A New Family of Modular Multilevel Converter Based on Modified Flying-Capacitor Multicell Converters

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***Abstract*—Modular multilevel converters (MMCs) are one of the next-generation multilevel converters intended for medium/high-voltage high-power market. This paper initially studies a modified topology for flying-capacitor multicell converters (FCMCs) as a modular submultilevel module. The main advantage of the modified FCMC, in comparison with the conventional one, is that the number and voltage rating of the required dc voltage sources are halved. Afterward, the MMC that comprises the series connection of the modified FCMCs used as submultilevel modules is proposed. Simulation results and experimental measurements taken from the four-cell-five-level laboratory prototype system of the modified FCMC as a modular submultilevel module are presented in order to validate its performance and advantages. Moreover, simulation results and experimental measurements of three cascaded two-cell-three-level modules (ultimately seven-level proposed MMC) and four cascaded two-cell-three-level modules (ultimately nine-level proposed MMC) are presented in order to validate its viability, merits and the proposed control strategy.**

***Index Terms*—Cascaded converters, cost and size diminution, dc voltage source abatement, flying-capacitor multicell converter (FCMC), modular multilevel converter (MMC), natural balancing.**

I. Introduction

To react to the high-power demand of energy systems and to fulfill deservedly the requirements of the industrial processes powered by large electric ac drive systems, two distinct solutions are recommended by power electronics research society: traditional two-level voltage/current source topologies comprising high-voltage/current-rated power switches based on developing and immature high-voltage semiconductor technology (currently 8 kV and 6 kA); and multilevel power converters covering a power range from several MW to tens of MW based on matured semiconductor technology of medium-voltage/current-rated power switches (currently 1.2 kV up to 6.6 kV) [1]–[8].

Although the first approach inherits the simplicity of power and control circuitry but, two-level power converters suffer from major disadvantages of augmented price of newer high-power semiconductors and power quality concerns, specifically as going higher in the power ranges, whereas, voltage/current source multilevel power converter topologies are considered nowadays as the state-of-the-art power conversion systems owing to noteworthy merits such as: extended power range due to the capability of the multilevel topologies to handle the voltage and power in the range of several kV and MW utilizing reliable medium-voltage insulated gate bipolar transistors (IGBTs), improved harmonic content of the switched output voltage, and hence increased power quality, increased reliance on power converter operation owing to possible fault-tolerant feature, lowered electromagnetic interference and upgraded electromagnetic compatibility, lowered switching losses, enhanced efficiency, and reduced amount of output filter, etc. [9]–[16].

Nowadays, there exist three commercial voltage/current-source multilevel power converters being well established in the medium-voltage and high-power energy management market as a cost-effective solution, that are, the neutral point clamped or diode-clamped converters, the cascaded H-bridge converters, and the flying capacitor (FC) or capacitor-clamped converters [12]–[25].

In the late decade, one of the most industrial and academic research-interest-oriented topologies as well as one of the most significant and promising structures of the multilevel converters have been the FC multicell (FCM) converter breed and its subtopologies referred as: stacked multicell (SM), double FCM (DFCM), and improved DFCM (I-DFCM) converters. The flying-capacitor multicell converters (FCMCs) are based on the tandem connection of the smaller two-level modular power converters called as power cells, wherein, each power cell is composed of an FC and a pair of medium-voltage IGBTs possessing a complementary state. Redundant switching states in FC converters permit the stabilization of voltage across the FCs at their requisite values. The commutation between the adjacent cells with their pertinent FCs charged to the required voltage values generates regularly stepped levels of chopped input voltage at the output side of these converters [20]–[30].

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The flying-capacitor-based multicell converters are particularly attractive due to the inherent asset of natural capacitor voltage balancing process. This balancing can be observed when all cells of the flying-capacitor-based multicell converters operate with the same duty cycle and interleaved switching strategy such as phase-shifted pulse-width modulation (PS-PWM) [31]–[37]. The voltage balance of the FCs that ensures the safe operation of the flying-capacitor-based multicell converters is a concern of utmost importance in these topologies. It is well demonstrated through a mathematical modeling of the FCM converters that natural capacitor voltage balancing process occurs if the PS-PWM modulation techniques are applied to the converter's modulation unit [35]–[43].

Addressing the aforementioned mentioned features, any effort to improve the topology or control methodology of the flying-capacitor-based converters such as FCM, SM, DFCM, and I-DFCM converters, make them more practical and efficient in the medium-voltage high-power applications. Hence, this paper initially investigates a modified topology of FCMCs as a modular submultilevel module. The outstanding merit of the modified FCMC (the submultilevel module), as compared to the conventional topology of an FCMC, is that the latter requires two dc voltage sources while the modified topology requires only one of those two dc voltage sources in order to produce the same voltage at the converters' output stage (i.e., the same number of voltage levels and peak-to-peak value at the converter output). In other words, the number and voltage rating of the required dc voltage sources are halved in the modified circuit topology. This amelioration is attained by adding four power switches to the conventional topology of an FCMC without applying any amendments to the number and voltage rating of the high-frequency power switches in each cell and their FCs. The control strategy for the modified FCMC is based on the PS-PWM technique; therefore, the natural balancing phenomenon of the FCs' voltages, one of the critical and crucial advantages of the FCMCs, is preserved in the submultilevel module. Despite all the advantages of FCMCs, their main practical issue roots in a significant diversity in the voltage rating of FCs whenever the high number of voltage levels is requisite. To suppress this issue, this paper proposes a cascade connection of the aforementioned submultilevel modules to structure the modular multilevel converters (MMCs) to have more modular configuration.

This paper is organized in the following structure. Section II provides a brief explanation on the conventional FCMC topology and its properties. In Section III, the modified configuration of the FCMC as a submultilevel module as well as its modulation strategy based on the PS-PWM technique is discussed. Afterward, the structure of the proposed MMC based on the series connection of the modified FCMC as submultilevel module is suggested and analyzed. Simulation results are presented in Section IV to validate the modified FCMC as well as the proposed MMC. Experimental measurements taken from the prototype system of the modified FCMC, i.e., four-cell-five-level converter is presented in Section V to validate the feasibility and viability of the submultilevel module. Subsequently, experimental results of the three cascaded two-cell-three-level modules (ultimately seven-level proposed MMC) and four-cascaded two-cell-three-level modules (finally nine-level proposed MMC) are presented in Section V to validate its merits and efficacy for medium-voltage and high-power applications.

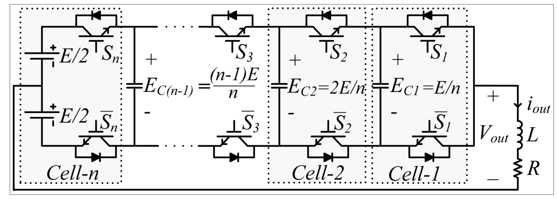

Fig. 1. n-cell-$n+1$-level FCMC producing the output voltage with peak-to-peak value of E.

TABLE I
STATES OF POWER SWITCHES IN A FOUR-CELL-FIVE-LEVEL FCMC

Output Voltage Level	State of Switches (S_4, S_3, S_2, S_1)	Number of States
+0.5E	(1,1,1,1)	1
+0.25E	(1,1,1,0) (1,1,0,1) (1,0,1,1) (0,1,1,1)	4
0	(1,1,0,0) (1,0,0,1) (0,0,1,1) (1,0,1,0) (0,0,1,1) (0,1,0,1)	6
-0.25E	(1,0,0,0) (0,1,0,0) (0,0,1,0) (0,0,0,1)	4
-0.5E	(0,0,0,0)	1

II. CONVENTIONAL CONFIGURATION OF FCMC

A typical configuration of an FCMC, as shown in Fig. 1, is based on *n cells* which are connected in series to form required converter leg and can produce $n+1$ levels of voltage with peak-to-peak value of E at the output. Each cell in FCMC is made-up by one FC and a pair of power switches with complementary control signals. It is worth noting that due to the identical output current and switching frequency, the capacitance of FCs are the same in order to obtain the same voltage ripple. However, FCs' dc voltage ratings are different and equal to E/n, $2E/n$, . . ., $(n-1)E/n$ [31]–[35]. As a result, each power switch sustains just a fraction of dc-link voltage, i.e., E/n. State of power switches for four-cell-five-level FCMC are also illustrated in Table I.

III. PROPOSED MMC BASED ON MODIFIED FCMC

As shown in Fig. 1, the conventional configuration of FCMC requires two dc voltage sources while the upper dc voltage source is utilized when the power switch S_n conducts, i.e., it is closed and its state is 1, and the lower dc voltage source is utilized when the power switch $\overline{S_n}$ conducts. As a result, each of two dc voltage sources is only required as its associated power switch conducts. It means that two dc voltage sources are not conducting simultaneously. This fact makes it possible to modify the converter topology by eliminating one of the dc voltage sources. To settle the aforesaid logic and to aim the elimination of one of the dc voltage sources, two auxiliary power switches with complementary states to each other (A and $\overline{A}$) must be added to the configuration of the FCMC in order to provide an appropriate path for ac current afterward removing the converter's midpoint. Such amendment to the FCMC topology is

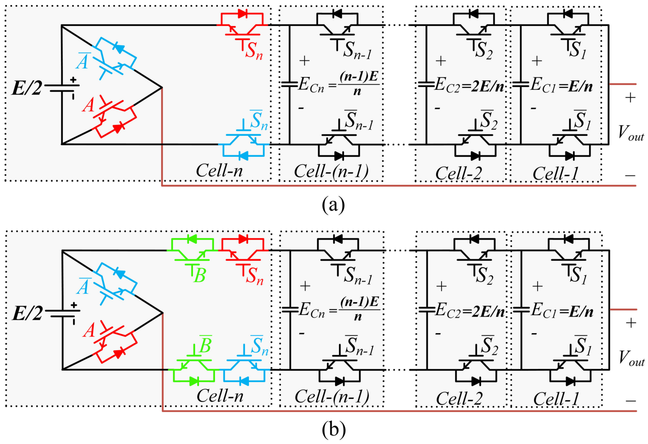

Fig. 2. Submultilevel module of n-cell-n+1-level modified FCMC based on only one dc voltage source with maximum peak-to-peak voltage of E. (a) First design. (b) Second design.

attained on the basis that FCs have got stabilized at their nominal values. Hence, the modified n-cell-n+1-level circuit topology of the FCMC breed can be achieved in a structure which is represented in Fig. 2(a). After equipping the FCMC with two power switches (A and $\overline{A}$) and removing one of the dc voltage sources, the direction of power of switches of S$_n$ and $\overline{\mathrm{S}_n}$ must be reversed due to the fact that the voltage rating of capacitor C_n in the nth cell (i.e., $E_{Cn} = (n-1)\,E/n$) is more than the voltage rating of the main dc-link (*E/*2) in the modified circuit in the steady state. However, it is worth mentioning that E_{Cn} is less than the main dc-link voltage (*E/*2) during the start-up transient. It means that after connecting the FCMC to the dc source, while the FCs have not been precharged or charged to their nominal dc voltages, the natural balancing mechanism starts to charge and regulate E_{Cn} at its steady-state value ($(n-1)\,E/n$) automatically. During the start-up transient state, the positive-average current flowing through the FC of C_n slowly charges C_n while it reaches to *E/*2 and onward it passes *E/*2 to get stabilized at its nominal dc voltage $(n-1)\,E/n$. Ultimately, the voltage of E_{Cn} will be higher than the main dc-link voltage (*E/*2). The aforesaid phenomenon implies that during FCs' voltage balancing transient it is mandatory to retain the direction of the power switches of S$_n$ and $\overline{\mathrm{S}_n}$ in their original position whereas they must be reversed and inverted after the start-up transient state. As a result, the bidirectional power switches must be used for power switches of S$_n$ and $\overline{\mathrm{S}_n}$ in the proposed FCMC topology. Hence, the second design of the modified FCMC can be achieved which is represented in Fig. 2(b) wherein another pair of complementary power switches (B and $\overline{B}$) with opposite directions to S$_n$ and $\overline{\mathrm{S}_n}$ are embedded to the circuit. However, the switches B and $\overline{B}$ can always stay ON after the start-up transient time. As an example, Fig. 3 presents the switching strategy, states of power switches, and the output voltage of the four-cell-five-level modified FCMC which is controlled by PS-PWM technique utilizing a modulation index equal to 0.8 (M = 0.8). In Fig. 3, the power switch is ON when its state is 1 and is OFF when its state is 0.

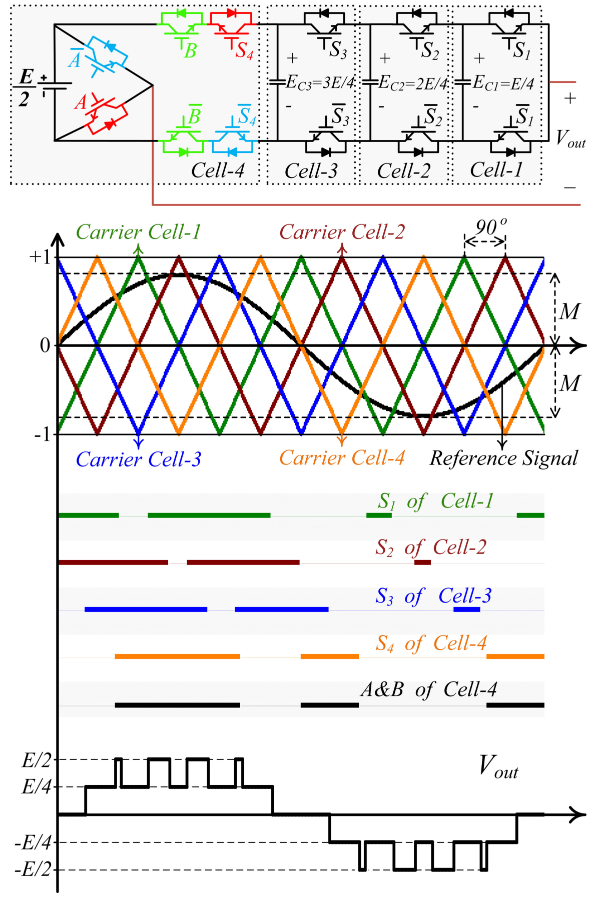

Fig. 3. Four-cell-five-level submultilevel module of the modified FCMC, its switching pattern based on the PS-PWM, states of the power switches and switched output voltage.

Comparing Figs. 1 and 2(b) clarifies that the conventional FCM requires dc voltage source with total voltage rating of E to produce an output voltage with peak-to-peak value of E whereas the modified FCMC just needs one dc voltage source with halved voltage rating (*E/*2) to produce the same output voltage (output switched voltage with peak-to-peak value of E). Elimination of one dc voltage source optimizes the structure of the FCMCs from size and cost points of view. Other parameters of the modified FCMC such as the voltage rating of FCs and power switches are as the same as those in the conventional topology.

FCs are very significant components from the cost and size points of view in any flying-capacitor-based converters. Furthermore, the voltage rating of dc capacitors has a profound impact on their price. In other words, capacitors possessing the higher voltage ratings retain much higher prices. Hence, it is feasible to conclude that the voltage rating of FCs is the most profound price-determining factor in any flying-capacitor-based converters. Since the FCs' voltages in FCMCs are more diverse whenever the number of cells is high, it is not more practical to have high number of cells in the FCMCs. To overcome to this obstacle, in this paper, an MMC comprising the cascade connection of the submultilevel modules, which are modified FCMCs, has been proposed. By employing this approach, it is

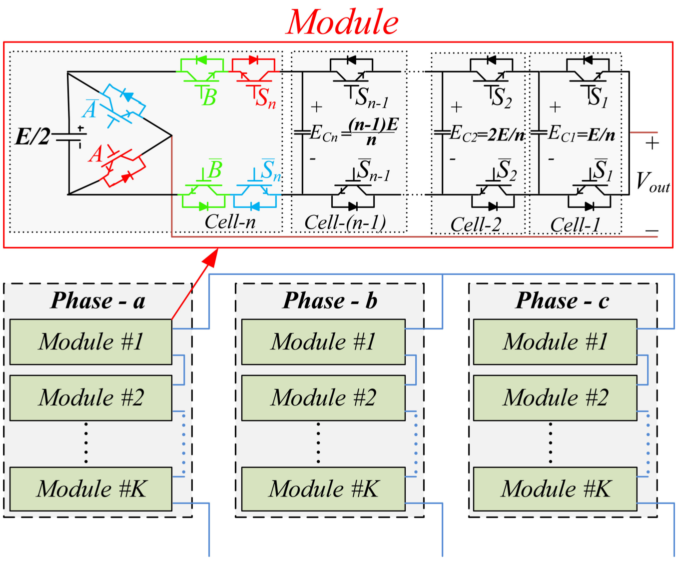

Fig. 4. Proposed MMC based on submultilevel module of n-cell-n+1-level modified FCMC.

more suitable and practical to increase the number of modules while all the modules will be identical. The generalized three-phase topology of the proposed MMC is shown in Fig. 4 wherein each phase is a series connection of K modules and each module is a modified n-cell-n+1-level FCMC. Therefore, this MMC can produce $K \cdot n + 1$ levels in each phase with peak-to-peak voltage of $K \cdot E$.

For instance, the seven-level proposed MMC made-up by two three-cell-four-level modules with its suggested switching pattern based on the PS-PWM, states of the power switches, and output voltage is shown in Fig. 5. It is worth mentioning that the number of triangle carriers in each module is the same as the number of cells in each module and they have been phase shifted by $2\pi/n$ in each module where n is the number of cells and equals to 3 in Fig. 5. Furthermore, the phase shift between the first triangle carriers of two adjacent modules is $2\pi/kn$ where k is number of modules connected in series in each phase and equals to 2 in Fig. 5. Moreover, states of power switches in the mentioned seven-level proposed MMC have been demonstrated in Table II wherein the voltage variation of each FC, i.e., $\Delta E_{Cx} = E_{Cx}(t + \Delta t) - E_{Cx}(t)$, is determined for each switching state by taking into account the direction of the load current. It is worth mentioning that the sates of power switches have been demonstrated just for the positive half cycle of the output voltage because they will be just inverted for the negative half-cycle of the output voltage.

IV. Simulation Results

In this section, simulation results are illustrated in two following parts. First, simulation results of the modified five-level FCMC are provided to verify its well performance. In the second part, simulation results of proposed MMC based on modified FCMC are illustrated to verify its effectiveness and switching pattern.

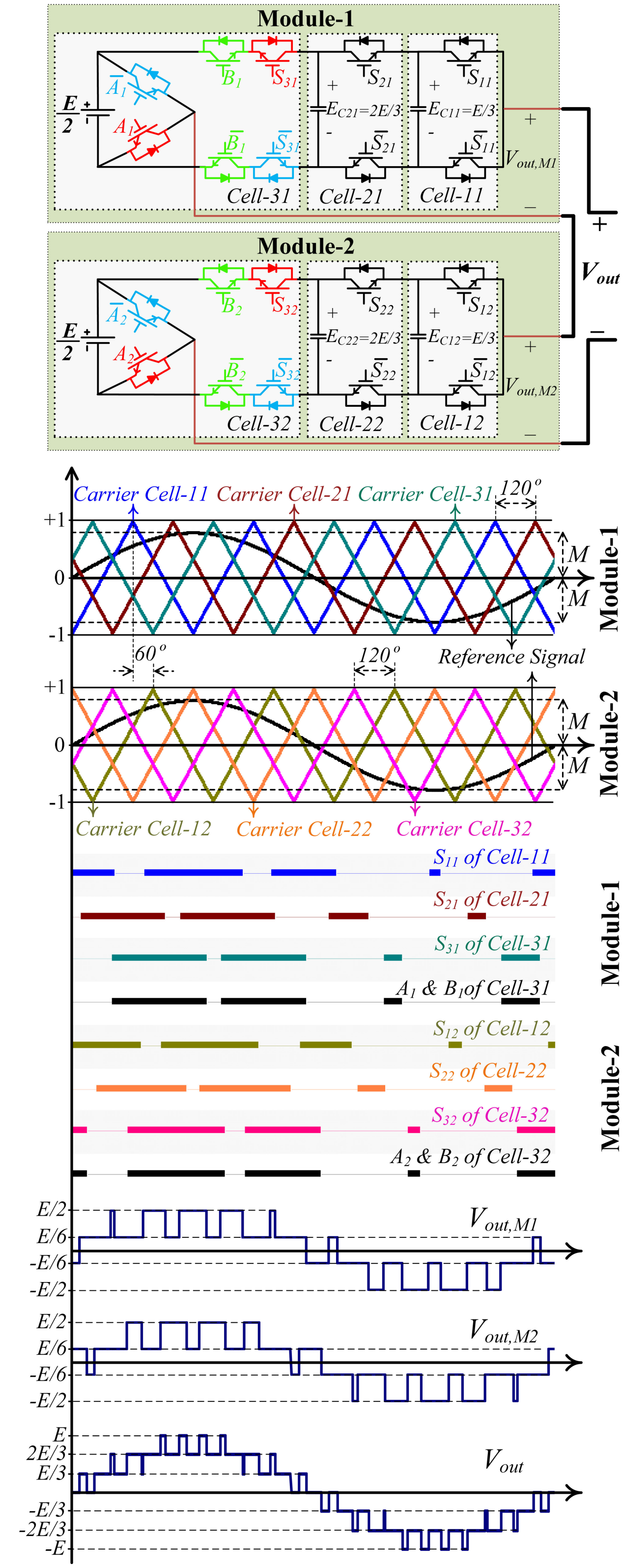

Fig. 5. Seven-level proposed MMC based on two three-cell-four-level modules, its switching pattern based on the PS-PWM, states of the power switches, and switched output voltage.

TABLE II
STATES OF POWER SWITCHES AND CHARGING/DISCHARGING PROCESS OF FCS IN SEVEN-LEVEL PROPOSED MMC BASED ON TWO THREE-CELL MODULES

<table>
<tr><th rowspan="2">Output Voltage</th><th rowspan="2">Output Voltage Module-1</th><th rowspan="2">Output Voltage Module-2</th><th colspan="2">State of switches</th><th rowspan="2">ΔE_{C22}</th><th rowspan="2">ΔE_{C12}</th><th rowspan="2">ΔE_{C21}</th><th rowspan="2">ΔE_{C11}</th><th rowspan="2">i_{Load}</th><th rowspan="2">Number of States</th></tr>
<tr><th>($A_2=B_2=S_{32}$, S_{22} , S_{12})</th><th>($A_1=B_1=S_{31}$, S_{21} , S_{11})</th></tr>
<tr><td>$+E$</td><td>$+E/2$</td><td>$+E/2$</td><td>(1,1,1)</td><td>(1,1,1)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>whatever</td><td>1</td></tr>
<tr><td rowspan="12">$+2E/3$</td><td rowspan="2">$+E/6$</td><td rowspan="2">$+E/2$</td><td rowspan="2">(0,1,1)</td><td rowspan="2">(1,1,1)</td><td>-</td><td>0</td><td>0</td><td>0</td><td>$i_{Load}>0$</td><td rowspan="12">6</td></tr>
<tr><td>+</td><td>0</td><td>0</td><td>0</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="2">$+E/6$</td><td rowspan="2">$+E/2$</td><td rowspan="2">(1,1,0)</td><td rowspan="2">(1,1,1)</td><td>0</td><td>+</td><td>0</td><td>0</td><td>$i_{Load}>0$</td></tr>
<tr><td>0</td><td>-</td><td>0</td><td>0</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="2">$+E/6$</td><td rowspan="2">$+E/2$</td><td rowspan="2">(1,0,1)</td><td rowspan="2">(1,1,1)</td><td>+</td><td>-</td><td>0</td><td>0</td><td>$i_{Load}>0$</td></tr>
<tr><td>-</td><td>+</td><td>0</td><td>0</td><td>$i_{Load}<0$</td></tr>
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<tr><td>0</td><td>0</td><td>+</td><td>0</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="2">$+E/2$</td><td rowspan="2">$+E/6$</td><td rowspan="2">(1,1,1)</td><td rowspan="2">(1,1,0)</td><td>0</td><td>0</td><td>0</td><td>+</td><td>$i_{Load}>0$</td></tr>
<tr><td>0</td><td>0</td><td>0</td><td>-</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="2">$+E/2$</td><td rowspan="2">$+E/6$</td><td rowspan="2">(1,1,1)</td><td rowspan="2">(1,0,1)</td><td>0</td><td>0</td><td>+</td><td>-</td><td>$i_{Load}>0$</td></tr>
<tr><td>0</td><td>0</td><td>-</td><td>+</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="12">$+E/3$</td><td rowspan="2">$+E/6$</td><td rowspan="4">$+E/6$</td><td rowspan="2">(0,1,1)</td><td rowspan="4">(1,1,0)</td><td>-</td><td>0</td><td>0</td><td>+</td><td>$i_{Load}>0$</td><td rowspan="12">6</td></tr>
<tr><td>+</td><td>0</td><td>0</td><td>-</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="4">$+E/6$</td><td rowspan="4">(1,1,0)</td><td>0</td><td>+</td><td>0</td><td>+</td><td>$i_{Load}>0$</td></tr>
<tr><td>0</td><td>-</td><td>0</td><td>-</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="4">$+E/6$</td><td rowspan="4">(1,0,1)</td><td>0</td><td>+</td><td>+</td><td>-</td><td>$i_{Load}>0$</td></tr>
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<tr><td>-</td><td>+</td><td>-</td><td>+</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="4">$+E/6$</td><td rowspan="4">(0,1,1)</td><td>+</td><td>-</td><td>-</td><td>0</td><td>$i_{Load}>0$</td></tr>
<tr><td>-</td><td>+</td><td>+</td><td>0</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="2">$+E/6$</td><td rowspan="2">(0,1,1)</td><td>-</td><td>0</td><td>-</td><td>0</td><td>$i_{Load}>0$</td></tr>
<tr><td>+</td><td>0</td><td>+</td><td>0</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="12">0</td><td rowspan="2">$+E/6$</td><td rowspan="2">$-E/6$</td><td rowspan="2">(1,0,1)</td><td rowspan="2">(0,0,1)</td><td>+</td><td>-</td><td>0</td><td>-</td><td>$i_{Load}>0$</td><td rowspan="12">6</td></tr>
<tr><td>-</td><td>+</td><td>0</td><td>+</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="2">$-E/6$</td><td rowspan="2">$+E/6$</td><td rowspan="2">(0,0,1)</td><td rowspan="2">(0,1,1)</td><td>0</td><td>-</td><td>-</td><td>0</td><td>$i_{Load}>0$</td></tr>
<tr><td>0</td><td>+</td><td>+</td><td>0</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="2">$+E/6$</td><td rowspan="2">$-E/6$</td><td rowspan="2">(0,1,1)</td><td rowspan="2">(0,1,0)</td><td>-</td><td>0</td><td>-</td><td>+</td><td>$i_{Load}>0$</td></tr>
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<tr><td rowspan="2">$-E/6$</td><td rowspan="2">$+E/6$</td><td rowspan="2">(0,1,0)</td><td rowspan="2">(1,1,0)</td><td>-</td><td>+</td><td>0</td><td>+</td><td>$i_{Load}>0$</td></tr>
<tr><td>+</td><td>-</td><td>0</td><td>-</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="2">$+E/6$</td><td rowspan="2">$-E/6$</td><td rowspan="2">(1,1,0)</td><td rowspan="2">(1,0,0)</td><td>0</td><td>+</td><td>+</td><td>0</td><td>$i_{Load}>0$</td></tr>
<tr><td>0</td><td>-</td><td>-</td><td>0</td><td>$i_{Load}<0$</td></tr>
<tr><td rowspan="2">$-E/6$</td><td rowspan="2">$+E/6$</td><td rowspan="2">(1,0,0)</td><td rowspan="2">(1,0,1)</td><td>+</td><td>0</td><td>+</td><td>-</td><td>$i_{Load}>0$</td></tr>
<tr><td>-</td><td>0</td><td>-</td><td>+</td><td>$i_{Load}<0$</td></tr>
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A. Simulation Results of Five-Level Modified FCMC

The output voltage of the modified four-cell-five-level FCMC with THD of 35% and the load current (increased by a coefficient of 10) both in the steady state, FC voltages in both transient and steady states, and also frequency spectrum of the output voltage are shown in Figs. 6–8, respectively. The converter is operated with a modulation index equal to 0.8 ($M = 0.8$) and controlled by the PS-PWM method wherein carriers' frequency is 5 kHz. As shown in Fig. 6, modified FCMC produces peak-to-peak voltage of 300 V while the total dc-link voltage is 300 V. In contrast, the total dc-link of 600 V is required to generate the same output voltage in the conventional FCMC. Fig. 7 illustrates that FCs reach their target voltage values without any feedback control due to the operation of modified FCMC based on the PS-PWM technique. As shown in Fig. 8 which demonstrates the frequency spectrum, the output voltage own harmonic clusters around the $\left(k \times 4 \times 5^{\mathrm{kHz}}\right)\mathrm{th}$ harmonic where k is an integer number and 4 is the number of carriers (the same as the number of cells) intersected with the reference waveform. The main circuit parameters used in the simulations are given in Table III.

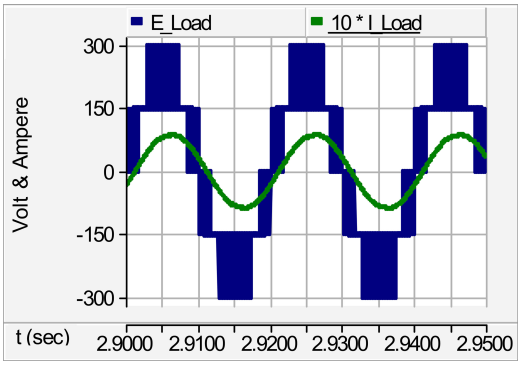


Fig. 6. Output voltage and load current (increased by coefficient of 10) of the four-cell-five-level modified FCMC.

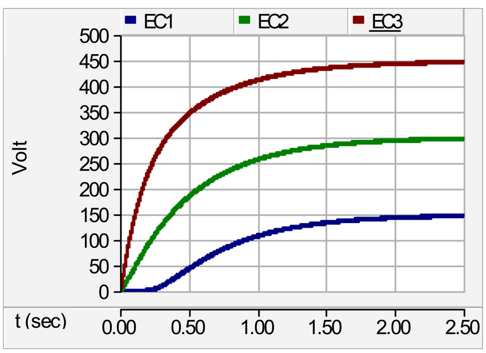


Fig. 7. FC voltages of the four-cell-five-level modified FCMC.

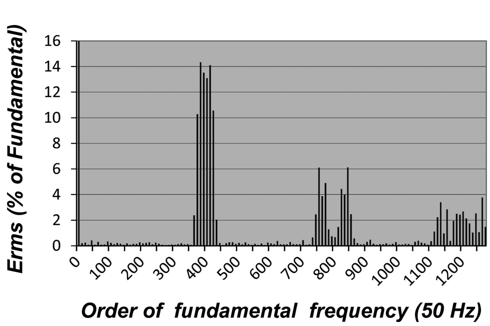


Fig. 8. Output voltage frequency spectrum of the four-cell-five-level modified FCMC.

B. Simulation Results of Proposed MMC Based on Modified FCMC

In this part, simulation results of seven-level and nine-level MMCs which are cascade connection of three and four modular units based on two-cell modified FCMC, respectively, are illustrated. The output voltage of the seven-level MMC with THD of 20% and the load current (increased by coefficient of a 10), both in the steady state as well as the frequency spectrum of output voltage are depicted in Figs. 9 and 10, respectively. The converter is operated with a modulation index equal to 0.92 ($M = 0.92$) and controlled by the PS-PWM technique wherein carriers' frequency is 5 kHz. As illustrated in Fig. 10 which demonstrates the frequency spectrum of the output voltage, the harmonic clusters place around the $\left(k \times 6 \times 5^{\mathrm{kHz}}\right)\mathrm{th}$ harmonic where k is an integer number and 6 is the number of carriers (the same as the number of all the cells) intersected with reference waveform. The dc-link voltage (*E*/2) is 116 V and resistive–inductive load (*R*–*L*) is 25 Ω and 30 mH.

TABLE III
MAIN PARAMETERS OF THE SIMULATED MODIFIED FCMC

System Parameters	Values
dc link voltage (*E/2*)	300 V
Internal flying capacitors (*C*)	680 *u*F
PS-PWM carrier frequency	5 kHz
Fundamental output voltage frequency	50 Hz
Resistive-inductive load (R_L- L_L)	25 Ω – 30 mH

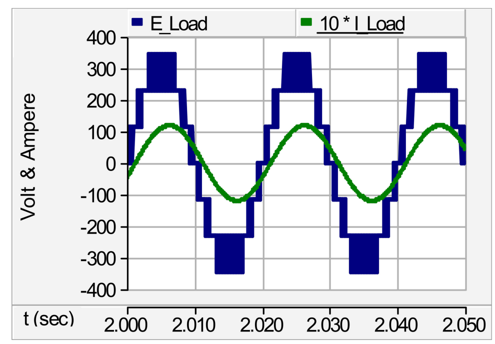


Fig. 9. Output voltage and load current (increased by coefficient of 10) of seven-level MMC based on three cascaded two-cell modified FCMCs.

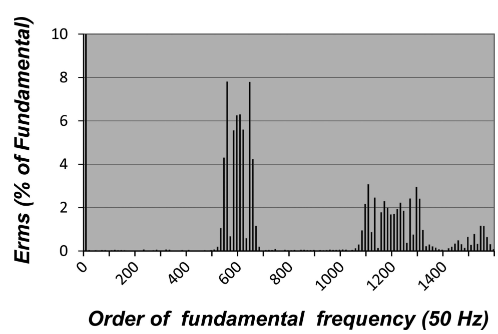


Fig. 10. Output voltage frequency spectrum of seven-level MMCs based on three cascaded two-cell modified FCMCs.

As another case, the nine-level MMC based on four cascaded two-cell modified FCMC has been studied and obtained simulation results is illustrated in Figs. 11 and 12.The output voltage's THD are 15% and its frequency spectrum is shown in Fig. 12 in which the output voltage has harmonic groups around the $\left(k \times 8 \times 5^{\mathrm{kHz}}\right)\mathrm{th}$ harmonic where k is the integer number and 8 is the number of carriers (the same as the number of all cells) intersected with reference signal. The converter is operated with a modulation index equal to 0.92 ($M = 0.92$) and controlled by the PS-PWM technique wherein the carriers' frequency is 5 kHz. The dc-link voltage (*E*/2) is 85 V and *R*–*L* is 25 Ω and 60 mH.

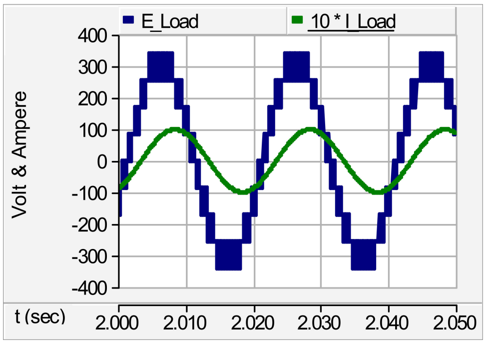


Fig. 11. Output voltage and load current (increased by coefficient of 10) of nine-level MMC based on four cascaded two-cell modified FCMCs.

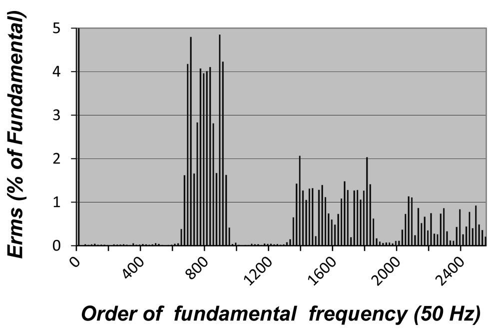


Fig. 12. Output voltage frequency spectrum of nine-level MMC based on four cascaded two-cell modified FCMCs.

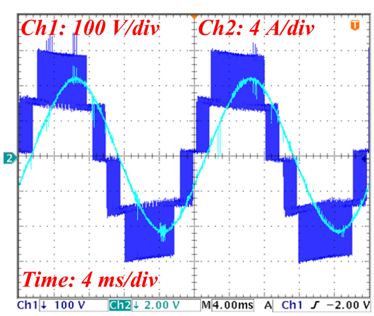


Fig. 13. Experimental results of the four-cell-five-level modified FCMC.

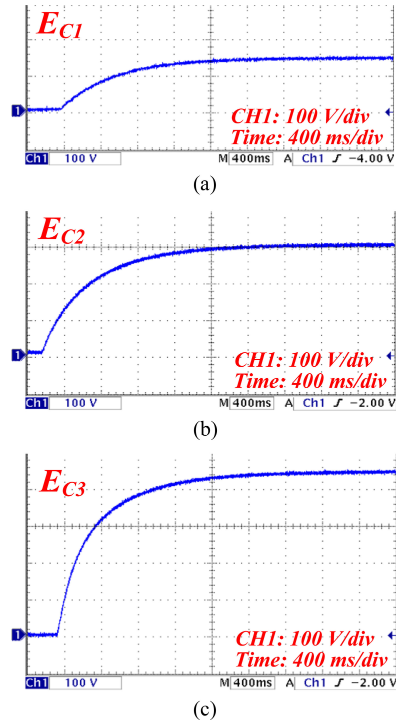


Fig. 14. Experimental results of the proposed four-cell-five-level FCMC: FC voltages (E_{C1}, E_{C2}, and E_{C3}).

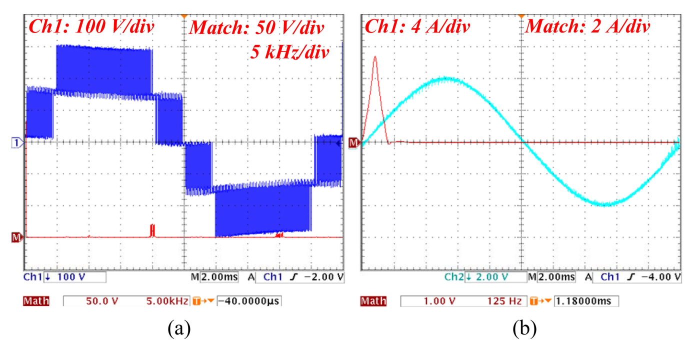


Fig. 15. Experimental results of the four-cell-five-level modified FCMC: frequency spectrum (a) output voltage; and (b) load current.

V. Experimental Results

A. Experimental Verification of a Five-Level Modified FCMC

To attest both the validity and feasibility of the modified FCMC, a four-cell-five-level prototype converter is built utilizing *Siemens BUP* 314*D* 1200 V 42 A IGBT modules. The measured output voltage and load current, FC voltages, and the frequency spectrum pertinent to the output voltage and load current taken from the four-cell-five-level prototype with the same parameters abridged in Table III are depicted in Figs. 13–15. As shown in Fig. 14, the voltages of FCs are stabilized and fixed at their requisite values, i.e., 150, 300, and 450 V, without any feedback signal in spite of elimination of one of the dc voltage sources; hence, this fact confirms and ascertains the validity of the modified FCMC and its performance. It is worth mentioning that the voltage rating of the dc voltage source utilized in the experiment is 300 V whereas two 300 V dc voltage sources (total

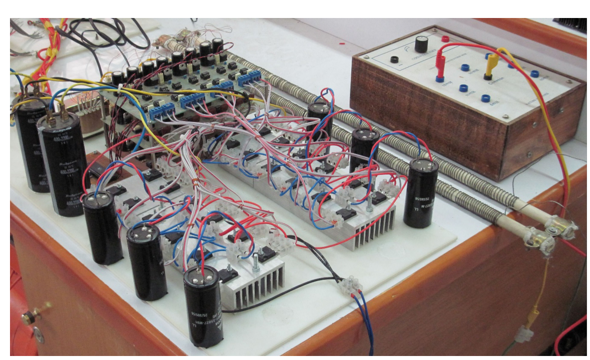
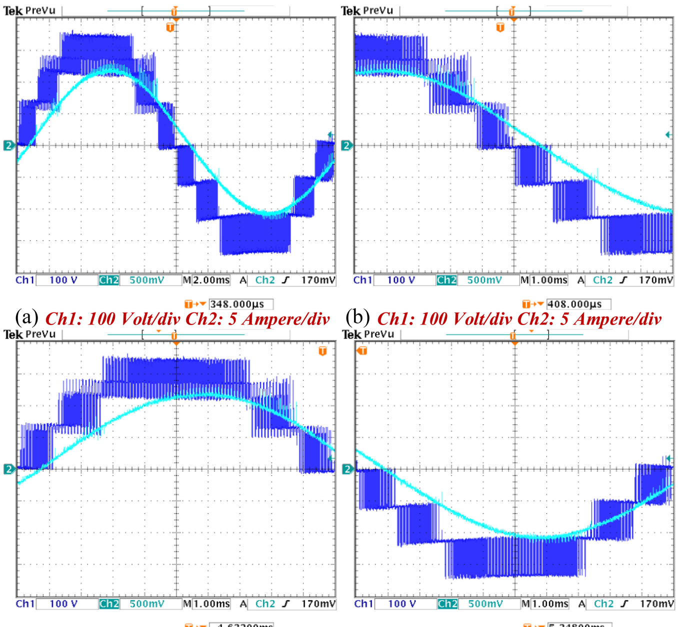
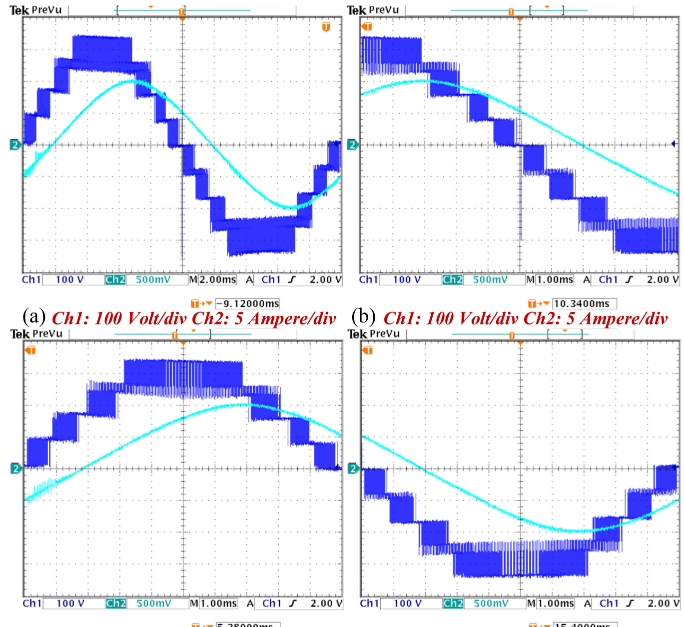


Fig. 16. Hardware implementation of the proposed MMC based on three-cascaded two-cell-three-level modified FCMC.



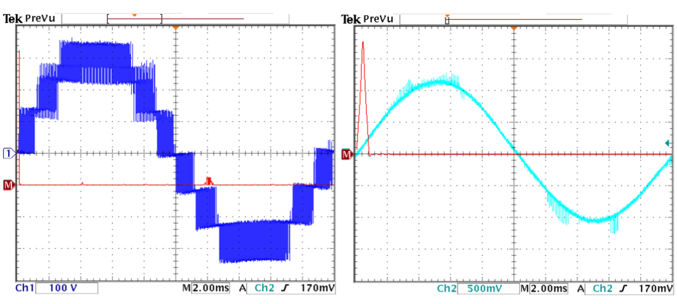
(a) *Ch1: 100 Volt/div Ch2: 5 Ampere/div* (b) *Ch1: 100 Volt/div Ch2: 5 Ampere/div* (c) *Ch1: 100 Volt/div Ch2: 5 Ampere/div* (d) *Ch1: 100 Volt/div Ch2: 5 Ampere/div*

Fig. 17. Experimental results: seven-level proposed MMC based on three-cascaded two-cell-three-level modified FCMCs: full and more detailed waveforms of output voltage and load current.



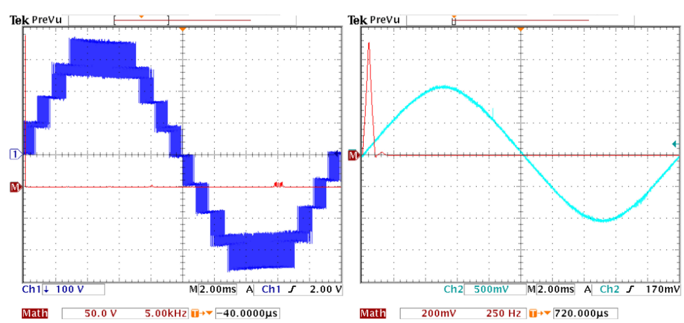
(a) *Ch1: 100 Volt/div Ch2: 5 Ampere/div* (b) *Ch1: 100 Volt/div Ch2: 5 Ampere/div* (c) *Ch1: 100 Volt/div Ch2: 5 Ampere/div* (d) *Ch1: 100 Volt/div Ch2: 5 Ampere/div*

Fig 19. Experimental results: nine-level proposed MMC based on four-cascaded two-cell-three-level modified FCMCs: full and more detailed waveforms of output voltage and load current.



(a) *Ch1: 100 Volt/div Math: 5 kHz/div* (b) *Ch2: 5 Ampere/div Math: 2 Ampere/div*

Fig. 18. Experimental results: frequency spectrum of seven-level proposed MMC based on three-cascaded two-cell-three-level modified FCMCs. (a) Output voltage. (b) Load current.



(a) *Ch1: 100 Volt/div Math: 5 kHz/div* (b) *Ch2: 5 Ampere/div Math: 2 Ampere/div*

Fig. 20. Experimental results: frequency spectrum of nine-level proposed MMC based on four-cascaded two-cell-three-level modified FCMCs. (a) Output voltage. (b) Load current.

voltage rating of 600 V) are required in the conventional FCMC to produce the same output voltages with the same FC voltages. It is worth noting that output voltage of n-cell modified FCMC as like as the conventional topology has group harmonics around the $(k \times n \times f_{\rm sw})$ th harmonic where k and $f_{\rm SW}$ are an integer number and the switching frequency, respectively. As shown in Fig. 15(a), output voltage of the four-cell modified FCMC has harmonic groups around integer multiples of 20 kHz, while switching frequency is 5 kHz.

B. Experimental Verification of the Proposed MMC Comprising Modified FCMC

To attest both the validity and viability of the proposed MMC topology, the seven-level and nine-level MMCs which are, respectively, the cascade connection of three and four modules each comprising one two-cell modified FCMC, are built. The constructed seven-level MMC is shown in Fig. 16. The experimentally measured output voltage and load current taken from the seven-level MMC are presented in Fig. 17. The dc-link voltage of each module is around 116 V and the *R–L* is 25 Ω and 30 mH. As shown in Fig. 18(a), output voltage of the seven-level MMC has harmonic groups around integer multiples of 30 kHz while the switching frequency is 5 kHz and the modulation index is 0.92. Furthermore, experimental studies were accomplished on nine-level prototype system of the proposed MMC in order to investigate and substantiate its feasibility for the higher number of cells and voltage levels. The measured output voltage and load current taken from the nine-level prototype are presented in Figs. 19 and 20. The dc-link voltage of each module is 85 V, the *R–L* is 25 Ω and 60 mH, and the modulation index is 0.92. As shown in Fig. 20(a), the output voltage of the proposed nine-level MMC has harmonic groups around integer multiples of 40 kHz while the switching frequency is 5 kHz.

VI. Conclusion

This paper initially studies modified topology of FCMC. The main advantage of the modified FCMC in comparison with the conventional topology was that the number and voltage rating of the required dc voltage sources reduced by 50%. Both simulation and experimental measurements taken from four-cell-five-level laboratory prototype systems of the modified FCMC were presented in order to validate its performance. FCs can be a significant price-determining factor in high-numbered-cell FCMCs. To negate this impact, MMC comprising the cascade connection of submultilevel modules which are based on the modified FCMC was proposed. The main advantage of the proposed MMC is reduction in the voltage rating of the FCs in whole circuit and making a circuit with more modularity. Moreover, a control method based on the PS-PWM technique was proposed for the suggested MMC to ensure the natural balancing of FCs's voltages. Finally, experimental results of the seven-level and nine-level proposed MMC were presented to validate its viability, well-performance, and effectiveness of its suggested modulation strategy.

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