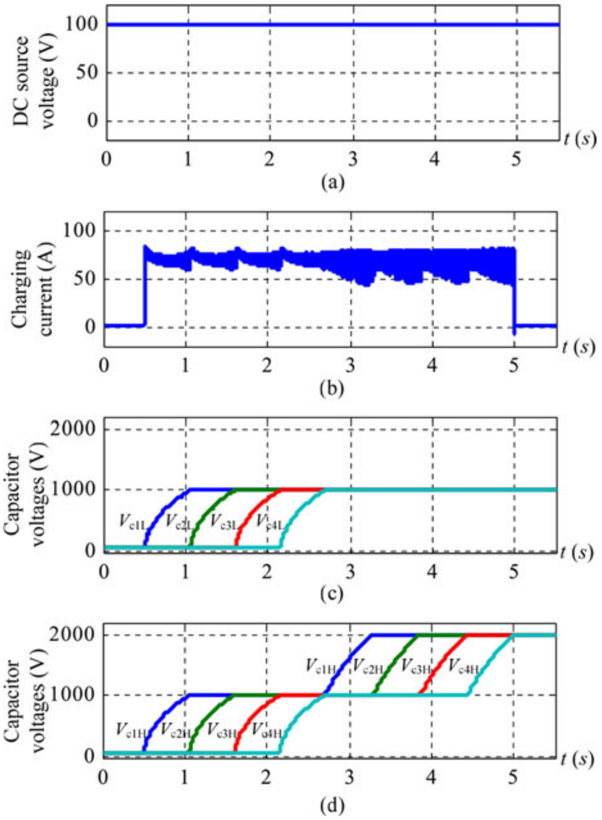

Fig. 9. Simulation results of precharging three-level FC SMs: (a) dc-source voltage, (b) charging current, (c) capacitor voltages $V_{c1L} - V_{c4L}$, and (d) capacitor voltages $V_{c1H} - V_{c4H}$.

Finally, the eight SM capacitors are charged to 1000 V two by two.

B. Precharge for Three-Level FC SM

Table II shows the simulation parameters for precharging MMC with three-level FC SMs. Two SMs each are employed in the top and the bottom arms in the simulation. The three-level FC SM is shown in Fig. 6. The capacitance values of C_L and C_H in the three-level FC SM are 4500 and 2250 μF, respectively. Arm inductance is 2.5 mH. The two capacitor voltages, V_{cL} and V_{cH}, are 1000 and 2000 V, respectively. The dc-source voltage for precharging is 100 V.

Fig. 9 shows the simulation results of precharging the three-level FC SMs. The dc-source voltage and the charging current are shown in Fig. 9(a) and (b), respectively. Fig. 9(c) and (d) shows the SM capacitor voltages. The V_{cxL} and V_{cxH} ($x = 1$, 2, 3, 4) in the figure denote the two capacitor voltages in SM*x*. V_{cxL} shown in Fig. 9(c) is the voltage of capacitor C_{xL}, whose nominal value is 1000 V. V_{cxH} shown in Fig. 9(d) is the voltage of capacitor C_{xH}, whose nominal value is 2000 V. SM1 and SM2 are in the top arm, whereas SM3 and SM4 are in the bottom arm. As shown in Fig. 9, the charging starts at $t = 0.5$ s. First, V_{cxL} and V_{cxH} in SM*x* are charged together to 1000 V, and then V_{cxH} is charged individually to 2000 V. The simulation results verify the proposed method.

TABLE III
EXPERIMENTAL PARAMETERS

Experimental Parameter	Value
Topology of SM	Half-bridge SM
Number of SMs per arm (n)	4
Nominal SM capacitor voltage	200 V
DC-source voltage for precharging	20 V
Capacitance of SM capacitor	4500 μF
Arm inductance	2.5 mH

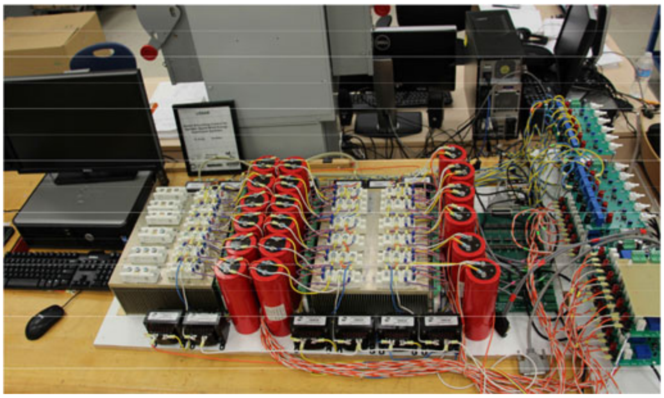

Fig. 10. Photograph of the laboratory prototype.

V. EXPERIMENTAL RESULTS

Experiments have been carried out to verify the proposed precharge method. Table III shows the experimental parameters. Half-bridge SMs are used in the experiment. Four SMs are employed in the top arm, and four SMs are employed in the bottom arm. The SM capacitance is 4500 μF, arm inductance is 2.5 mH, nominal SM capacitor voltage is 200 V, and the dc-source voltage for precharging is 20 V. The experimental prototype is shown in Fig. 10.

Two charging strategies are carried out in experiment. One is to charge the capacitors one by one. The other is to charge the capacitors two by two.

Fig. 11 shows the experimental results of charging the capacitors one by one. The top waveform in Fig. 11(a) is the dc-source voltage used for precharging. The voltage is 20 V. At $t = t_1$, the dc voltage source is applied to the circuit. At $t = t_2$, precharging starts. The charging current is shown in the second waveform in Fig. 11(a). The charging current is approximately 14 A. The

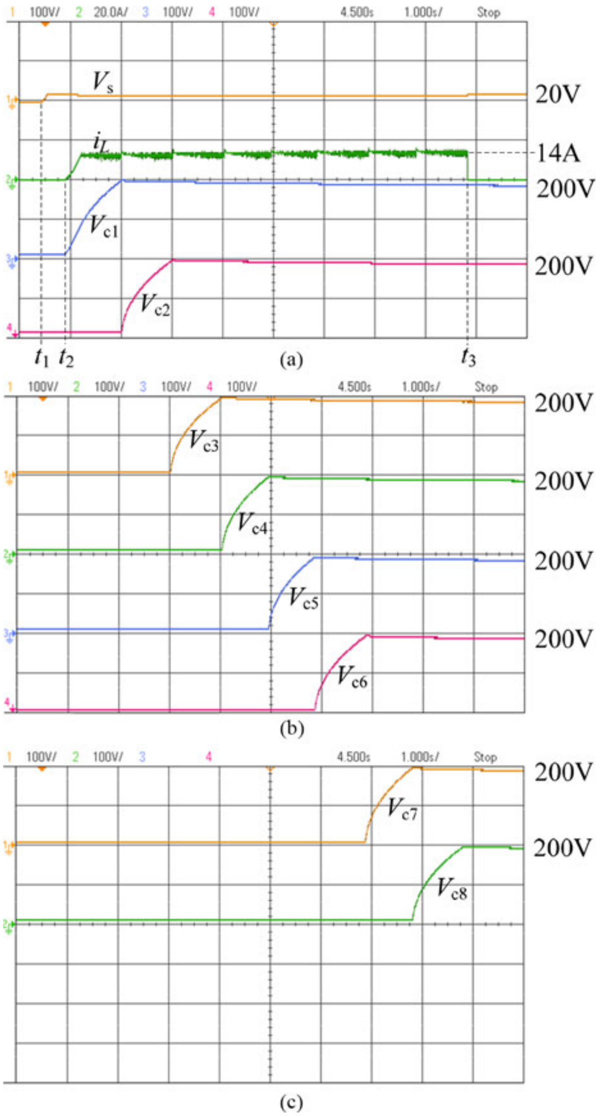

Fig. 11. Experimental results of precharging half-bridge SMs one by one: (a) dc-source voltage, charging current, and capacitor voltages $V_{c1} - V_{c2}$, (b) capacitor voltages $V_{c3} - V_{c6}$, and (c) capacitor voltages $V_{c7} - V_{c8}$.

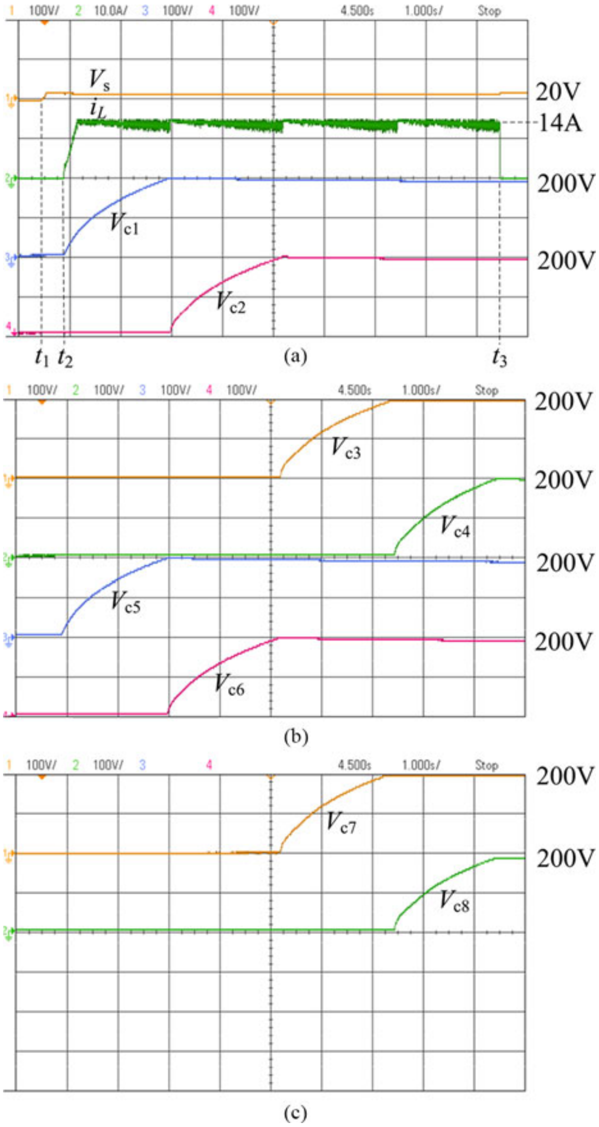

Fig. 12. Experimental results of precharging half-bridge SMs two by two: (a) dc-source voltage, charging current, and capacitor voltages $V_{c1} - V_{c2}$, (b) capacitor voltages $V_{c3} - V_{c6}$, and (c) capacitor voltages $V_{c7} - V_{c8}$.

$V_{c1} - V_{c8}$ in Fig. 11(a)–(c) are the SM capacitor voltages. V_{c1} is first charged. After charging V_{c1} to the nominal value of 200 V, V_{c2} starts to charge. As shown in the waveforms, the eight SM capacitors are charged one by one. At $t = t_3$, all of the capacitors are charged to 200 V. The charging process finishes, and the charging current becomes zero.

Fig. 12 shows the experimental results of charging the eight capacitors two by two. As shown in Fig. 12, the dc voltage source is applied at $t = t_1$, and charging starts at $t = t_2$. One SM capacitor in the top arm and one SM capacitor in the bottom arm are paired as a group and charged simultaneously. The eight capacitors are divided into four groups as follows: V_{c1} and V_{c5}, V_{c2} and V_{c6}, V_{c3} and V_{c7}, and V_{c4} and V_{c8}. The group of V_{c1} and V_{c5} is charged first, followed by V_{c2} and V_{c6}, V_{c3} and V_{c7}, and V_{c4} and V_{c8} sequentially. At $t = t_3$, the charging process finishes. All of the SM capacitors are charged to 200 V. The experimental results verify the effectiveness of the proposed method.

VI. CONCLUSION

A simple and cost-effective precharge method for MMC by using a low-voltage dc source is proposed in this paper. The proposed method employs a low-voltage dc source on dc bus, and requires no high-voltage dc source, charging resistor and bypass breakers. It takes advantages of the existing power devices, arm inductors, and SM capacitors in MMC, and configures them into boost circuit for the precharging. The proposed method is simple and cost-effective. Moreover, the characteristics of the boost circuit render the precharge method highly flexible. For instance, the voltage of the dc source is low and not restricted to a certain value. The SM capacitors can be charged in different groups. In addition, it is applicable to different SM topologies, including SMs with different capacitor voltages. The effectiveness of the proposed method is verified by simulation and experimental results.

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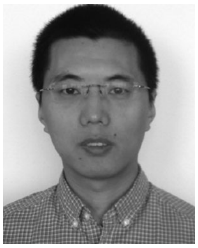

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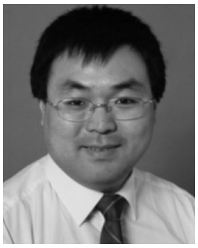

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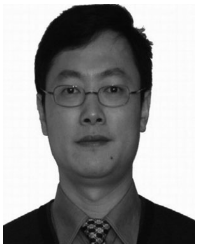

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