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MSHE-PWM Control of Modular Multilevel Direct Current Transmission System

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Abstract: In order to optimize the electric energy quality of HVDC access point, a modular multilevel selective harmonic elimination pulse-width modulation (MSHE-PWM) method is proposed. On the basis of keeping the minimum action frequency of the power device, MSHE-PWM method can meet the requirement for accurately eliminating low-order harmonics in the output PWM waveform. Firstly, establish the basic mathematical model of MMC topology and point out the voltage balance control principle of single modules; then, analyze offline gaining principle and realization way of MSHE-PWM switching angle; finally, verify MSHE-PWM control performance on the basis of MMC reactive power compensation experimental prototype. The experimental result shows that the proposed MSHE-PWM method can meet such performance indexes as low switching frequency and no lower-order harmonics, and has verified the feasibility and effectiveness thereof for optimizing the electric energy quality of HVDC access point.

Keywords: Modular multilevel, multilevel selective harmonic elimination, dynamic reactive power compensation, low switching frequency.

1. INTRODUCTION

Along with the gradually deepened research on smart power grids in the 21st century, the power electronic technology plays an increasingly important role in modern power grids [1, 2]. As a new topology developed by Siemens for the direct current power transmission system with extra-high voltage and large power, modular multilevel converter (MMC) has been put into industrial application in HVDC systems in various regions including U.S. and Europe. MMC topology particularly has such advantages as modular design, fault-tolerant operation, single power supply and adaption to severe power grids, so MMC has become the popular tendency of the industrial application for extra-high voltage HVDC, and such international manufacturers as Siemens, ABB and Alston currently sell relevant products.

As the key link of MMC topology control, multilevel PWM technology directly determines the output voltage quality, the switching frequency, the harmonic distribution characteristics, etc. of HVDC current conversion system. At present, the popular PWM control strategies include two types: carrier phase-shifting PWM [3] and carrier disposition PWM [4]. Essentially, the above two PWM methods both belong to carrier modulation and are limited by carrier wave ratio required by PWM technology, so the switching frequency of HVDC system is usually above 1kHz and accordingly causes various problems, such as MMC topology device overheating and electromagnetic interference [5, 6].

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In order to optimize the electric energy quality of HVDC access point, a modular multilevel selective harmonic elimination pulse-width modulation (MSHE-PWM) method is proposed. On the basis of keeping the minimum action frequency of the power device, MSHE-PWM method can meet the requirement for accurately eliminating the low-order harmonics in the output PWM waveform. Firstly, establish the basic mathematical model of MMC topology and point out the voltage balance control principle of single modules; then, analyze offline gaining principle and realization way of MSHE-PWM switching angle; finally, verify MSHE-PWM control performance on the basis of MMC reactive power compensation experimental prototype. The experimental result shows that the proposed MSHE-PWM method can meet such performance indexes as low switching frequency and no lower-order harmonics, and has verified the feasibility and effectiveness thereof for optimizing the electric energy quality of HVDC access point.

2. MATHEMATICAL MODEL OF MMC TOPOLOGY

MMC topology structure is as shown in Fig. (**1**). The upper and lower bridge arms are composed of N single modules (SM) and one bridge arm reactor L_{arm} which are in serial connection, wherein SM is composed of two switching elements and one energy-storage capacitor, and each SM can have three operating states, namely connected state, disconnected state and locked state. The output voltage V_{arm} of the bridge arm can be freely adjusted in the range of $0 \sim V_d$ through controlling the connection-disconnection of various SMs. According to Kirchhoff's law, the mathematical model of single-phase MMC topology is established as:

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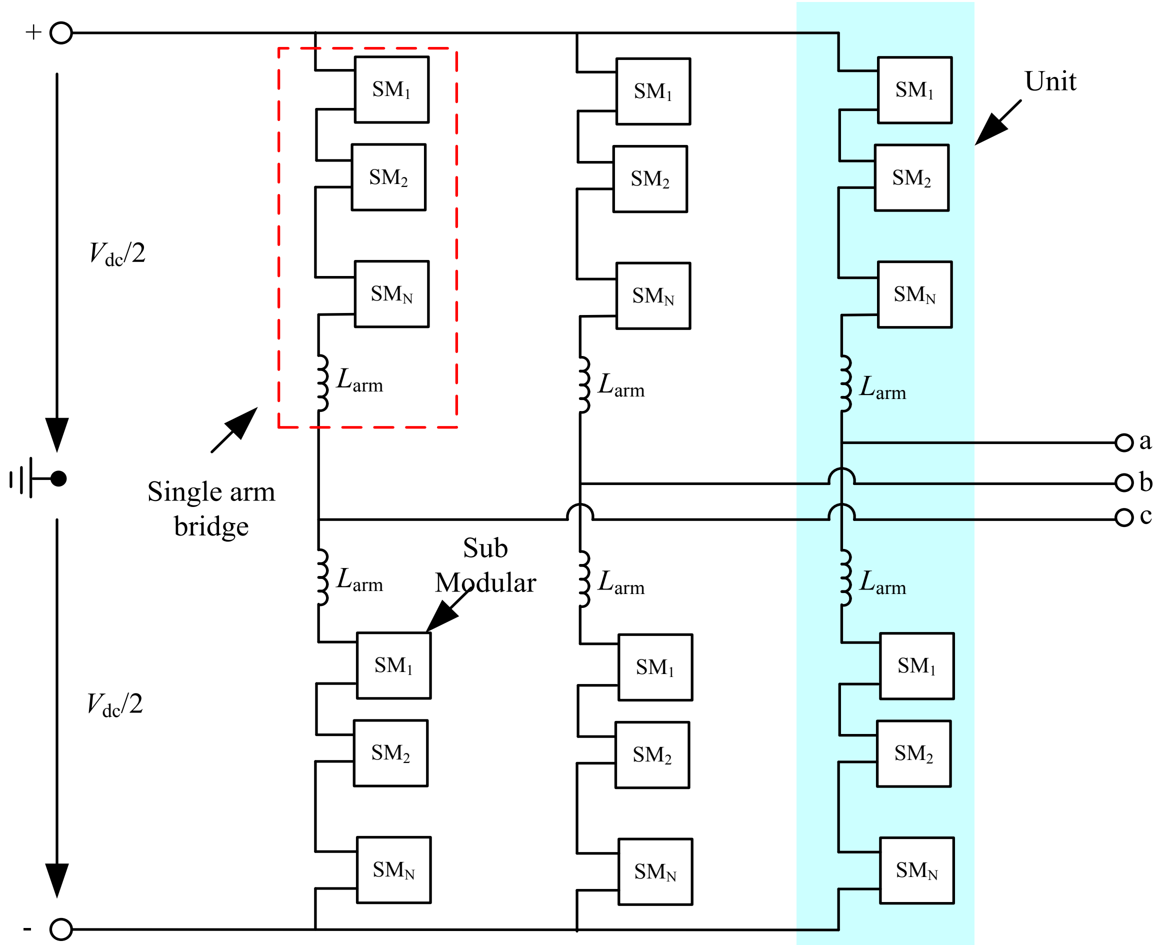


Fig. (1). MMC Topology Structure.

$$V_{arm} = \sum_{i=1}^{N} S_{SM} V_c + L_{arm} \frac{di_{arm}}{dt} \tag{1}$$

In the formula: S_{SM} is SM operating state, namely 1 for connection, 0 for disconnection and locking for state keeping; V_c is SM capacitor voltage.

Simplify formula (1) for upper and lower bridge arms to obtain:

$$\frac{V_{DC}}{2} - V_{upper} - R_{arm} i_{upper} - L_{arm} \frac{di_{upper}}{dt} - V_{middle} = 0 \tag{2}$$

$$-\frac{V_{DC}}{2} + V_{lower} + R_{arm} i_{lower} + L_{arm} \frac{di_{lower}}{dt} - V_{middle} = 0 \tag{3}$$

After addition and subtraction operations for formulae (2) and (3), deduce the output voltage and current as:

$$V_{upper} - V_{lower} + 2V_{middle} + R_{arm}\left(i_{upper} - i_{lower}\right) + L_{arm}\left(\frac{d\left(i_{upper} - i_{lower}\right)}{dt}\right) = 0 \tag{4}$$

$$V_{DC} - V_{upper} - V_{lower} + 2V_{middle} - R_{arm}\left(i_{upper} - i_{lower}\right) - L_{arm}\left(\frac{d\left(i_{upper} + i_{lower}\right)}{dt}\right) = 0 \tag{5}$$

Define the output current (i_{out}) of bridge arm as the current difference of upper and lower bridge arms, and define the circular current (i_{circ}) of bridge arm as half of the current sum of upper and lower bridge arms, namely:

$$i_{out} = i_{upper} - i_{lower} \tag{6}$$

$$i_{circ} = \frac{i_{upper} + i_{lower}}{2} \tag{7}$$

3. VOLTAGE BALANCE CONTROL OF SMS

For MMC topology, maintaining SM voltage balance is the precondition of realizing PWM strategy. According to Fig. (**1**), the bridge arm of each phase includes 2N SM units, so the expected voltage amplitude of each SM unit shall be:

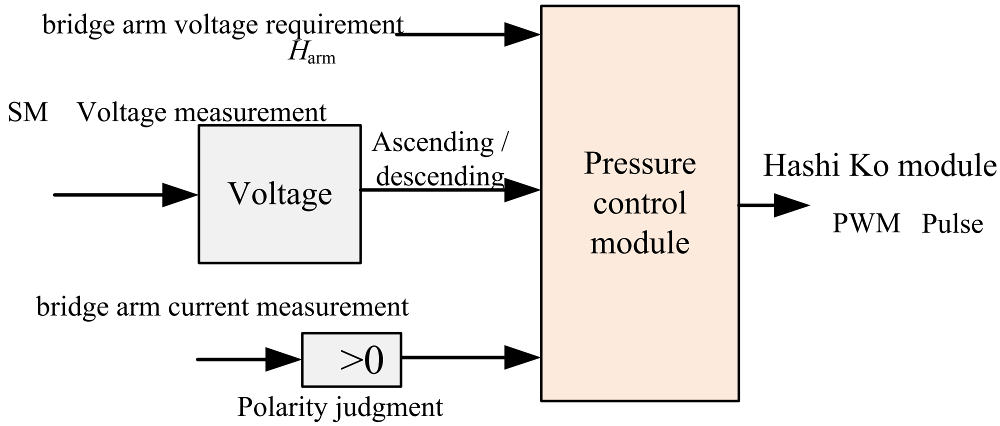


Fig. (2). Voltage Balance Principle of SMs.

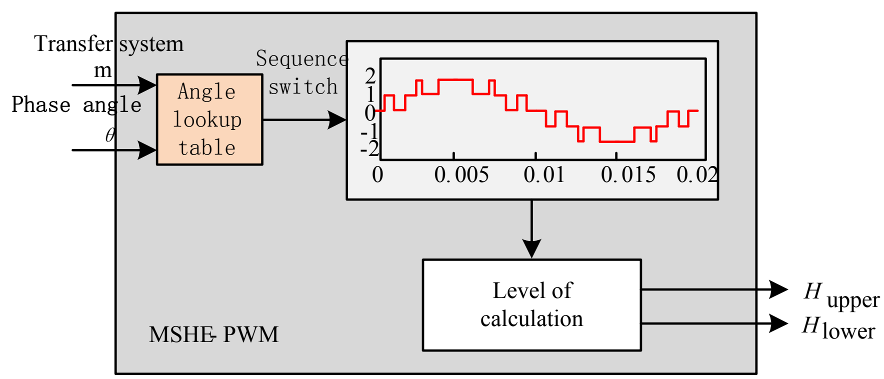


Fig. (3). MMC Topology MSHE - PWM Principle.

$$V_{SM} = \frac{V_{DC}}{N} \tag{8}$$

The charge-discharge process of bridge arm current to the capacitor of SM unit is the essential cause of resulting in the voltage fluctuation of SM unit, and the mathematical description for SM voltage change is as shown in formula (8):

$$\Delta V_c = \frac{1}{C_{SM}} \int_0^T S_{SM} i_{arm} \tag{9}$$

In the formula: voltage variation ΔV_c is jointly determined by SM state S_{SM} and bridge arm current i_{arm}.

The voltage balance control principle of SMs is as shown in Fig. (**2**). The voltage balance control algorithms of abc three-phase capacitors are independent of each other and the specific procedures are as follows:

(1) When the bridge arm current is positive value (I_{arm}>0) and one SM needs to be connected, the SM with lowest voltage is selected at this moment;

(2) When the bridge arm current is positive value (I_{arm}>0) and one SM needs to be disconnected, the SM with high voltage is selected at this moment;

(3) When the bridge arm current is negative value (I_{arm}<0) and one SM needs to be connected, the SM with highest voltage is selected at this moment;

(4) When the bridge arm current is positive value (I_{arm}<0) and one SM needs to be connected to the bridge arm, the SM with lowest voltage class is selected at this moment;

4. MSHE-PWM PRINCIPLE

MSHE-PWM is a synchronous PWM optimization technology for multilevel topology and aims at solving a nonlinear transcendental equation set for eliminating specific harmonics in order to ensure the quality of the multilevel PWM waveform output under low switching frequency. MMC topology MSHE-PWM principle is as shown in Fig. (**3**). It is necessary to inquire angle form according to the expected voltage modulation degree m and phase angle θ to obtain the level output by MMC phase voltage. In order to ensure the direct-current voltage stabilization of MMC topology and avoid inter-phase circular current and the significant fluctuation of capacitor voltage of SMs, SM unit numbers N_{upper} and N_{lower} of upper and lower bridge arms shall be complementarily output; in other words, the total module number connected for each phase at each moment shall be the same [7-10].

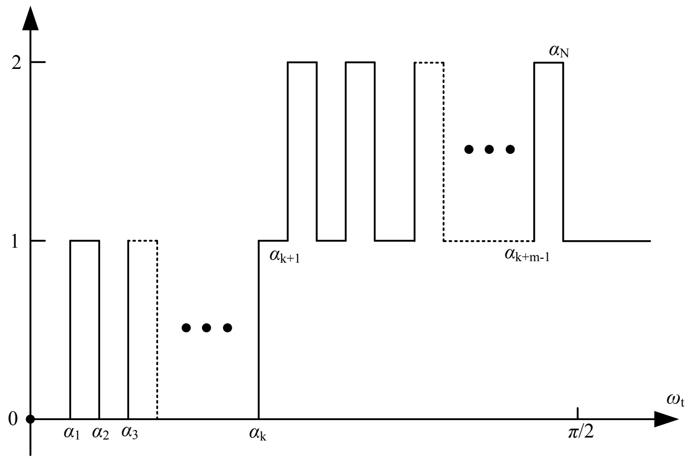


Fig. (4). Quarter Five Level SHE - PWM Phase Voltage Distribution.

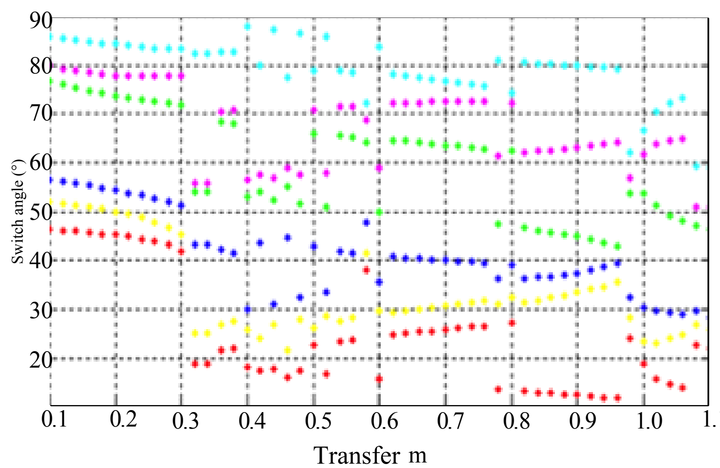


Fig. (5). Five level MSHE-PWM Solution Trajectory When k/m=3/3.

$$N_{\text{upper}} + N_{\text{lower}} = N \quad (10)$$

$$N_{\text{upper}} - N_{\text{lower}} = \text{Level} \quad (11)$$

Quarter five level MSHE-PWM phase voltage distribution is as shown in Fig. (**4**). Therein, $\alpha_1 \sim \alpha_N$ are the switching angles corresponding to N groups of phase voltages. Under the condition of taking $\alpha_1 \sim \alpha_N$ as the system variables, the ideal phase voltage equation is as follows:

$$\begin{aligned} &\sum_{i=1}^{k}(-1)^{i-1}\cos(\alpha_i)+\sum_{i=k+1}^{N}(-1)^{i-(1+k)}\cos(\alpha_i)=M \\ &\sum_{i=1}^{k}(-1)^{i-1}\cos(n\alpha_i)+\sum_{i=k+1}^{N}(-1)^{i-(1+k)}\cos(n\alpha_i)=0 \end{aligned} \quad (12)$$

In the formula, M is system modulation degree, M∈[0, 2]; *n*=5, 7, …, 3*N*-2, and N is odd number.

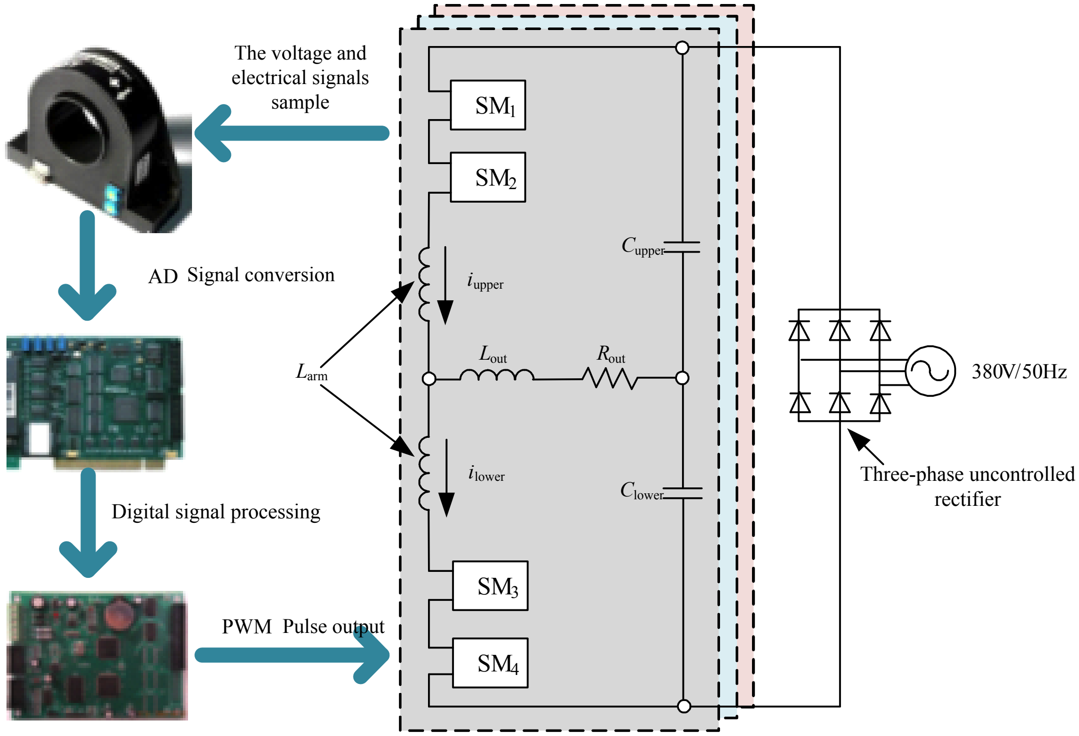
A_1 is assumed as the amplitude of the fundamental component of the modulation voltage and shall meet the following constraint conditions:

$$\begin{aligned} &A_1 = \frac{4V_{dc}}{\pi} \cdot M \\ &0 < \alpha_1 < \alpha_2 < \cdots \alpha_{k+m} < \frac{\pi}{2} \end{aligned} \quad (13)$$

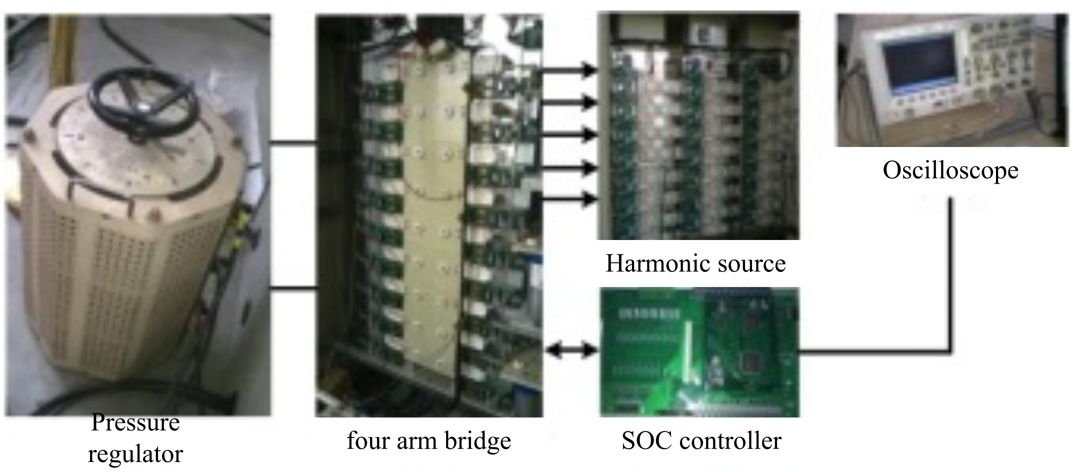
Under the condition of meeting the constraint conditions in formula (13), it is necessary to solve the nonlinear transcendental equation set as shown in formula (12) [11]. According to the analysis chart 4, $\alpha_1 \sim \alpha_k$ are the switching angles corresponding to the voltage jump from state 0 to state 1 and $\alpha_{k+1} \sim \alpha_m$ are the switching angles corresponding to the voltage jump from state 1 to state 2, *N*=*k*+*m*. *k* and *m* can be odd number or even number, and in order to accelerate the offline iteration solution, a hidden system constraint is added to reduce the system solution domain, namely *k*=3, *m*=3, N=6. The five level MSHE-PWM solution trajectory when k/m=3/3 is given in Fig. (**5**).

5. EXPERIMENTAL VERIFICATION

In order to verify the feasibility and effectiveness of MSHE-PWM control method, one set of 380V/55kW HVDC



(**a**) Structure Principle

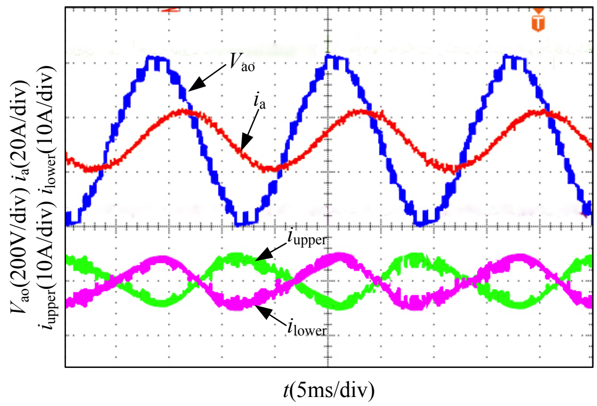


(**b**) Machine sample

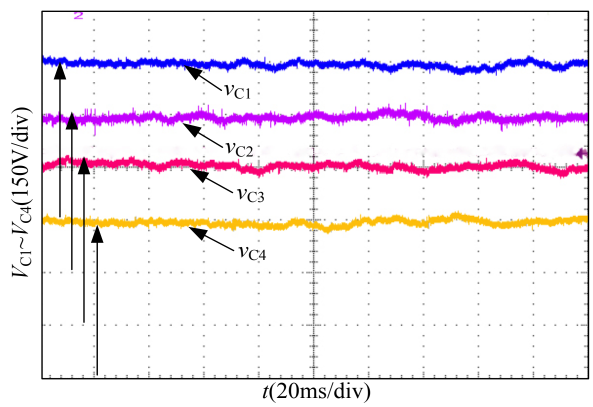
Fig. (6). 380 v / 55 kw Prototype.

system experimental prototype as shown in Fig. (**6a**) is established. In consideration of the requirement of MMC topology for multi-path PWM pulse, Sparten 3e FPGA of Xilinx Corporation is selected as the core controller, and 75GB124D of Semikron Corporation is selected as IGBT switching device. The MSHE-PWM method principle is as shown in Fig. (**6b**), therein: network voltage = 380V, DC bus voltage u_{dc}= 600V, filter reactor L=1.2mH, and equivalent resistance R=0.8Ω.

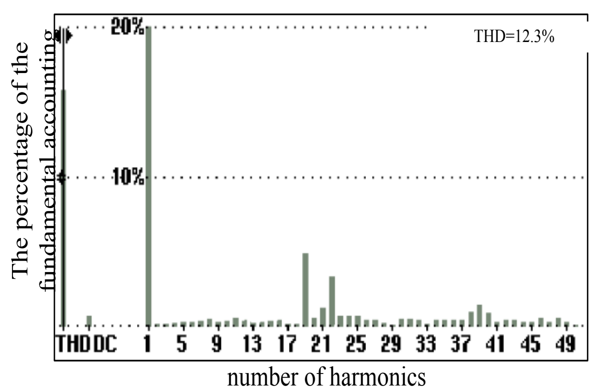
The experimental results of MMC topology controlled by MSHE-PWM are as shown in Fig. (**7**). In Fig. (**7a**), the line voltage V_{ab} at the load side is 17-level step wave, phase-a output current i_a is sine wave, phase-a bridge arm currents i_{upper} and i_{lower} are composed of DC component and second harmonics; the capacitor voltage V_{C1}-V_{C4} of SM unit of upper bridge arm are as shown in Fig. (**7b**), and according to the figure, V_{C1}-V_{C4} all fluctuate around the expected value 150V, and within the fluctuation range of 10%(15V), the effectiveness of the voltage balance control of SMs has been verified; the spectral analysis result of the line voltage V_{ab} at the load side as shown in Fig. (**7c**) indicates that MSHE-PWM can effectively eliminate all harmonics of 17 (850Hz) line voltages V_{AB} and the corresponding total harmonic distortion (THD) is 12.3%, so MSHE-PWM can ensure the quality of



(**a**) Prototype



(**b**) Module Capacitor Voltage



(**c**) Line Voltage Frequency Spectrum

Fig. (7). Experimental Results of MMC Topology Controlled by MSHE-PWM

the line voltage waveform output by MMC topology under low switching frequency [12-16].

CONCLUSION

In order to optimize the electric energy quality of HVDC access point, the article proposes a MSHE-PWM method for MMC topology. The experimental results have verified the feasibility and effectiveness of this method and the following conclusions can be obtained: 1) the application of MSHE-PWM technology in MMC topology control can realize the design requirement of no low-order harmonics in PWM waveform under low switching frequency and accordingly ensure the electric energy quality of access point of HVDC system; 2) the voltage balance control of SMs can make SM capacitor voltage kept at the same level to ensure the realizability of MSHE-PWM technology in MMC topology.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENTS

Declared none.

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