

Control of Hexagonal Modular Multilevel Converter for 3-phase BTB System

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Abstract— The Modular Multilevel Converter (MMC) with cascaded full bridge cells is available for AC/AC transmission system without transformers in high voltage line. This research applied a Hexagonal MMC (H-MMC) to 3-phase AC-AC back-to-back (BTB) system. The H-MMC has six arm modules with floating capacitors and is required to regulate the input-output power and capacitor voltages by controlling currents in arm modules. Theory of the power flow of H-MMC is analyzed and the control scheme of the power flow and capacitor voltage regulation is proposed. Currents in the arm modules are controlled by the internal model principle and H-MMC can operate appropriately. Effectiveness of the proposed control method is presented in simulation and experiment.

Keywords— modular multilevel converter, AC/AC converter, back to back system, power flow control

I. INTRODUCTION

In recent years, energy conservation problems have been important due to CO₂ emission, abandoning nuclear generation and so on. In such situation, renewable energy systems have been focused and a lot of photovoltaic and wind power generation systems have introduced all over the world. However renewable energy generations give influence of voltage fluctuation to power grid because of their unstable output and reverse power flow. Therefore it is important to maintain the voltage of power line. This importance will increase by promotion of the electricity liberalization. In general, AC/AC transmission system is introduced for power flow control. Many kinds of AC/AC system such as back-to-back (BTB) system, cycloconverter and matrix converter are developed and investigated.

On the other hands, several kinds of multilevel converter for high voltage and less harmonics are investigated. Conventional multilevel converter has transformers on DC bus, which is one of the reasons of heavy and large system. A modular multilevel converter (MMC)[1]-[9] is one of the transformer-less converter and applies to high voltage and high power conversion. The MMC consists of cascaded switching device modules with floating capacitors.

The multilevel converter such as the MMC can improve waveform and reduce harmonics by multilevel voltage output. The triple star type MMC[6] and the

hexagonal type MMC[7][8] are constructed as a 3-phase AC/AC converter. The hexagonal MMC (H-MMC) can be applied to power flow control system instead of BTB system. In addition, this is less flexibility than the triple star type MMC and conventional multilevel BTB system, but is able to realize to reduce a number of cells compared with those systems. This H-MMC topology is expected for a wide range of fields such as a wind power converter, a grid connection converter and high voltage motor drive.

In this paper, H-MMC is investigated and applied to BTB system for a power flow controller. Theory of the power flow of H-MMC is analyzed and the control scheme of the power flow and capacitor voltage regulation for H-MMC is proposed. Effectiveness of the proposed control is shown by simulation and experiment in typical cases.

II. CONFIGURATION OF CIRCUIT

Fig.1 shows the configuration of H-MMC. The H-MMC has 6 arm-modules connected in hexagonal ring shape. These modules consist of multiple cascade full bridge cells which have floating capacitors. Each arm module has a buffer reactor for preventing short circuit and current regulation. The number of cells in an arm-module is 2 as shown in Fig.1(a). Number of these can be increased depending on usage situation. In Fig.1(a), terminals of R,S,T are primary side of power line and terminals of U,V,W are secondary side. Primary power via R,S,T can be flowed to floating capacitors and secondary side via UVW. This configuration means that RST-delta connection and UVW-delta connection overlap each other. Thus each arm module has primary and secondary line-to-line current.

The power on primary side, the power on secondary side and all the voltages of floating capacitors in cells are required to regulate by controlling output of the modules. When the arm current is controlled in case of different frequencies between primary and secondary side, it is necessary that two frequency components are controlled at the same time. In this research, the internal model principle is applied to the current control to obtain a good current regulation.

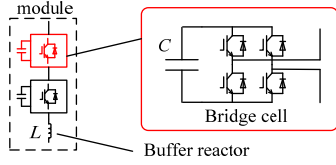
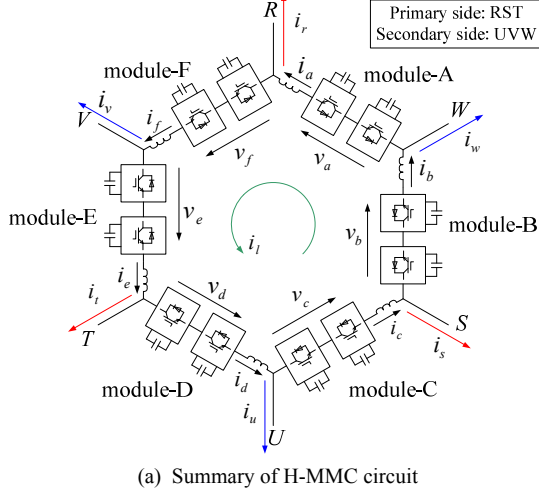


Fig. 1. Circuit configuration of H-MMC

III. CONTROL OF HEXAGONAL TYPE MMC

When H-MMC is applied to a power converter, it is able to convert frequency and voltage arbitrarily without transformer. At this time, currents of each arm module must be controlled to be non-sinusoidal waveform, which is due to overlap line-to-line currents of primary and secondary. It is important that every capacitor voltage is managed to be constant and arm currents are exactly controlled without steady state error. In this study, capacitor voltages are kept by current control based on analysis the power flow in H-MMC. When the line-to-line current i_{rs} is current for primary node R - S and the line-to-line current i_{vw} is current for secondary node X - Y , current of arm-module A is calculated in (1).

$$i_a = i_{rs} + i_{vw} \quad (1)$$

Other currents of modules are obtained the same as (1).

A. PQ-coordinate transformation

The control of primary and secondary power is realized by the pq-coordinate transform. In particular, the primary power control is handled in the pq-current in order to regulate all the floating capacitor voltages. Thereafter the pq-quantity is transformed to 3-phase quantity and the primary 3-phase currents are controlled together with the secondary 3-phase currents by the arm modules.

The pq-transform is defined as following equation.

$$\begin{bmatrix} F_p \\ F_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin \omega_0 t & \sin \left(\omega_0 t - \frac{2\pi}{3} \right) & \sin \left(\omega_0 t - \frac{4\pi}{3} \right) \\ \cos \omega_0 t & \cos \left(\omega_0 t - \frac{2\pi}{3} \right) & \cos \left(\omega_0 t - \frac{4\pi}{3} \right) \end{bmatrix} \begin{bmatrix} f_u \\ f_v \\ f_w \end{bmatrix} \quad (2)$$

, where F_p and F_q are active and reactive component respectively. f_u, f_v and f_w are 3-phase components. ω_0 is an angular frequency the same as u, v, w -phase one.

B. Power flow control in secondary side

Power in secondary side can be controlled to arbitrarily value by using the pq-theory. The pq currents in secondary side are converted to 3-phase line-to-line currents with voluntary frequency, which are controlled by the arm modules.

C. Power flow control in primary side

Power in primary side can be controlled in accordance with the secondary power by the pq-theory. In this control, however, the primary power is also controlled to maintain each capacitor voltage. The pq-current references in primary side are calculated from capacitor voltages in modules because there is relevance between the primary power and the capacitor voltage. Then power flows involved in arm-modules are analyzed. The average power of each arm-module is constructed by overlap of primary and secondary power, which is defined as P_A, P_B, P_C, P_D, P_E and P_F , respectively. These average powers are calculated by the following equations.

$$\begin{aligned} P_{ACE} &= P_A = P_C = P_E \\ &= \frac{V_1 I_1}{\sqrt{3}} \cos \left(\phi_1 - \frac{\pi}{6} \right) - \frac{V_2 I_2}{\sqrt{3}} \cos \left(\phi_2 - \frac{5\pi}{6} \right) \end{aligned} \quad (3)$$

$$\begin{aligned} P_{BDF} &= P_B = P_D = P_F \\ &= -\frac{V_1 I_1}{\sqrt{3}} \cos \left(\phi_1 - \frac{5\pi}{6} \right) + \frac{V_2 I_2}{\sqrt{3}} \cos \left(\phi_2 - \frac{\pi}{6} \right) \end{aligned} \quad (4)$$

, where V_1 and I_1 are RMS volumes in primary side, V_2 and I_2 are RMS volumes in secondary side. ϕ_1 is the power factor angle in primary side, and ϕ_2 is the power factor angle in secondary side.

And the average power is calculated by (5).

$$P_x = \frac{1}{T} \int_{t-T}^t P_x dt = \frac{1}{T} \int_{t-T}^t v_x i_x dt \quad (5)$$

$$(X = A-F, x = a-f)$$

(3) and (4) show that modules A,C,E and modules B,D,F have the same average power P_{ACE} and P_{BDF} respectively. Following equations show sum of P_{ACE} and P_{BDF} .

$$P_{ACE} + P_{BDF} = V_1 I_1 \cos \phi_1 + V_2 I_2 \cos \phi_2 \quad (6)$$

(6) shows the fluctuation of energy in H-MMC. If (6) is positive, all the capacitor voltages increase because the energy is stored in H-MMC. Otherwise, all the capacitor voltages decrease because the energy is emitted from H-MMC. Therefore, it is desirable that (6) is maintained to 0 in order to operate H-MMC exactly at steady state. In this case, (7) is obtained.

$$v_L^* = |K_{DV}(v_{C_BDF} - v_{C_ACE})| \quad (13)$$

The total loop current reference is calculated by (14).

$$i_l^* = i_{l1}^* + i_{l2}^* + i_L^* \quad (14)$$

(14) is added to current reference of each arm module and (13) is added to voltage reference of arm module B,D,F and subtracted to voltage reference of arm module A,C,E.

E. Internal model principle

Power conversion and module voltage balance are controlled by regulating currents in H-MMC. Currents of modules are expressed by the following equations.

$$i_a^* = i_{rs}^* + i_{vw}^* + i_l^* \quad (15)$$

Other current references of modules are obtained the same as (15). Each module current has both frequencies in primary and secondary side. Therefore it is difficult to regulate the current of arm-modules accurately.

In this research, the module current is directly controlled by applying the internal model principle. The internal model principle has a merit that the applied controller can realize current control without steady error. It is defined that the transfer function of control system has mathematical model of reference signal. $G_C(s)$ is the transfer function of controller which includes two sinusoidal function models.

$$G_C(s) = \frac{K_{Sc1}s}{s^2 + \omega_1^2} + \frac{K_{Sc2}s}{s^2 + \omega_2^2} \quad (16)$$

Based on (16), Control strategy of current controller of each module is shown in (17).

$$v_x^* = K_{pc}(i_x^* - i_x) + \left(\frac{K_{Sc1}\omega_1^2 s}{s^2 + 2\zeta\omega_1 s + \omega_1^2} + \frac{K_{Sc2}\omega_2^2 s}{s^2 + 2\zeta\omega_2 s + \omega_2^2} \right) (i_x^* - i_x) \quad (17)$$

$$(x = a - f)$$

First term in the right side is a proportional control, and second term is a control of the internal model principle with damping. The damping coefficient is valid at transient, but is 0 in steady state. The controller has sinusoidal internal model of primary and secondary frequencies.

F. Voltage balance in each module

Voltage balance in each module is introduced[1]. Because unbalance in each arm module occurs due to variations of individual differences of capacitance, switching delay and so on. The balancing control is given by (18).

$$v_{B-xn}^* = -K_B(\bar{v}_{Cx} - v_{C-xn})i_x \quad (18)$$

$$\bar{v}_{Cx} = \frac{\sum_{n=1}^N v_{C-xn}}{N} \quad (19)$$

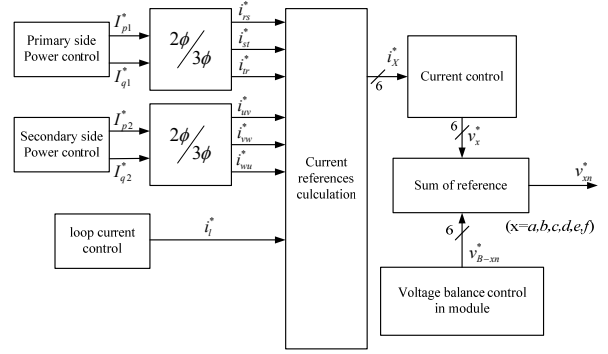


Fig. 4. Configuration of total control system

where (19) is average value of cell capacitor voltages in an arm module and N is the number of cells. v_{C-xn} is capacitor voltage, v_{B-xn}^* is voltage reference value for balancing capacitor voltage in each module. Index '-xn' means n -th cell in x -module. This control can adjust voltage balance among cells in an arm module because of exchange of power among cells. Voltage reference values in (13), (17) and (18) are summed up and output from each cell.

The configuration of overall control system is shown in Fig.4.

IV. SIMULATION

Simulation is performed to verify the proposed control methods by using interconnection circuit of power line in Fig.5. Table I shows the parameters of the circuit, and table II shows the control gains. In this research, the H-MMC has 2 full-bridge cells per an arm module, and each cell is operated the uni-pole PWM switching with shifted triangular wave of which phase is shifted according to the number of modules. The line voltage becomes 9-levels in case of 4 cells in line-to-line modules. The H-MMC can realize multilevel voltage output by this PWM switching pattern.

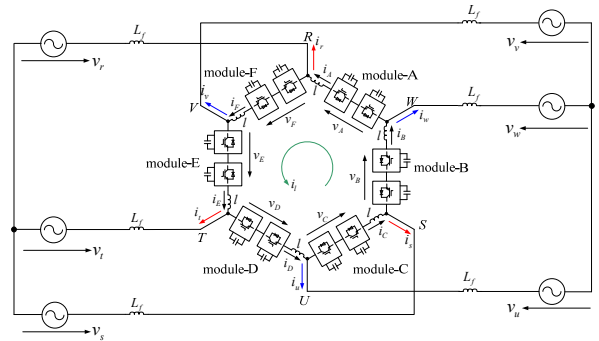


Fig. 5. Simulation circuit

TABLE I
PARAMETERS OF CIRCUIT

V_1	200Vrms	V_2	200Vrms
l	5mH	C	5000 μ F
v_c^*	200V	L_f	3mH

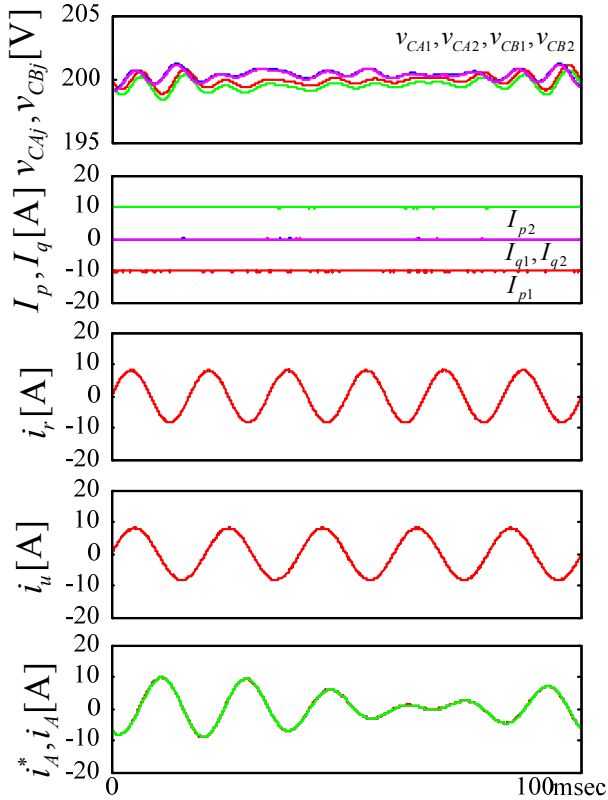


Fig. 6. Simulation result ($f_1: 60\text{Hz}, f_2: 50\text{Hz}$)

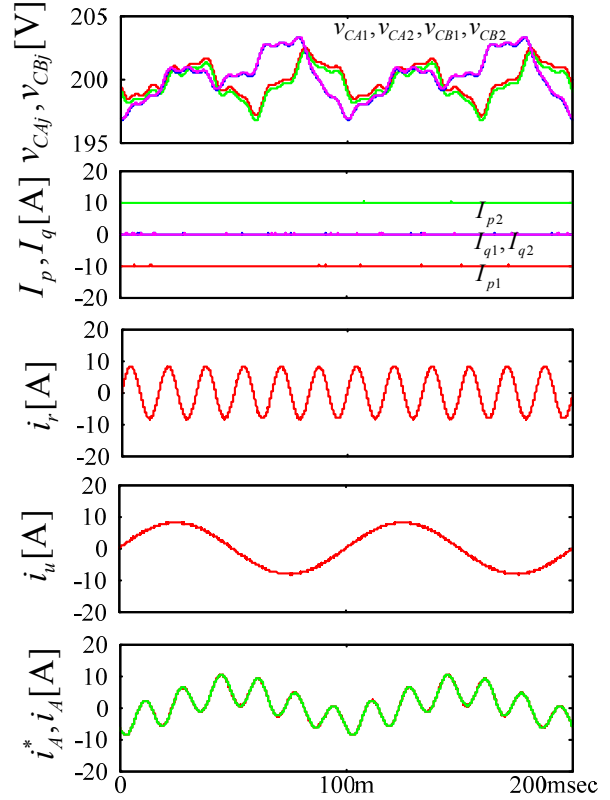


Fig. 7. Simulation result ($f_1: 60\text{Hz}, f_2: 10\text{Hz}$)

TABLE II
GAINS OF CONTROL

K_{P1}	1.5	K_{I1}	5.0
K_{Se1}	0.1	K_{Se2}	0.1
K_{Pc}	40	K_L	0.5
K_{DI}	1.5	K_{DV}	15
K_B	0.1		

Fig.6 shows a simulation result that input frequency is 60Hz and output frequency is 50Hz. It is confirmed that I_{p1} and I_{p2} are the same absolute value 10A but opposite sign at steady state. This means that received active power of H-MMC from primary side is the same value as the supplied active power to secondary side. Average voltage of all floating capacitors is maintained to be constant value around 200V. On the other hand, current of primary side, secondary side and arm module can be outputted accurately. Especially, current of arm module is precisely regulated by the internal model principle in spite of mixed frequency.

Fig. 7 shows a simulation result that input frequency is 60Hz and output frequency is 10Hz. The good result is obtained like Fig.6. These simulation results show that H-MMC is able to convert exactly regardless of frequency and voltage. The H-MMC can be applied to grid connection converter as a power flow controller and a power conditioner for wind generators.

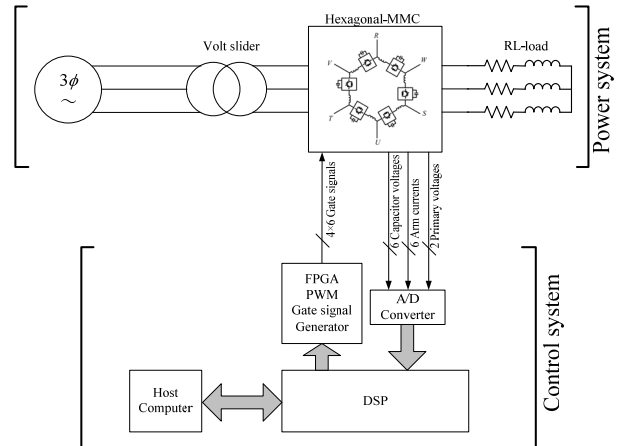


Fig. 8. Experimental system

TABLE III
PARAMETERS OF EXPERIMENTAL CIRCUIT

V_1	12Vrms	V_2	12Vrms
l	1.5mH	C	3300 μF
R	22 Ω	L	10mH
v_C^*	30V		

V. EXPERIMENT

Experimental system is constructed for a basic test of H-MMC as shown in Fig.8. This system has single cell per arm module and power scale of circuit is small in Table III. All the controls are executed by the DSP (TI : TMS320C6713-225) and PWM of the shifted triangular

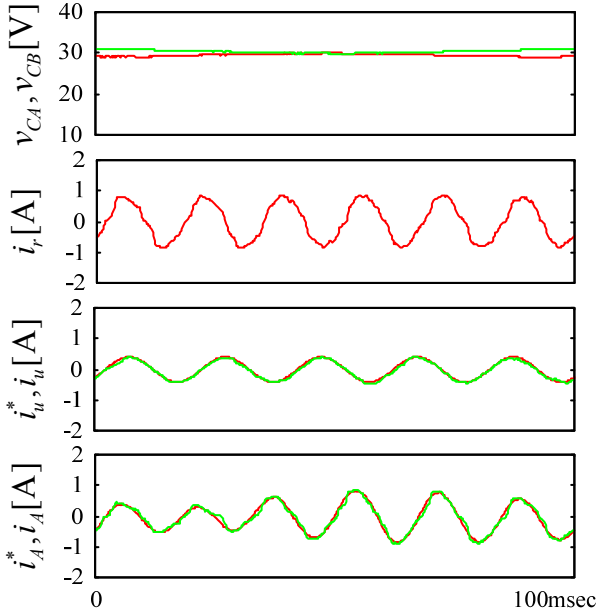


Fig. 9. Experimental result ($f_1 : 60\text{Hz}, f_2 : 50\text{Hz}$)

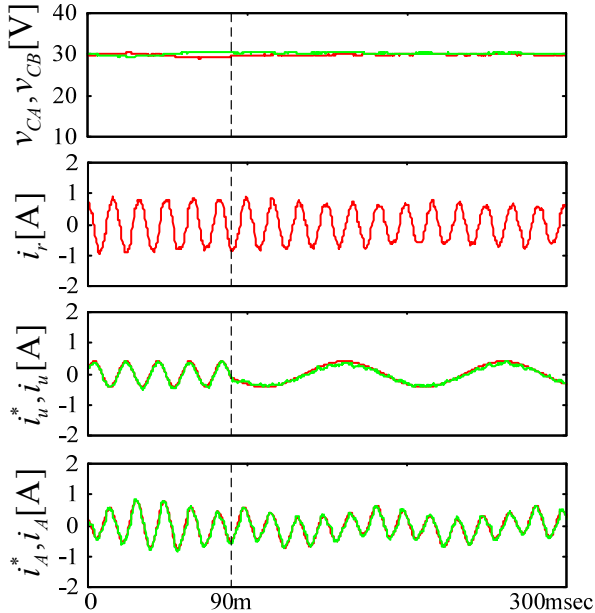


Fig. 10. Experimental result ($f_1 : 60\text{Hz}, f_2 : 50 \text{ to } 10\text{Hz}$)

wave is executed by the FPGA (Xilinx : XC3S1500-4FG456C). Switching frequency of each cell is 10kHz and sampling period of DSP is 100 μs in the experiment.

Fig.9 shows an experimental result that input frequency is 60Hz and output frequency is 50Hz. Voltage of each floating capacitor is maintained to be constant value around 30V. Current of primary side, secondary side and arm module can be outputted accurately. Current of arm module is precisely regulated by the internal model principle in spite of mixed frequency. This behavior is very similar to the simulation.

Fig.10 shows an experimental result that input frequency is 60Hz and output frequency changes from 50Hz to 10Hz by step. Output current in secondary side changes smoothly and regulated correctly. Voltage of capacitor

keeps constant around 30V without influence of change.

Experimental results clarify that the proposed control method for H-MMC is able to work correctly and has good performance for power flow and voltage regulation of floating capacitors.

VI. CONCLUSIONS

This paper investigated a new control of Hexagonal MMC for 3-phase BTB system. The H-MMC is applied to grid connection system and proposed how to control the power flow in primary and secondary side and the floating capacitor voltage of the H-MMC. In the H-MMC, sinusoidal currents with mixed frequency are controlled directly by using the internal model principle controller. The simulation and the experiment demonstrated that the proposed control method is able to control exactly and have a good performance. We intend to increase the number of cell of the experimental system and test in the near future.

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