

Letters

Start-Up Operation of a Modular Multilevel Converter With Flying Capacitor Submodules

Apparao Dekka, *Student Member, IEEE*, Bin Wu, *Fellow, IEEE*, and Navid R. Zargari, *Fellow, IEEE*

Abstract—The three-level flying capacitor (3L-FC) submodule significantly reduces the magnitude of circulating currents, voltage ripple, and footprint size and improves the efficiency of the modular multilevel converter (MMC). Due to the above advantages, the 3L-FC submodule becomes an alternative for the conventional half-bridge submodule in the MMC. Each 3L-FC submodule consists of two floating capacitors with different nominal voltage rating. The precharging of floating capacitors without inrush current is one of the major challenges in the 3L-FC-based MMC. This paper proposes a sequence of design steps to precharge the floating capacitors in the 3L-FC-based MMC. The proposed approach is highly effective to charge the outer and inner capacitors of each 3L-FC submodule to their nominal value. The superiority of the proposed approach is verified through the MATLAB simulations and dSPACE/DS1103 experiments on a laboratory prototype of the 3L-FC-based MMC.

Index Terms—Modular multilevel converter (MMC), soft-charging, three-level flying capacitor (3L-FC).

I. INTRODUCTION

MODULAR multilevel converters (MMCs) are widely used in high-voltage high-power applications [1]. These converters are designed to handle a voltage of 6.6–220 kV by using 5–200 submodules (SMs) per arm. The standard SMs such as half-bridge (HB) and full-bridge (FB) SMs are widely employed in an MMC [2]. Among them, the HB-SM has a simple construction and easy to control (see Fig. 1). Alternatively, several multilevel SMs such as cascaded HB, a three-level flying capacitor (3L-FC), a three-level neutral-point clamped, and a double-clamp SM are developed for the MMC [3]. These SMs reduce the footprint size and improve the efficiency of the MMC. Among them, the flying capacitor SM generates a smaller voltage ripple and circulating currents compared with the HB-SM

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A. Dekka is with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, ON M5B 2K3 Canada (e-mail: dapparao@ieec.org).

B. Wu is with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, ON M5B 2K3 Canada (e-mail: bwu@ee.ryerson.ca).

N. R. Zargari is with the Medium Voltage R&D Department, Rockwell Automation, Cambridge, ON N1R 5X1 Canada (e-mail: nrzargari@ra.rockwell.com).

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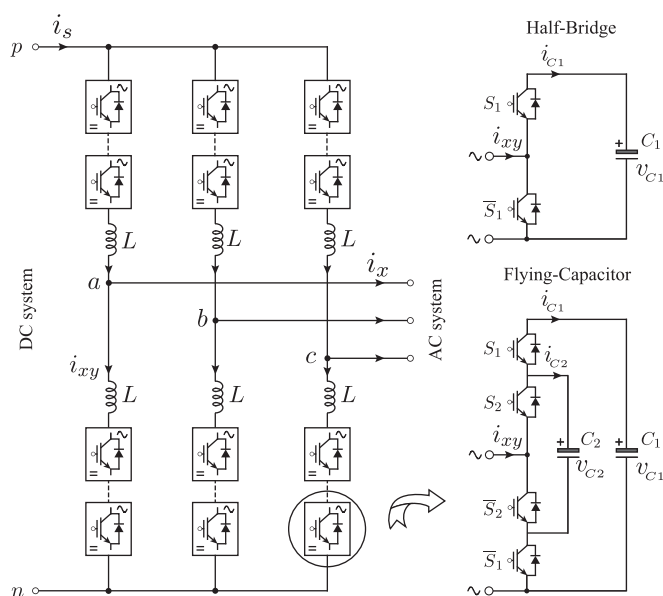


Fig. 1. MMC with a 3L-FC SM.

[4]. These features make the 3L-FC SM as an ideal solution for MMC-based motor drive systems. Over the past few years, several studies have been conducted on a 3L-FC-based MMC results in new modulation schemes, voltage-balancing methods, and model-predictive control methods [5]–[7]. Currently, the 3L-FC-based MMC is under study for the transformerless motor drive systems.

The 3L-FC SM has two floating capacitors, as shown in Fig. 1. For the three-level operation of the FC-SM, the outer capacitor voltage (v_{C1}) must be maintained at twice that of the inner capacitor voltage (v_{C2}) [4]. These floating capacitors have zero initial voltage and must be charged to its nominal voltage without inrush current. During the start-up process, the simultaneous charging of two floating capacitors with different nominal voltages is difficult and challenging one.

In the literature, several uncontrolled and controlled precharging methods are discussed for the HB-SM-based MMC only [8]–[11]. In uncontrolled charging methods, the charging resistor is inserted in the system to limit the inrush current during the start-up process. In [8], the precharging process through ac grid is presented. In this approach, the charging resistors are con-

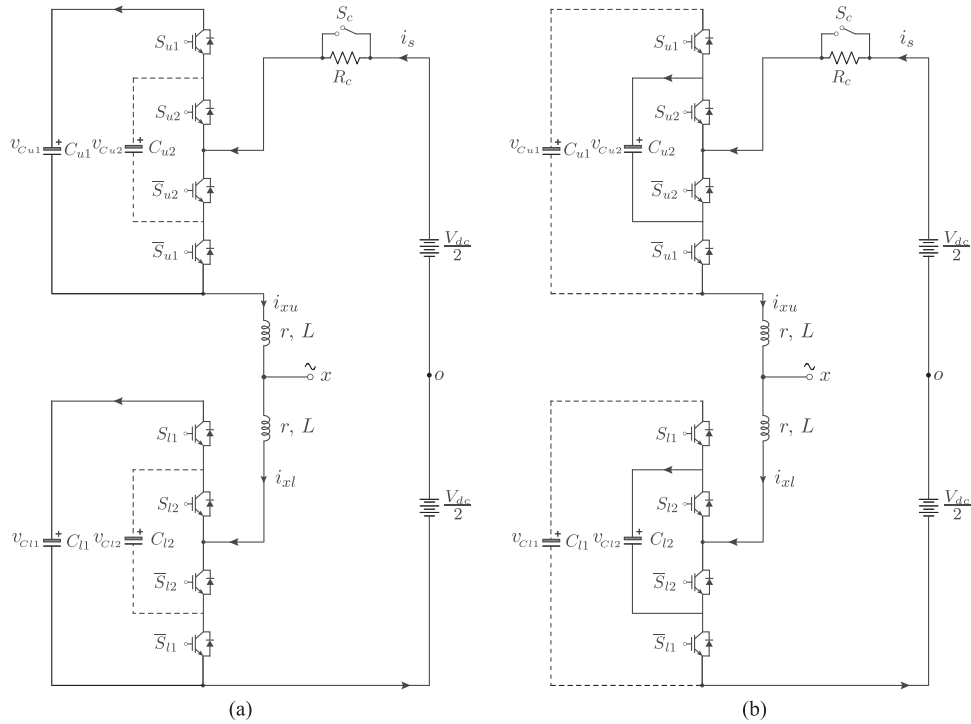


Fig. 2. Start-up operation of the 3L-FC-based MMC. (a) Stages I and III. (b) Stage II.

ected in series with the ac grid and rectifier. This approach is suitable to precharge the floating capacitors in both rectifier and inverter systems [8]. However, it requires a medium-voltage three-phase bypass switch, which is costly. Alternatively, the charging resistors are connected in series with the inductor in each arm to limit the inrush current [9]. The charging resistor, arm inductor, and SM capacitor forms an RLC damping circuit. These RLC elements are designed such that it has an overdamping response to avoid the oscillations in the dc-bus current and resulting in a large response time [9]. This approach is also costly due to the need of a higher number of medium-voltage bypass switches and the charging resistors.

In [10] and [11], the precharging process with the help of auxiliary source is presented. The nominal voltage of the auxiliary source is equal to the SM rated capacitor voltage and is connected to the dc-bus terminals p and n (see Fig. 1). In this approach, each SM is inserted one after another in the arm to charge the capacitor. This method is highly effective for the SMs (HB-SM and FB-SM) with equal capacitor voltage only. In controlled precharging methods, each SM capacitor voltage is maintained at their reference value by using a closed-loop controller [8]. This approach has a fast response time and effectively minimizes the inrush current. This approach is also suitable to the SMs with equal capacitor voltage only [8]. The existing methods are mainly designed to precharge the capacitors in the HB-SM-based MMC, and there are no studies in the literature about the precharging of the 3L-FC-based MMC.

This paper proposes a simple and effective precharging method for the 3L-FC-based MMC. The precharging process of the 3L-FC-based MMC is divided into three stages. In each stage, either the uncontrolled or the controlled charging method

is used to precharge the outer and inner capacitors of each 3L-FC SM to their nominal value. During the uncontrolled charging process, the charging resistor is connected in series with the dc bus to limit the inrush current. Unlike the existing methods, the proposed approach is cost effective and requires single charging resistor and bypass switch. In the controlled charging process, the closed-loop controller is used to limit the inrush current. The detailed analysis and the principle of start-up operation are presented in the subsequent sections of this paper. The simulations and experimental studies are presented to validate the effectiveness of the proposed precharging method.

II. START-UP OPERATION OF THE MMC

A. Principle of Start-Up Operation

The start-up operation of the 3L-FC-based MMC system is divided into three stages. In each stage, either the outer or the inner capacitor of the 3L-FC SM is charged by using an uncontrolled or the controlled charging technique. By doing so, the outer and inner capacitors of each 3L-FC SM are smoothly charged to its nominal voltage without any inrush current.

1) *Stage I: Uncontrolled Charging Process of the SM Outer Capacitor:* The equivalent circuit of stage-I start-up operation is shown in Fig. 2(a). In this process, the precharging of SM capacitors is achieved by using the main dc-bus voltage (V_{dc}). When the dc source (V_{dc}) is connected to the MMC terminals, the SM outer capacitors are automatically charged in an uncontrolled manner. In this stage, the switching state ③, as shown in Table I, is applied to all the SMs in each leg. Thus, the SM inner capacitors C_{u2} and C_{l2} in upper and lower arms are completely bypassed, and their voltages are maintained at a zero value. The

TABLE I
SWITCHING STATES OF A 3L-FC SM

| S_{pq} | S_1 | S_2 | v_{pq} | $i_{xy} > 0$ | $i_{xy} \leq 0$ |
|----------|-------|-------|-------------------|--------------------------------------|--------------------------------------|
| ① | 0 | 0 | 0 | $v_{C1} \approx, v_{C2} \approx$ | $v_{C1} \approx, v_{C2} \approx$ |
| ② | 0 | 1 | v_{C2} | $v_{C1} \approx, v_{C2} \uparrow$ | $v_{C1} \approx, v_{C2} \downarrow$ |
| ③ | 1 | 0 | $v_{C1} - v_{C2}$ | $v_{C1} \uparrow, v_{C2} \downarrow$ | $v_{C1} \downarrow, v_{C2} \uparrow$ |
| ④ | 1 | 1 | v_{C1} | $v_{C1} \uparrow, v_{C2} \approx$ | $v_{C1} \downarrow, v_{C2} \approx$ |

\approx – No change, \uparrow – Increasing, \downarrow – Decreasing.

SM outer capacitors C_{u1} and C_{l1} are charged through an antiparallel diode of the insulated-gate bipolar transistor (IGBT) devices to a maximum voltage of

$$v_{Cu1} = v_{Cl1} = \frac{V_{dc}}{2N} \quad (1)$$

where N represents the number of SMs per arm. To limit the magnitude of charging current, an external charging resistor (R_c) with a bypass switch (S_c) is connected in series with the dc-bus voltage. The magnitude of charging current is given by

$$i_s = \frac{V_{dc} - v_{Cu1} - v_{Cl1}}{R_c}. \quad (2)$$

For a normal operation of the MMC, the outer capacitors (C_{u1} and C_{l1}) in the upper and the lower arms should be charged to a voltage of

$$v_{Cu1} = v_{Cl1} = \frac{V_{dc}}{N} \quad (3)$$

but the uncontrolled charging process can charge the SM outer capacitors to a 50% of its nominal voltage.

2) *Stage II: Uncontrolled Charging Process of the SM Inner Capacitor:* The equivalent circuit of stage-II start-up operation is shown in Fig. 2(b). In this process, the switching state ① is applied to all the SMs in each leg. Thus, the SM inner capacitors are charged in an uncontrolled manner. During this process, the antiparallel diode of devices S_{u1} and S_{l1} is reverse biased, and there is no effect on the SM outer capacitor voltage (C_{u1} and C_{l1}). The inner capacitors C_{u2} and C_{l2} are slowly charged through the antiparallel diode of S_{u2} and S_{l2} to a maximum voltage of

$$v_{Cu2} = v_{Cl2} = \frac{V_{dc}}{2N}. \quad (4)$$

The magnitude of charging current is given as

$$i_s = \frac{V_{dc} - v_{Cu2} - v_{Cl2}}{R_c} \quad (5)$$

and it is controlled by using a charging resistor (R_c). For a normal operation of the MMC, the SM inner capacitors should be charged to a voltage of

$$v_{Cu2} = v_{Cl2} = \frac{V_{dc}}{2N} \quad (6)$$

which is equal to the capacitors actual voltage given in (4) during the uncontrolled charging process.

3) *Stage III: Controlled Charging Process of the SM Outer Capacitor:* In 3L-FC SMs, the outer capacitor cannot fully charge to its nominal value through the uncontrolled charging process. Hence, it requires a controlled charging technique to precharge the outer capacitors voltage to its nominal value. The equivalent circuit of stage-III operation is similar to the stage-I operation, as shown in Fig. 2(a). The precharging resistor (R_c) is bypassed by closing the contactor S_c . In this stage, the outer capacitors are slowly charged to its nominal value by controlling the magnitude of charging current using a closed-loop controller, as shown in Fig. 3. The closed-loop control system has an outer voltage and an inner current control loop. The voltage control loop regulates the average dc voltage per leg and provides a reference charging current per leg (i_s^*). The reference charging current is given by

$$i_s^* = k_{pv} (v_{Ct}^* - v_{Ct}) + k_{iv} \int (v_{Ct}^* - v_{Ct}) dt \quad (7)$$

where v_{Ct}^* represents the reference average dc voltage per leg, v_{Ct} represents the actual average dc voltage per leg, and k_{pv} and k_{iv} are the gains of the voltage PI controller. The reference charging current per leg (i_s^*) is compared with the actual charging current flowing through each leg (i_s). The current error is controlled by using a current PI controller, and its output is equal to the reference voltage command (v_{dct}^*). The reference voltage command is given by

$$v_{dct}^* = k_{pi} (i_s^* - i_s) + k_{ii} \int (i_s^* - i_s) dt \quad (8)$$

where i_s is the actual charging current flowing through each leg of the converter. The reference voltage command v_{dct}^* is added to the feedforward dc-voltage component to obtain the upper and lower arm reference voltage commands. These voltage commands are used with a pulse width modulator and voltage-balancing approach to achieve the equal charging of the SM outer capacitors in each leg. By doing so, the outer capacitors voltage is boosted from $\frac{V_{dc}}{2N}$ to $\frac{V_{dc}}{N}$, which is equal to their nominal voltage.

B. Design Steps of Start-Up Operation

The sequence of design steps to precharge the SM capacitors in the 3L-FC-based MMC is as follows:

- 1) insert the charging resistor (R_c) in series with the dc bus, keep the bypass switch (S_c) in “OPEN” position;
- 2) apply the switching state ③, as shown in Table I, to all the SMs in the upper and lower arms;
- 3) build the dc-bus voltage to its rated voltage;
- 4) measure the outer capacitors voltage v_{Cu1} and v_{Cl1} ;
- 5) if these capacitors voltage are equal to $\frac{V_{dc}}{2N}$, then apply the switching state ①, as shown in Table I, to all the SMs;
- 6) measure the inner capacitors voltage v_{Cu2} and v_{Cl2} ;
- 7) if these capacitors voltage are equal to $\frac{V_{dc}}{2N}$, then bypass the charging resistor (R_c) by closing the bypass switch (S_c);
- 8) activate the closed-loop controller as shown in Fig. 3. The controller slowly boosts the outer capacitors voltage from $\frac{V_{dc}}{2N}$ to their rated value of $\frac{V_{dc}}{N}$;

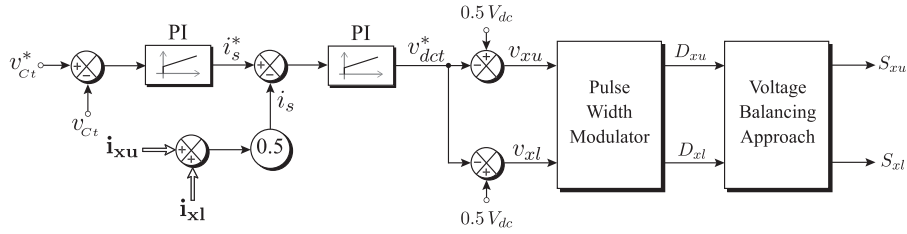


Fig. 3. Start-up current controller.

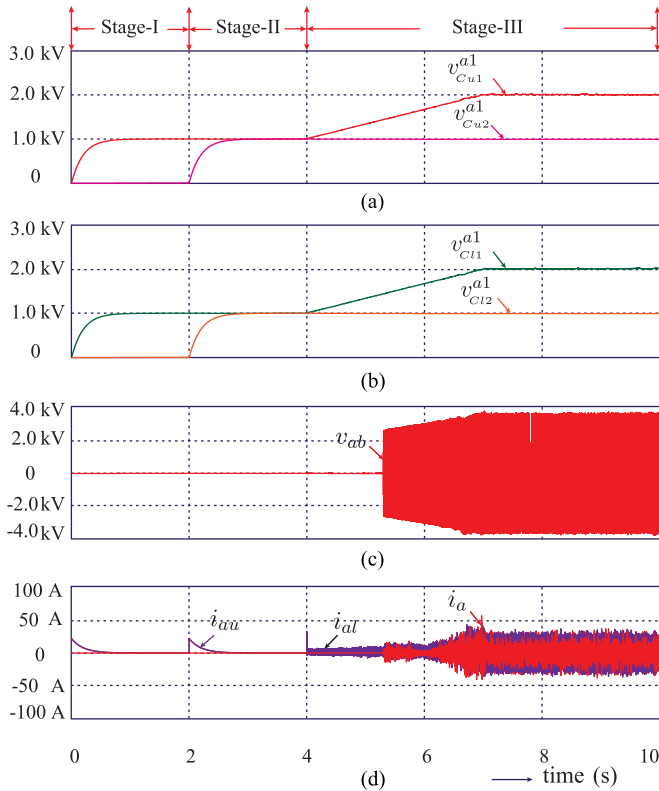


Fig. 4. Simulation results for start-up operation of the 3L-FC based MMC. (a) Outer and inner capacitor voltage of SM-1 in upper arm. (b) Outer and inner capacitor voltage of SM-1 in lower arm. (c) Output voltage. (d) Upper, lower arm and output current waveforms.

- 9) the start-up process ends after charging the outer capacitors voltage to $\frac{V_{dc}}{N}$ and the inner capacitors voltage to $\frac{V_{dc}}{2N}$ value.

III. SIMULATION AND EXPERIMENTAL VALIDATION

The performance of the proposed start-up process is validated through MATLAB simulations and dSPACE/DS1103 experiments on a laboratory prototype of the 3L-FC-based MMC.

A. Simulation Validation

The start-up performance of the 3L-FC-based MMC is shown in Fig. 4. Initially, all the SM capacitors have zero voltage. From $t = 0$ to 2 s, the switching state ③ is applied to all the SMs. The SM outer capacitors are charged to a voltage of 1 kV through the antiparallel diodes of IGBT devices. To limit the magnitude of

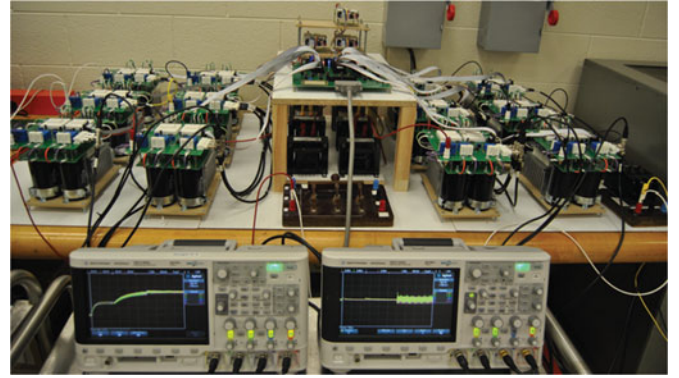


Fig. 5. Experimental setup of the 3L-FC based MMC.

charging current, a charging resistor $R_c = 50 \Omega$ with a contactor (S_c) is connected in series with the dc bus. The magnitude of charging current is slowly decreased, and eventually, it will become zero when the sum of outer capacitors voltage in each leg is equal to the voltage of dc bus. During stage-I, the SMs' inner capacitor is completely bypassed, and their voltage is maintained at zero value.

At $t = 2$ s, the switching state ① is applied to all the SMs. In this stage, the outer capacitor is bypassed and the inner capacitor is connected to the dc bus through the charging resistor and antiparallel diode of IGBT devices. The charging current flowing through the inner capacitor becomes zero when the inner capacitor of each SM is charged to a voltage of 1 kV. At $t = 4$ s, the charging resistor is bypassed, and the closed-loop start-up controller is activated. In this stage, the closed-loop controller boosts the SM outer capacitors voltage from half the rated value (1 kV) to its rated value (2 kV). The closed-loop controller is used along with the balancing approach to ensure the uniform charging of all the SM outer capacitors. During this process, the inner capacitor voltage is maintained at its rated value. Once the SM outer and inner capacitors are charged to its rated value, then the normal operation of the MMC can be started.

B. Experimental Validation

The experimental studies are conducted on a 3L-FC-based three-phase MMC laboratory prototype, as shown in Fig. 5. The experimental prototype is controlled by dSPACE/DS1103 R&D control platform. The prototype is designed to handle the 208-V/3-kVA power capacity with a total dc-bus voltage of 350 V. The rated voltage of the outer capacitor is 350 V, and the inner capacitor is 175 V.

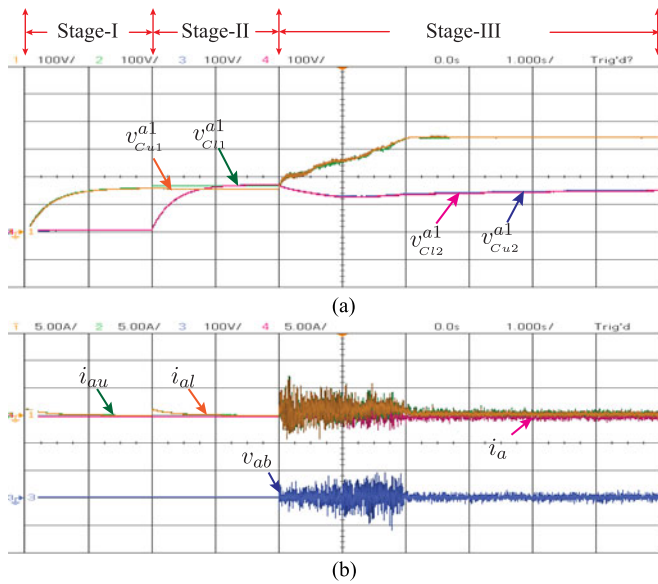


Fig. 6. Experimental results for start-up operation of the 3L-FC-based MMC. (a) Outer and inner capacitor voltage of SM₁ in the upper and lower arms. (b) Upper, lower arm, output current, and output voltage. [Scope-(i): Ch-1: upper arm SM₁ outer capacitor voltage ($v_{C_{u1}}^{a1}$) (100 V/div), Ch-2: lower arm SM₁ outer capacitor voltage ($v_{C_{l1}}^{a1}$) (100 V/div), Ch-3: upper arm SM₁ inner capacitor voltage ($v_{C_{u2}}^{a1}$) (100 V/div) and Ch-4: lower arm SM₁ inner capacitor voltage ($v_{C_{l2}}^{a1}$) (100 V/div). Scope-(ii): Ch-1: upper arm current (i_{au}) (5 A/div), Ch-2: lower arm current (i_{al}) (5 A/div), Ch-3: line-line voltage (v_{ab}) (100 V/div) and Ch-4: phase-a line current (i_a) (5 A/div). Time scale: 1 s/div].

The performance of the proposed start-up approach for the 3L-FC-based MMC is shown in Fig. 6. In stages I and II, the outer and inner capacitors are charged to 175 V by using the charging resistor (R_c). In stage III, the charging resistor is bypassed. The outer capacitor voltage is boosted from 175 to 350 V by using a current controller with a voltage-balancing approach [4]. In this approach, the reference signal is slowly varied at a rate of 0.0035 V/sample (i.e., the outer capacitor voltage should reach to 350 V from 175 V within 2-s period). During this process, the inner capacitor voltage has slightly reduced from the nominal value due to the delay in the switching of IGBT devices and device losses, etc. However, the outer and inner capacitor voltages are reached to their nominal value at steady state. With the proposed approach, the SM outer and inner capacitors are smoothly charged to its nominal voltage without any inrush current.

IV. CONCLUSION

In this paper, a simple precharging method is proposed for the 3L-FC-based MMC. The principle of precharging operation is analyzed through an equivalent circuit. The precharging process of the 3L-FC based MMC is divided into three stages. In each stage, the outer and inner capacitors of each SM are precharged to its nominal value by using an uncontrolled and controlled charging techniques. The simulation and experimental studies are presented to validate the performance of the start-up method for the 3L-FC-based MMC. The results show that the SM outer and inner capacitors are smoothly precharged to its nominal voltage without any inrush current.

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